US012062964B2

(12) **United States Patent**
Mawatari et al.

(10) **Patent No.: US 12,062,964 B2**
(45) **Date of Patent: Aug. 13, 2024**

(54) **ARMATURE**

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(72) Inventors: **Yuki Mawatari**, Kariya (JP); **Akito Tamura**, Kariya (JP); **Hiroyuki Tsuchiya**, Kariya (JP); **Akira Fukushima**, Kariya (JP); **Yuki Takahashi**, Kariya (JP)

(73) Assignee: **DENSO CORPORATION**, Kariya (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 377 days.

(21) Appl. No.: **17/411,318**

(22) Filed: **Aug. 25, 2021**

(65) **Prior Publication Data**

US 2021/0384789 A1 Dec. 9, 2021

Related U.S. Application Data

(63) Continuation of application No. PCT/JP2020/006904, filed on Feb. 20, 2020.

(30) **Foreign Application Priority Data**

Feb. 25, 2019 (JP) 2019-032186

(51) **Int. Cl.**
H02K 3/50 (2006.01)
H02K 11/33 (2016.01)

(52) **U.S. Cl.**
CPC ***H02K 3/50*** (2013.01); ***H02K 11/33*** (2016.01); *H02K 2203/09* (2013.01)

(58) **Field of Classification Search**
CPC H02K 3/28; H02K 3/50; H02K 21/12; H02K 1/278; H02K 11/225; H02K 11/33;
(Continued)

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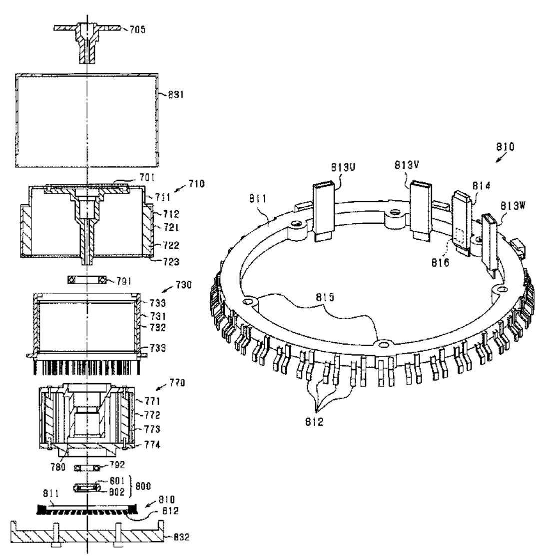
Primary Examiner — Alex W Mok
(74) *Attorney, Agent, or Firm* — Oliff PLC

(57) **ABSTRACT**

An armature which radially faces a magnetic field-producing unit equipped with a magnet unit having a plurality of magnetic poles includes a housing, an armature core, a multi-phase armature winding, and bus bars. The housing includes a cylinder and a disc-shaped end plate placed in contact with one of axially opposed ends of the cylinder. The armature core is disposed on a portion of the cylinder which radially faces the magnet unit. The armature winding is disposed on a portion of the armature core which radially faces the magnet unit. The bus bars electrically connect phase windings of the armature winding together. The armature also includes a bus bar module which is of a circular or C-shape extending along the circumference of the armature core. The bus bar module is secured to the cylinder, the end plate, or one of axially opposed ends of the armature core.

14 Claims, 77 Drawing Sheets



(58) **Field of Classification Search**
CPC H02K 1/20; H02K 1/2786; H02K 3/47; H02K 9/19; H02K 2203/09
USPC 310/71
See application file for complete search history.

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FIG.1

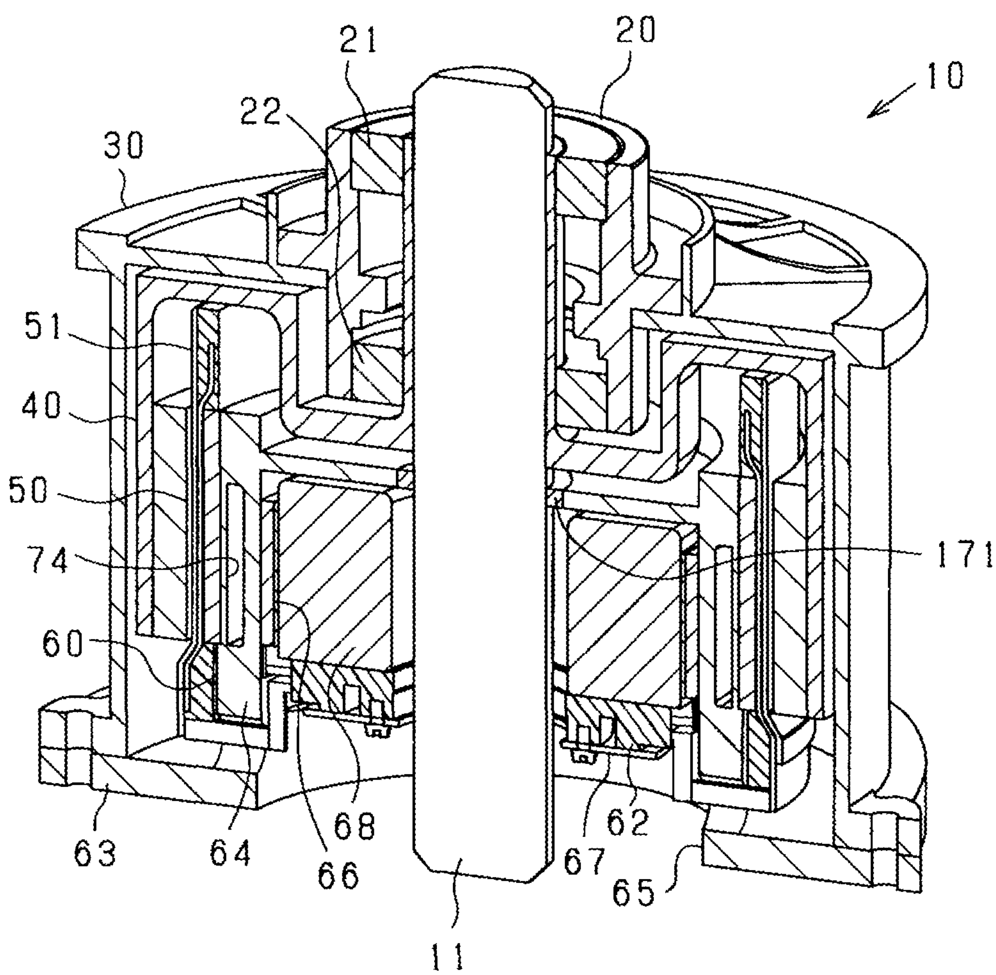


FIG.2

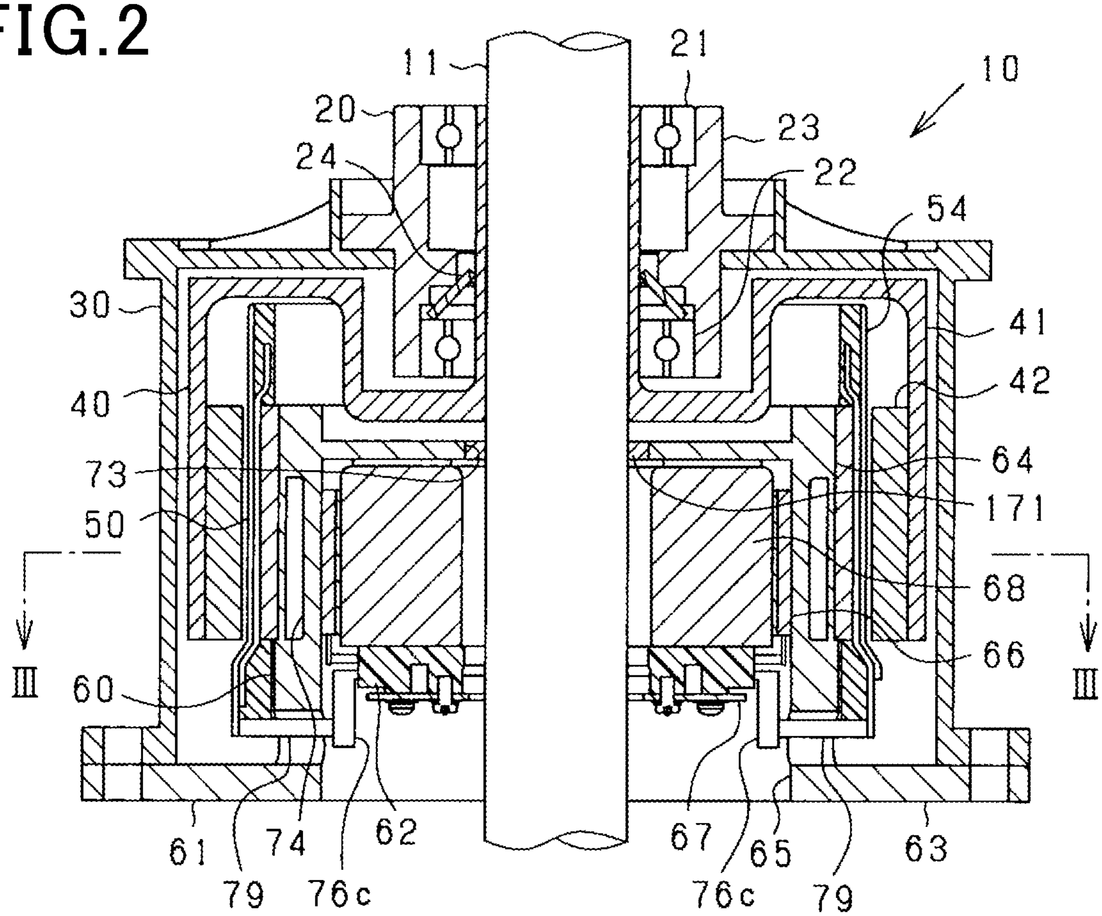

11
21
10
20
23
24
22
54
30
41
40
42
73
64
50
171
68
66
III
60
III
67
65
62
74
61
63
79
76c
76c
79

FIG.3

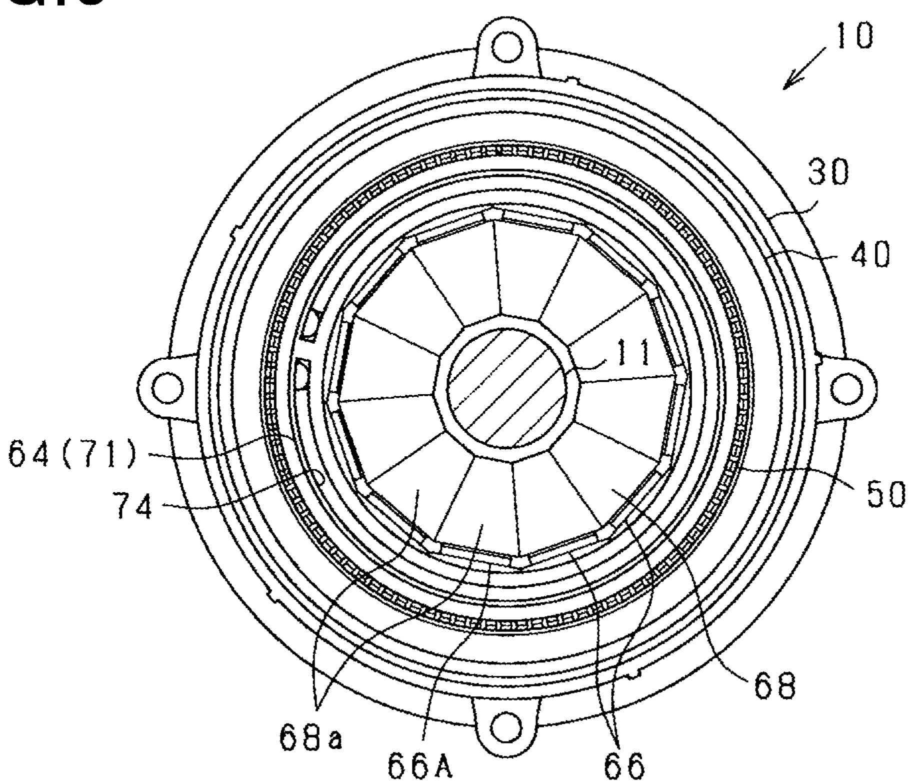

10
30
40
11
64(71)
74
50
68
68a
66A
66

FIG.4

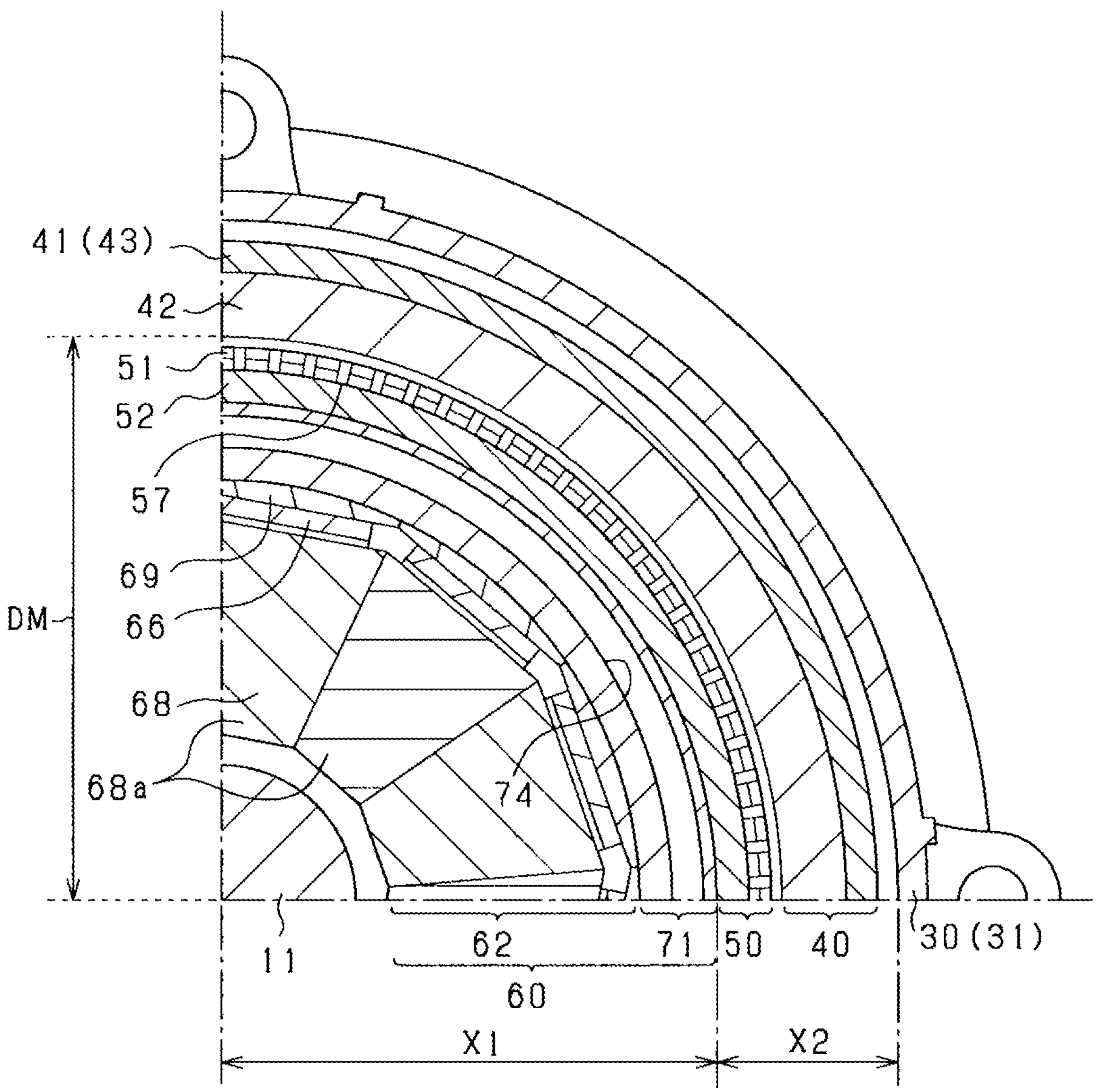


FIG.5

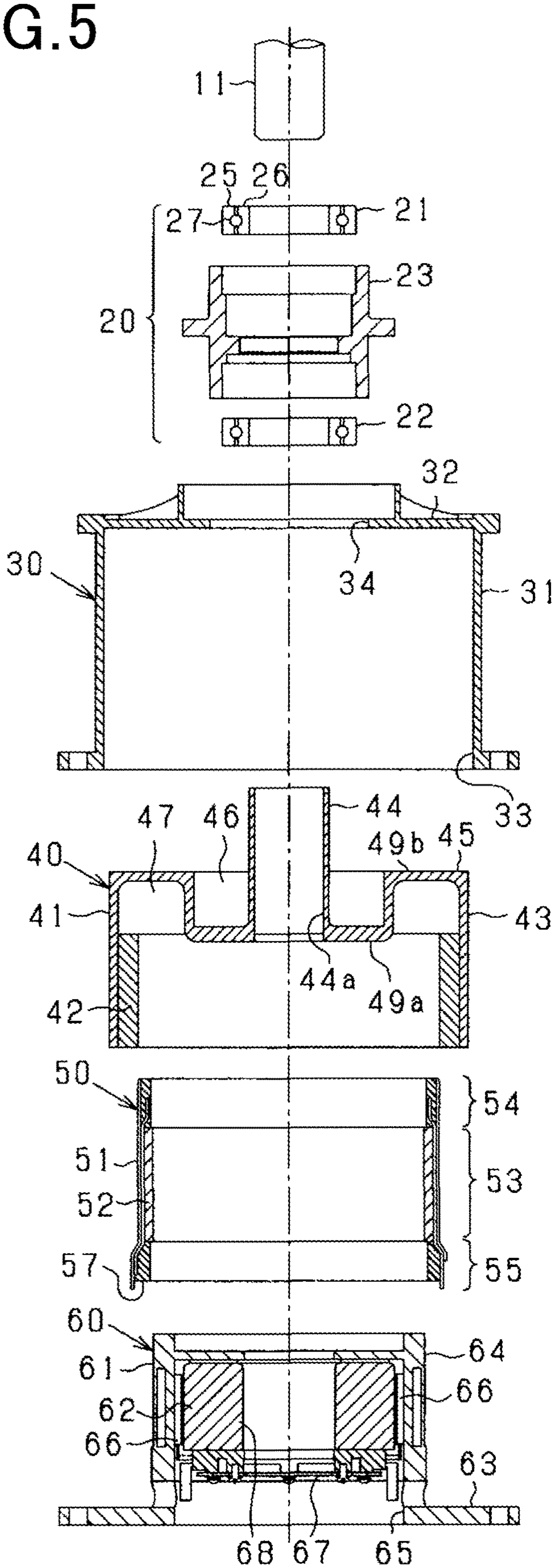
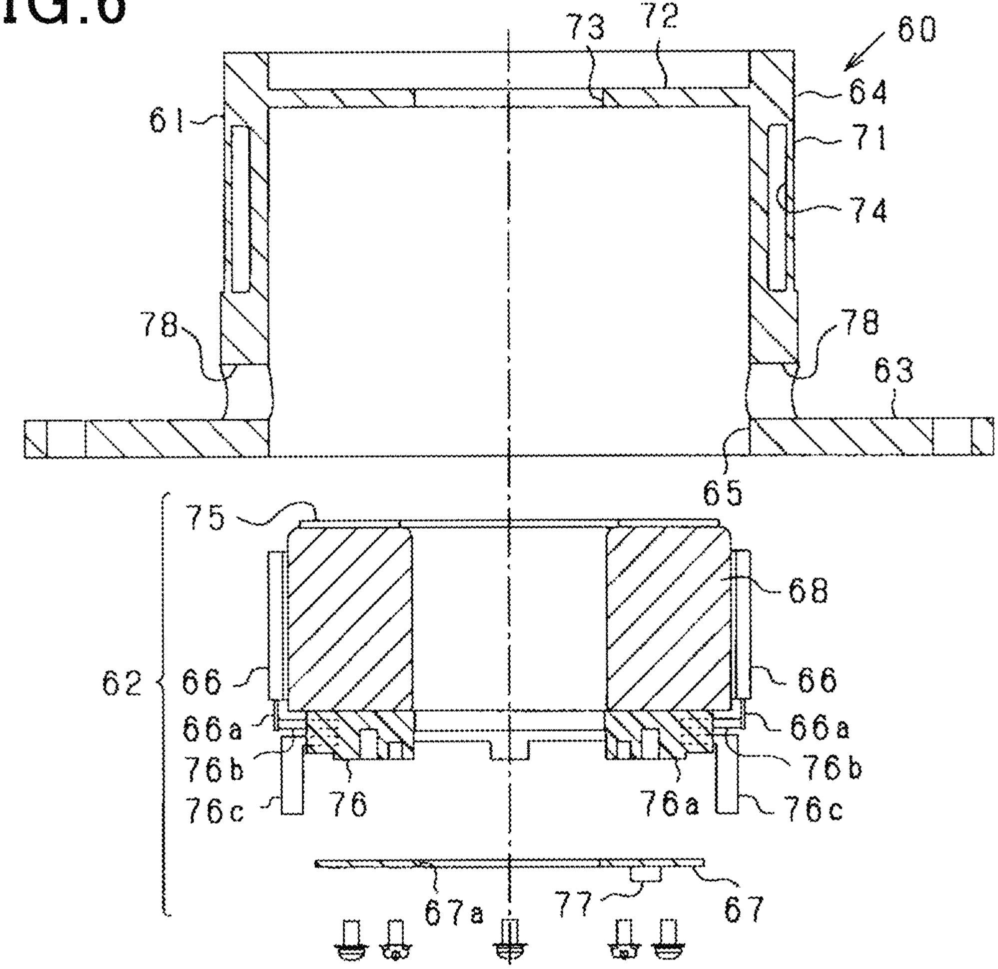
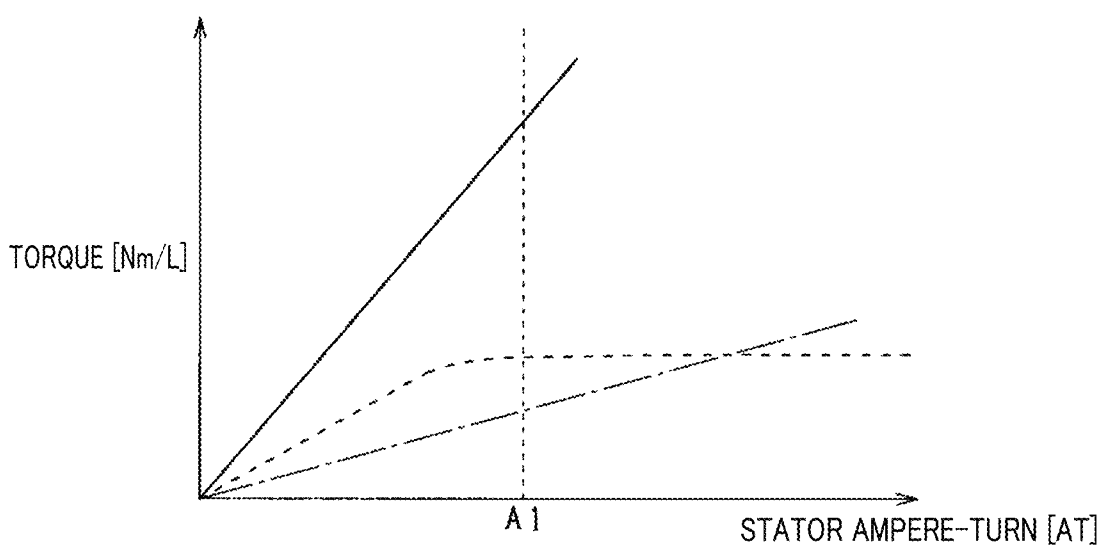

11
25
26
27
21
23
20
22
32
30
34
31
33
44
47
46
49b
45
40
41
43
44a
49a
42
50
54
51
53
52
57
55
60
64
61
66
62
66
63
68
67
65

FIG.6



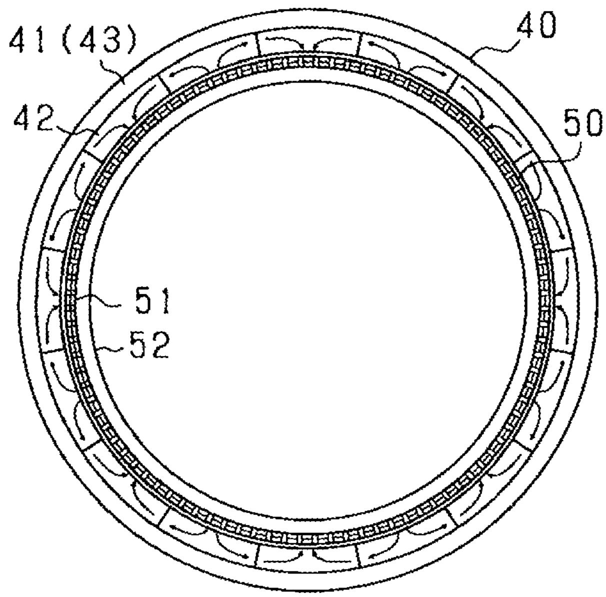
60
73
72
64
61
71
74
78
78
63
65
75
68
62
66
66
66a
66a
76b
76b
76c
76
76a
76c
67a
77
67

FIG.7



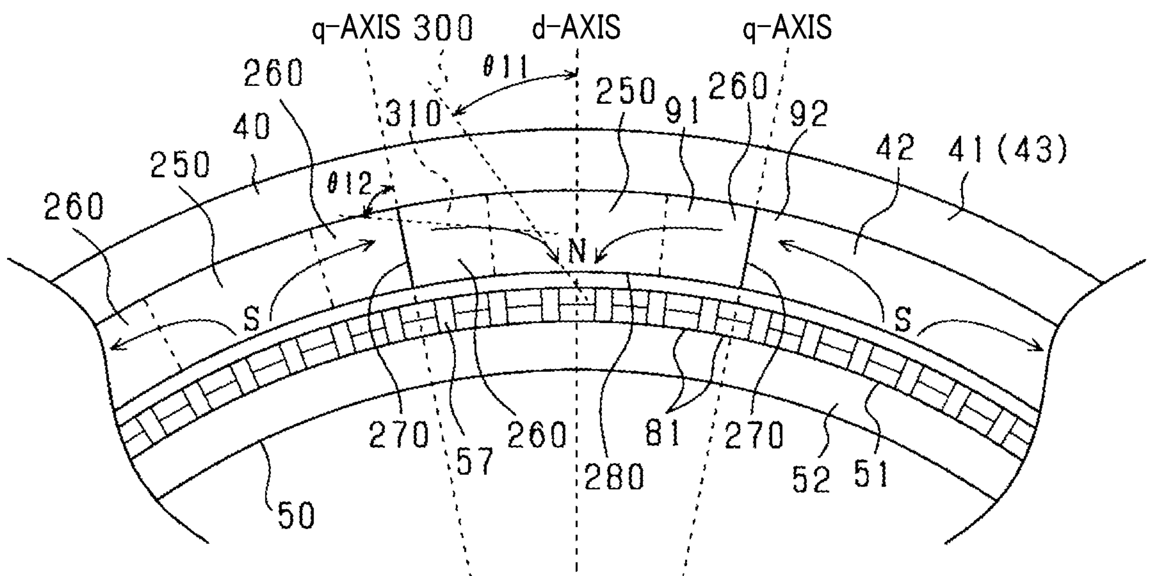
TORQUE [Nm/L]
A1
STATOR AMPERE-TURN [AT]

FIG.8



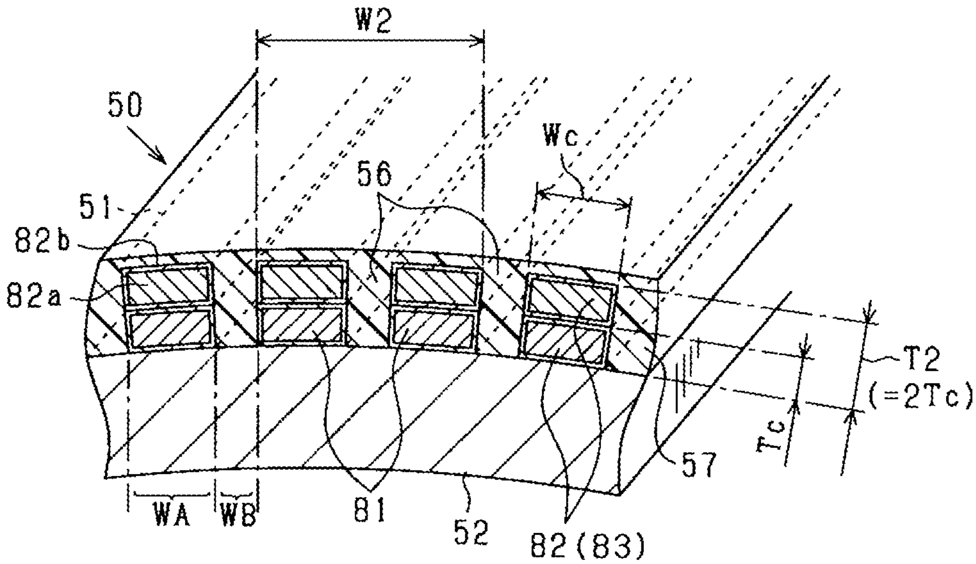
41 (43)
40
42
50
51
52

FIG.9



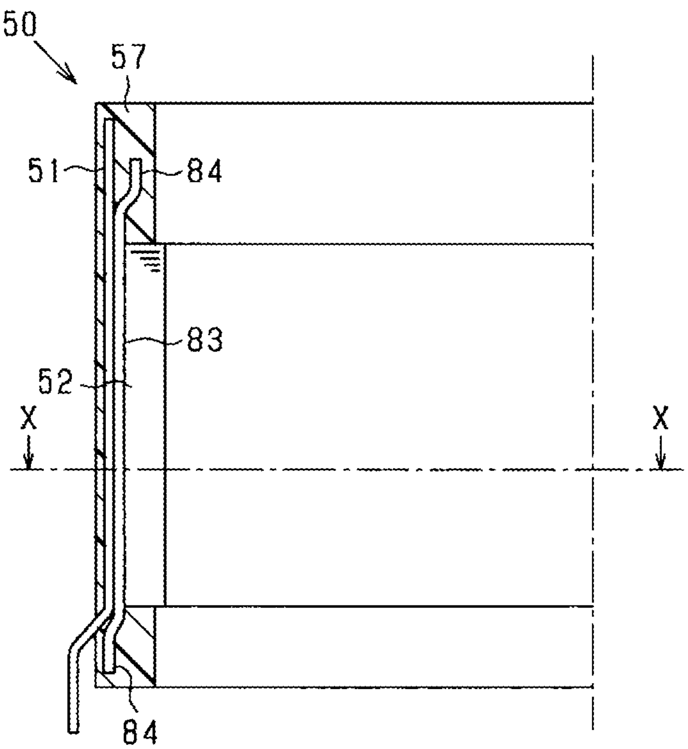
q-AXIS 300
d-AXIS
q-AXIS
θ11
260
310
250
91
260
92
40
42
41 (43)
250
θ12
260
N
S
S
270
57
260
280
81
270
52
51
50

FIG.10



W2
50
56
Wc
51
82b
82a
T2
(=2Tc)
Tc
57
WA
WB
81
52
82(83)

FIG.11



50
57
51
84
83
52
X
X
84

FIG.12

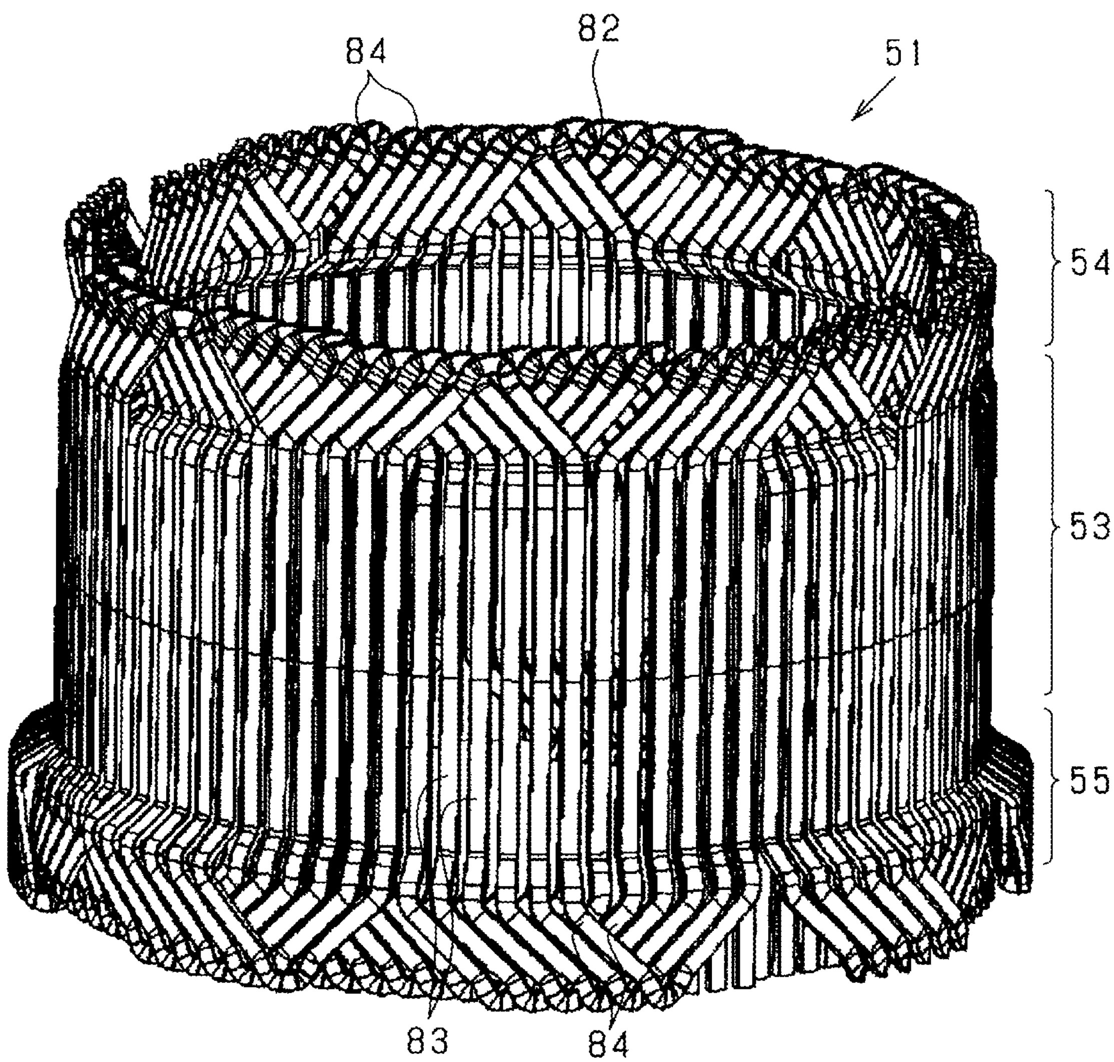


FIG.13

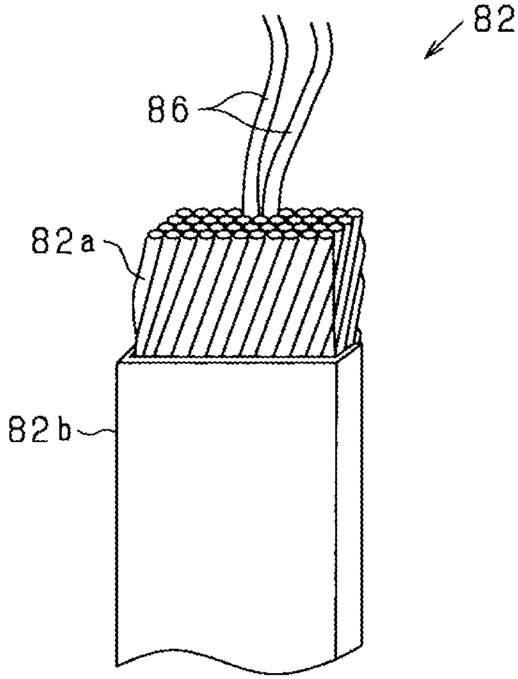


FIG.14

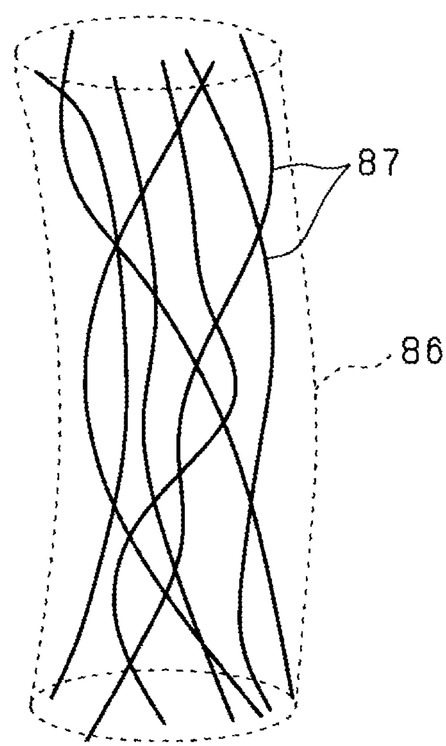


FIG.15(a)

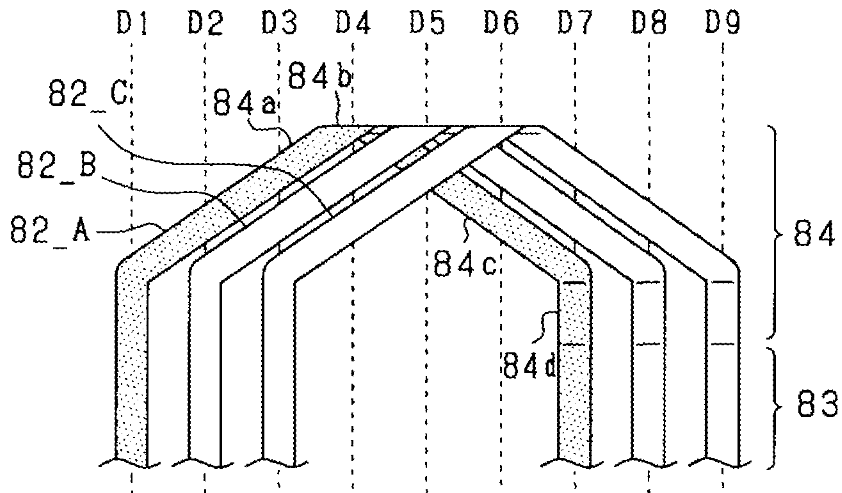


FIG.15(b)

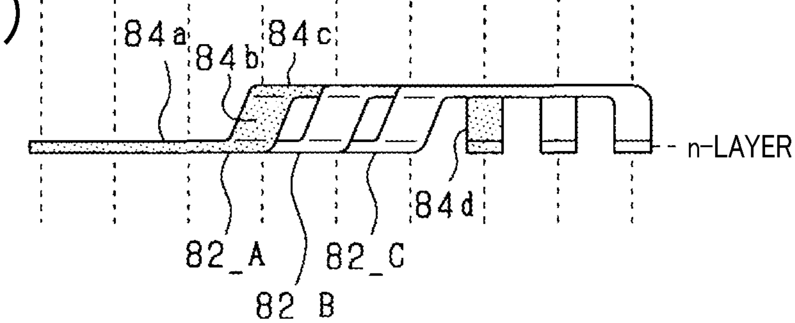


FIG.16

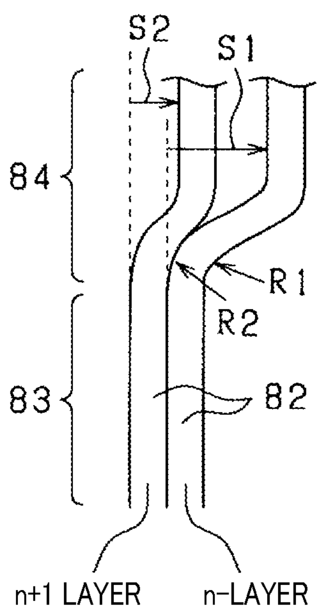


FIG.17

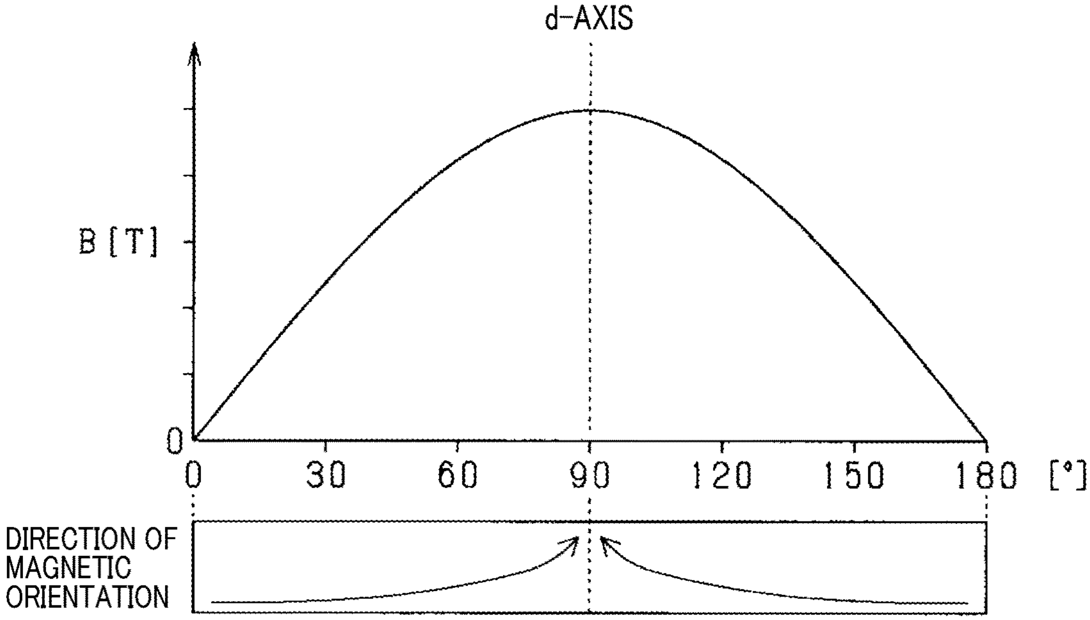

d-AXIS
B [T]
0
0
30
60
90
120
150
180
[°]
DIRECTION OF MAGNETIC ORIENTATION

FIG.18

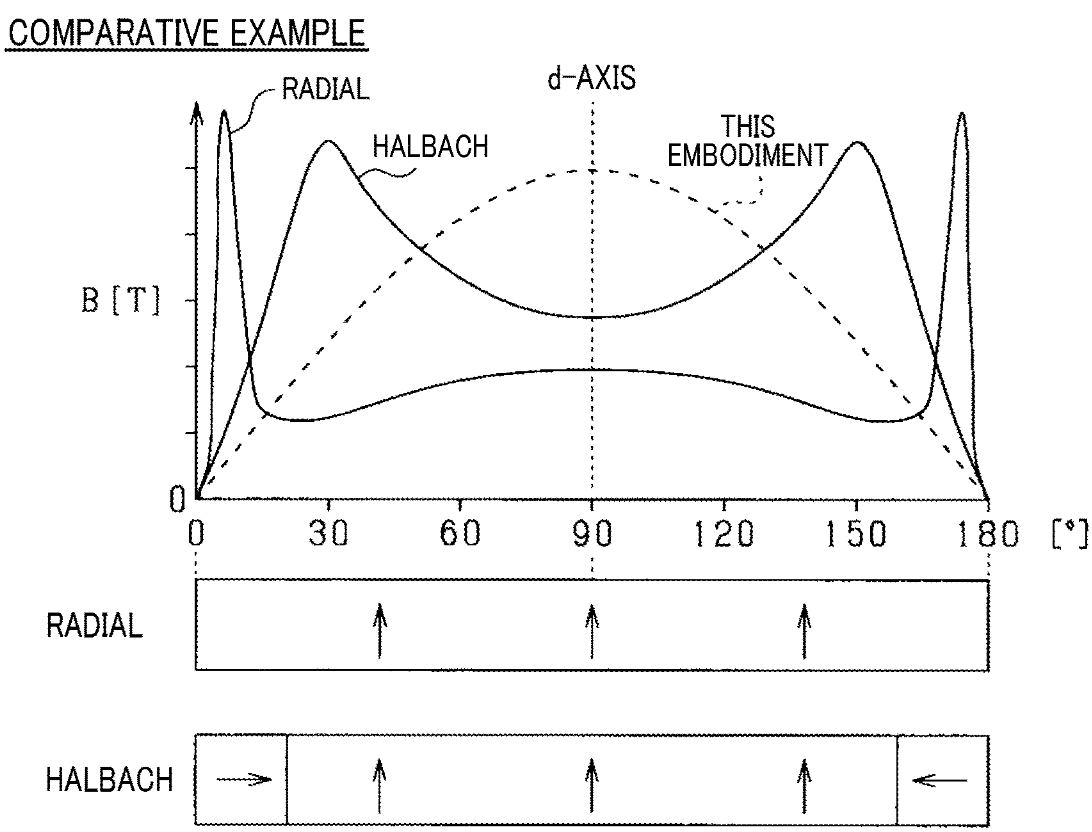

COMPARATIVE EXAMPLE
RADIAL
d-AXIS
HALBACH
THIS EMBODIMENT
B [T]
0
0
30
60
90
120
150
180
[°]
RADIAL
HALBACH

FIG.19

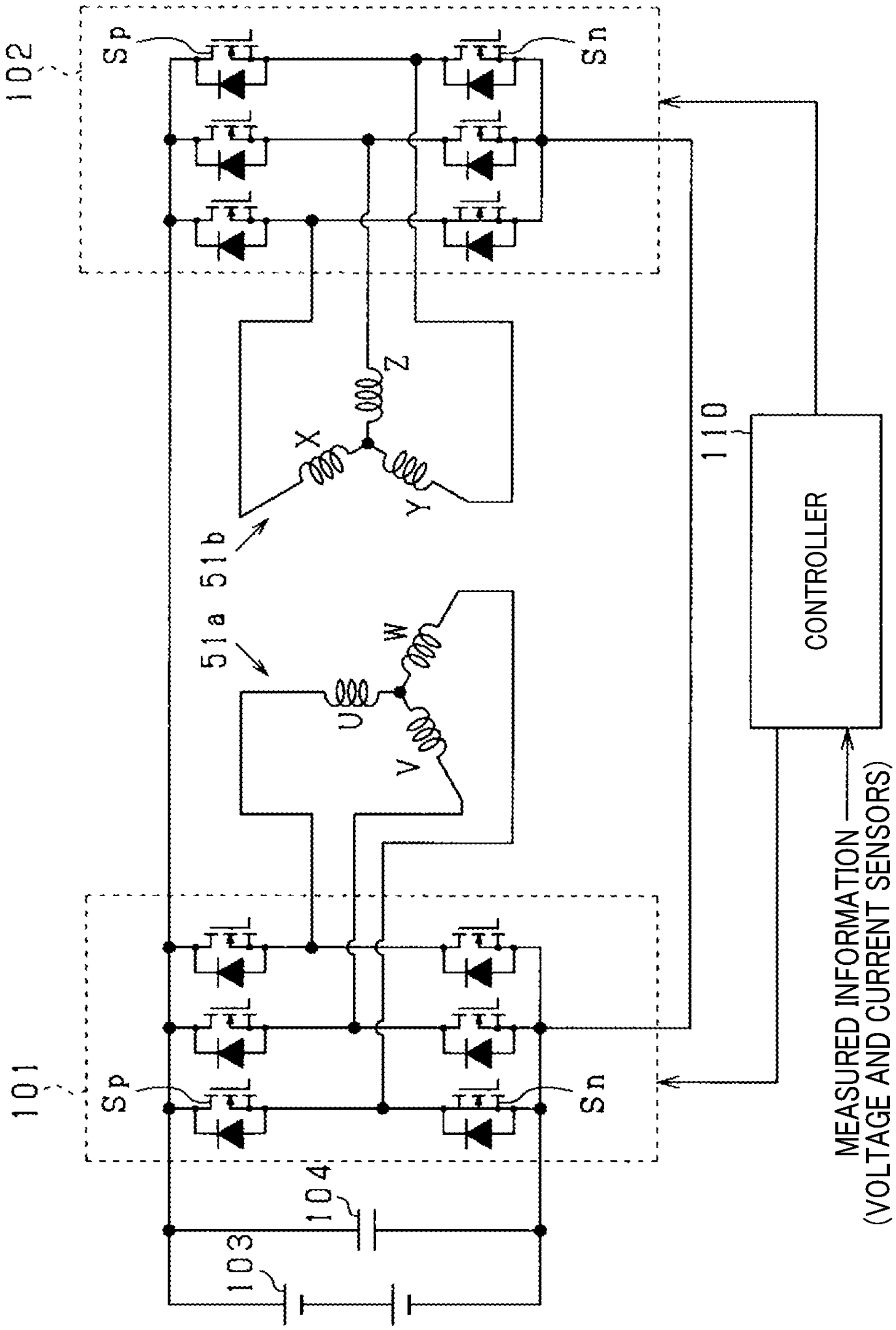

102
Sp
Sn
Sp
Sn
101
104
103
51a
51b
U
V
W
X
Y
Z
110
CONTROLLER
MEASURED INFORMATION
(VOLTAGE AND CURRENT SENSORS)

FIG.20

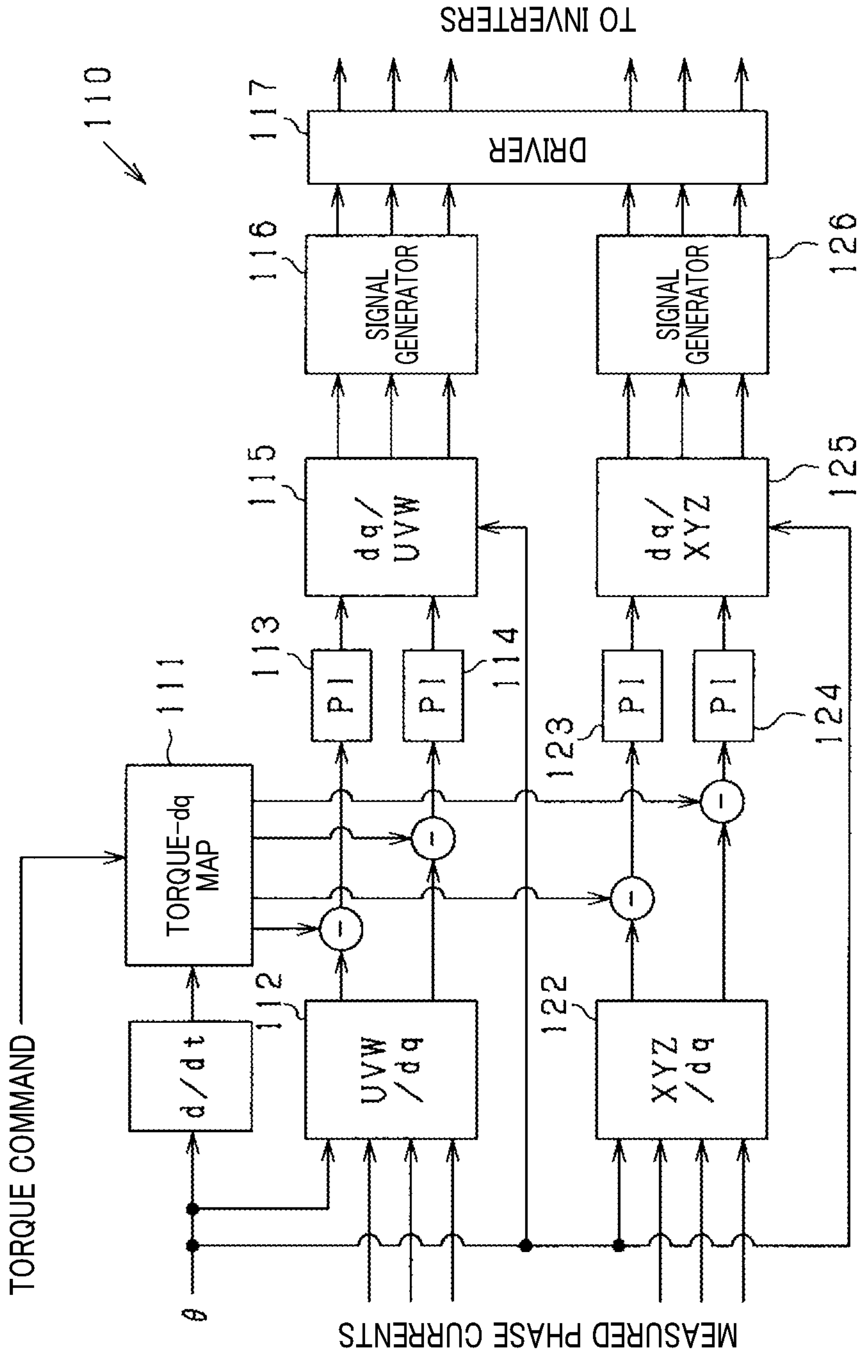

110
TO INVERTERS
117
DRIVER
116
SIGNAL GENERATOR
126
SIGNAL GENERATOR
115
dq/UVW
125
dq/XYZ
113
PI
114
PI
123
PI
124
PI
111
TORQUE-dq MAP
d/dt
112
UVW/dq
122
XYZ/dq
TORQUE COMMAND
θ
MEASURED PHASE CURRENTS

FIG.21

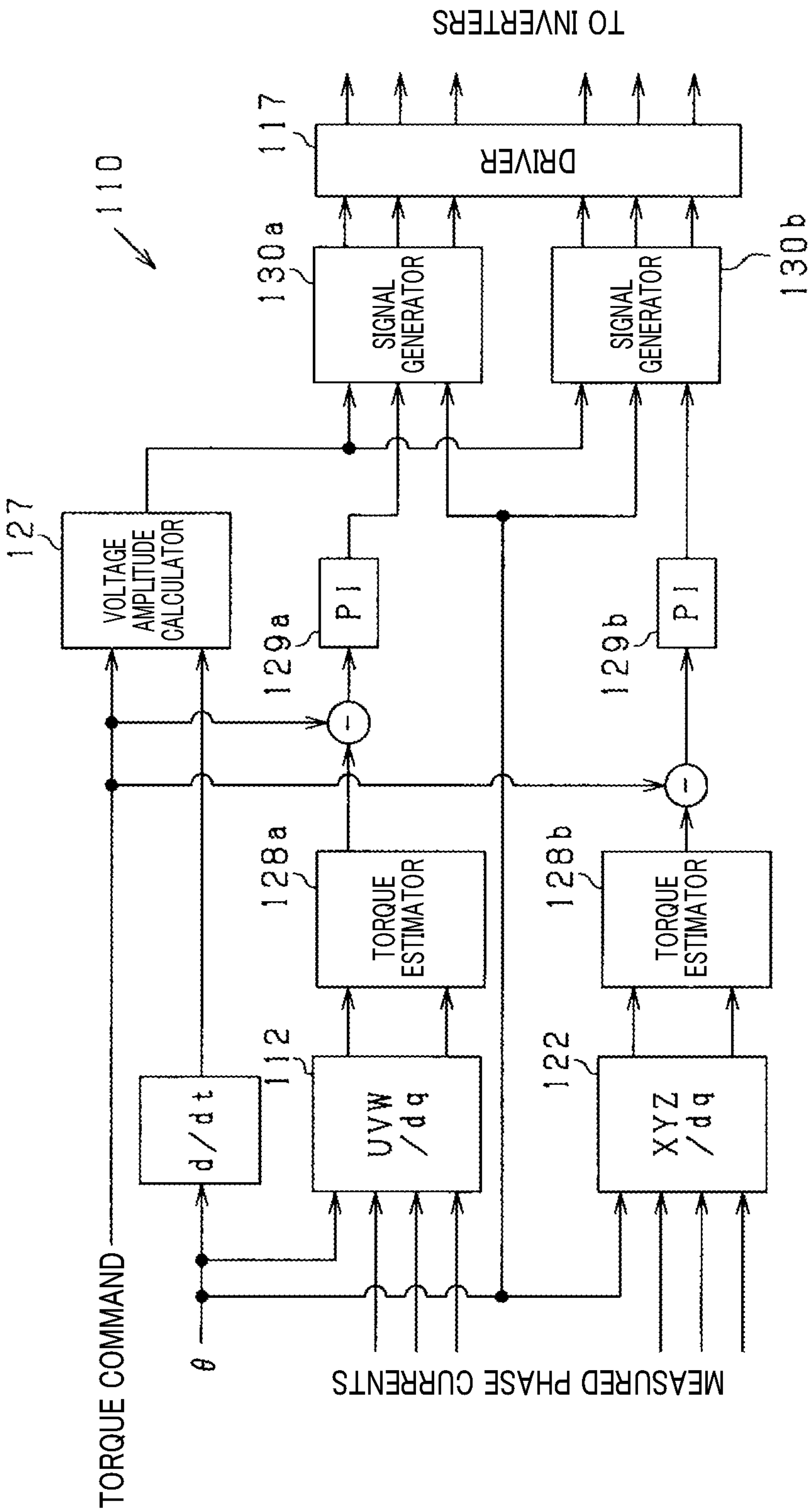

110
TO INVERTERS
117
DRIVER
130a
SIGNAL GENERATOR
130b
SIGNAL GENERATOR
127
VOLTAGE AMPLITUDE CALCULATOR
129a
PI
129b
PI
128a
TORQUE ESTIMATOR
128b
TORQUE ESTIMATOR
112
UVW /dq
122
XYZ /dq
d/dt
TORQUE COMMAND
θ
MEASURED PHASE CURRENTS

FIG. 22

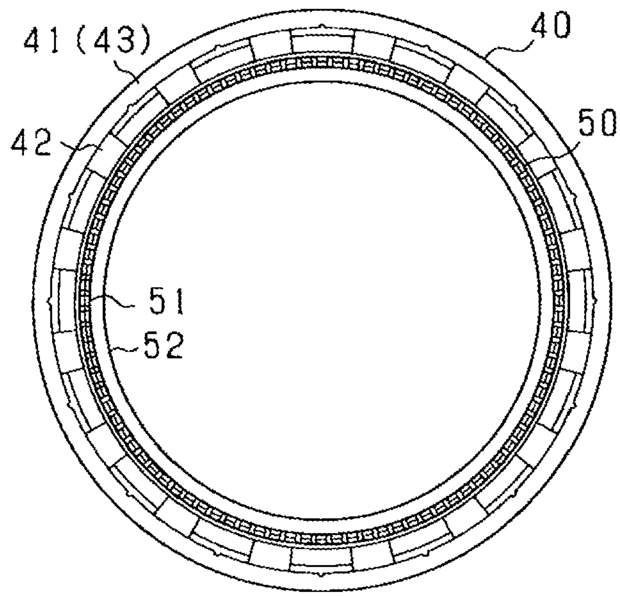

41 (43)
40
42
50
51
52

FIG. 23

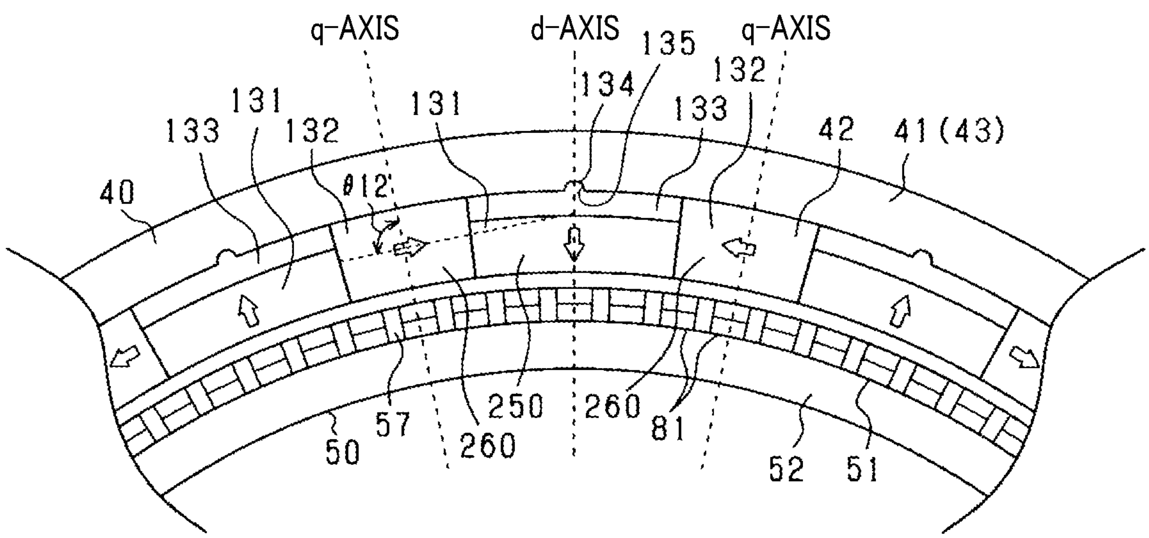

q-AXIS
d-AXIS
q-AXIS
135
134
132
131
131
133
133
132
133
42
41 (43)
40
θ12
57
50
250
260
260
81
52
51

FIG.24(a)

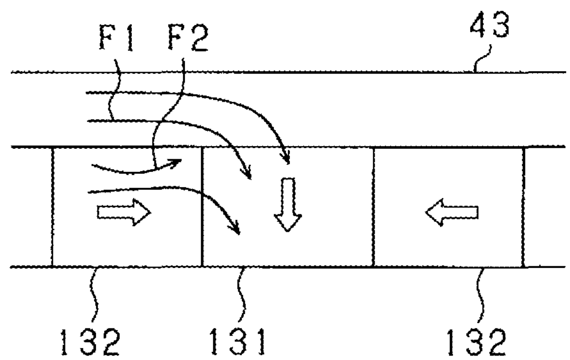


FIG.24(b)

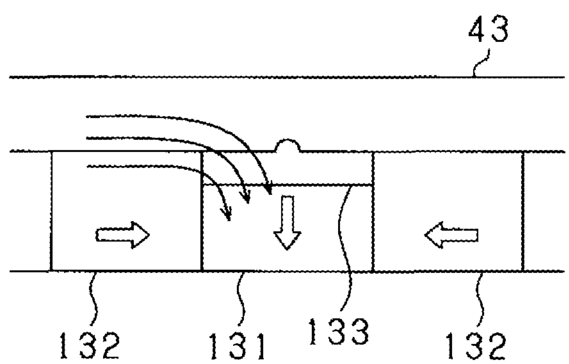


FIG.25

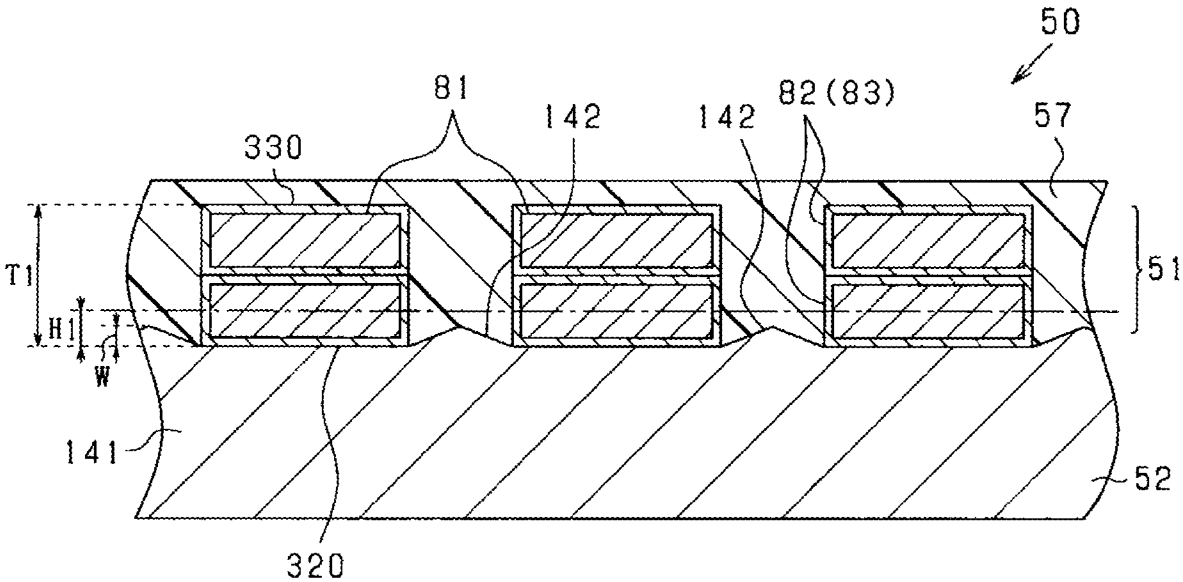

50
81
142
142
82(83)
57
330
T1
H1
W
51
141
52
320

FIG.26

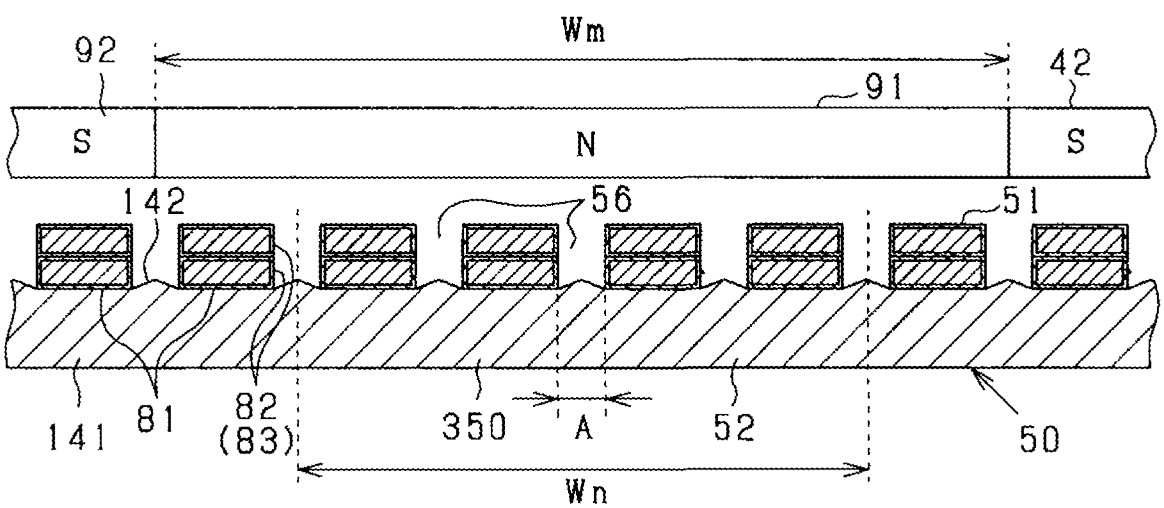

Wm
92
42
91
S
N
S
142
56
51
141
81
82
(83)
350
A
52
50
Wn

FIG.27

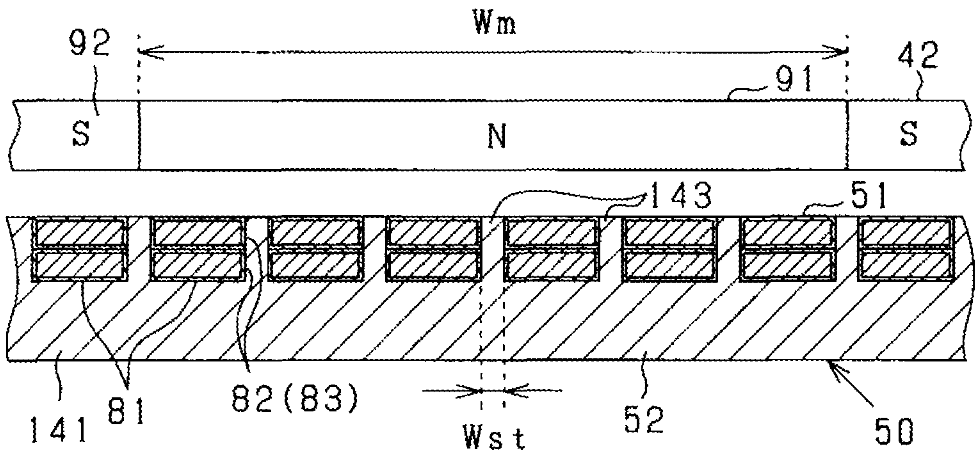


FIG.28

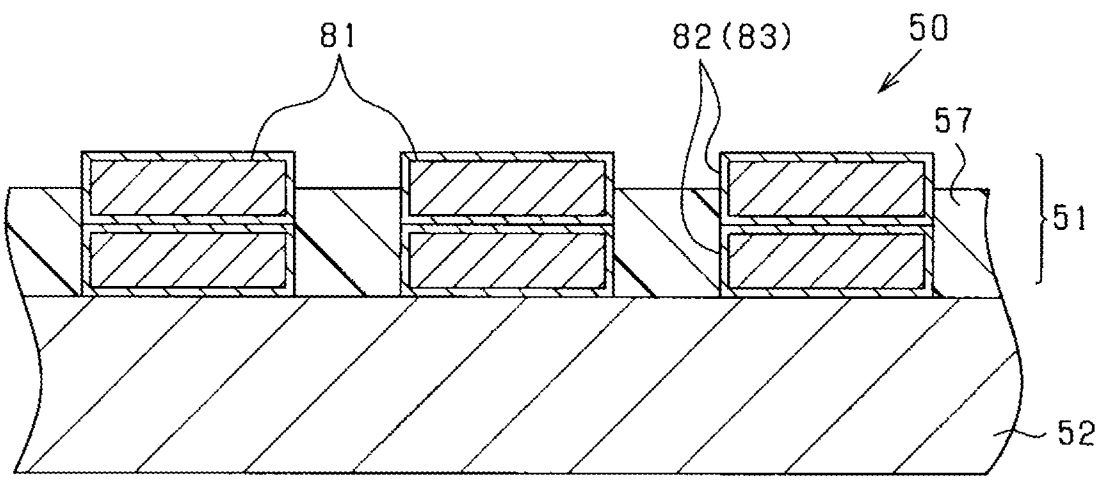


FIG.29

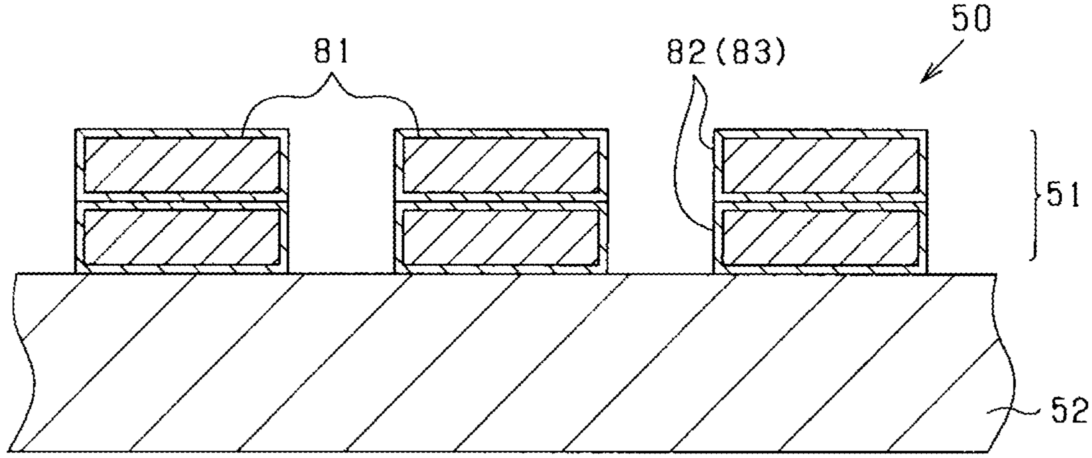


FIG.30

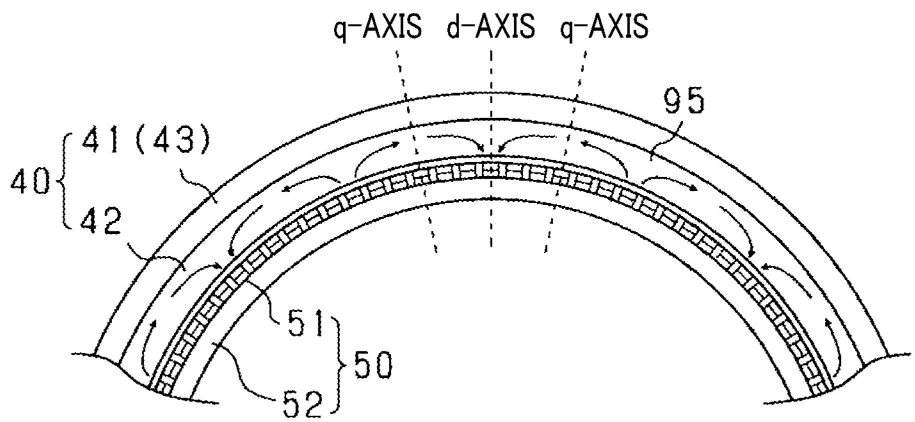


FIG.31

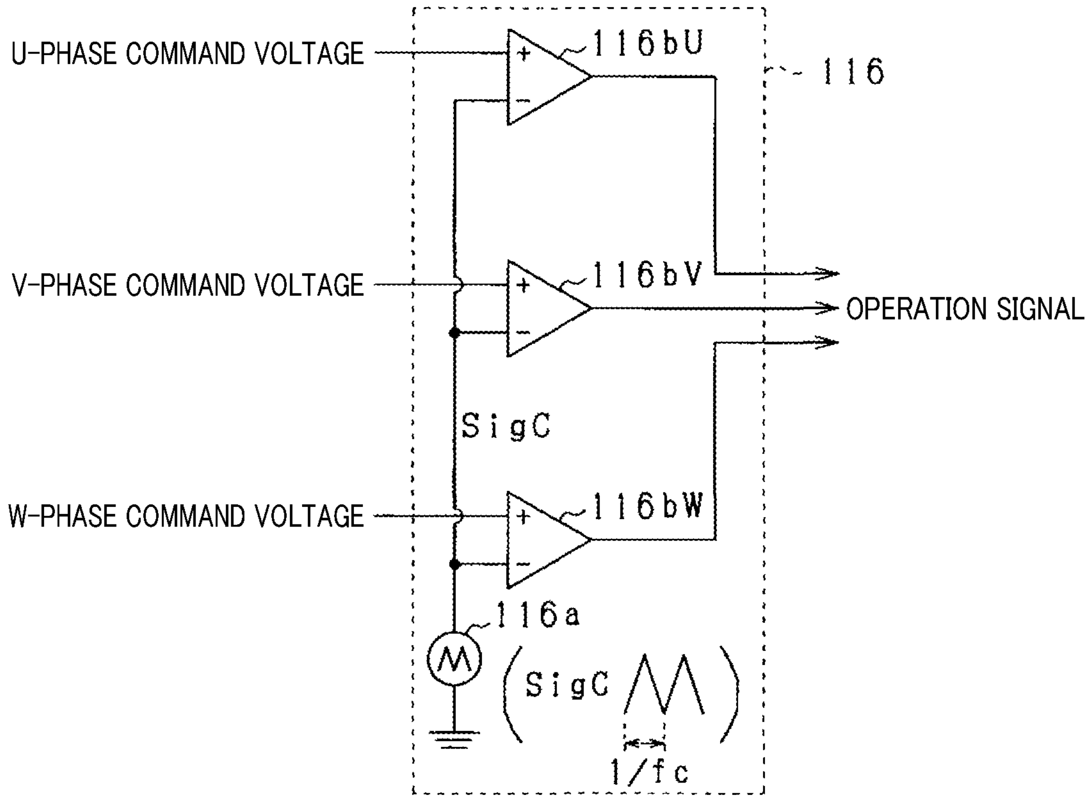

U-PHASE COMMAND VOLTAGE
116bU
116
V-PHASE COMMAND VOLTAGE
116bV
OPERATION SIGNAL
SigC
W-PHASE COMMAND VOLTAGE
116bW
116a
SigC
1/fc

FIG.32

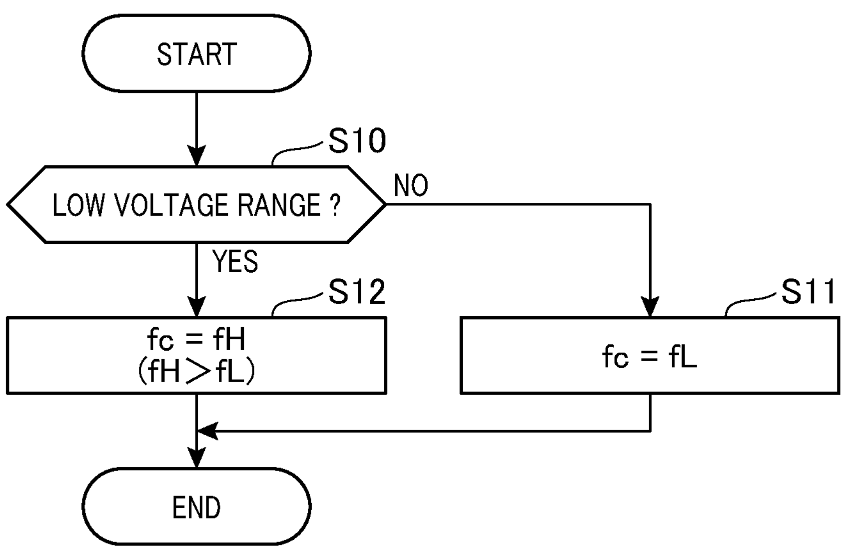

START
S10
LOW VOLTAGE RANGE ?
NO
YES
S12
fc = fH
(fH > fL)
S11
fc = fL
END

FIG.33(a) FIG.33(b) FIG.33(c)

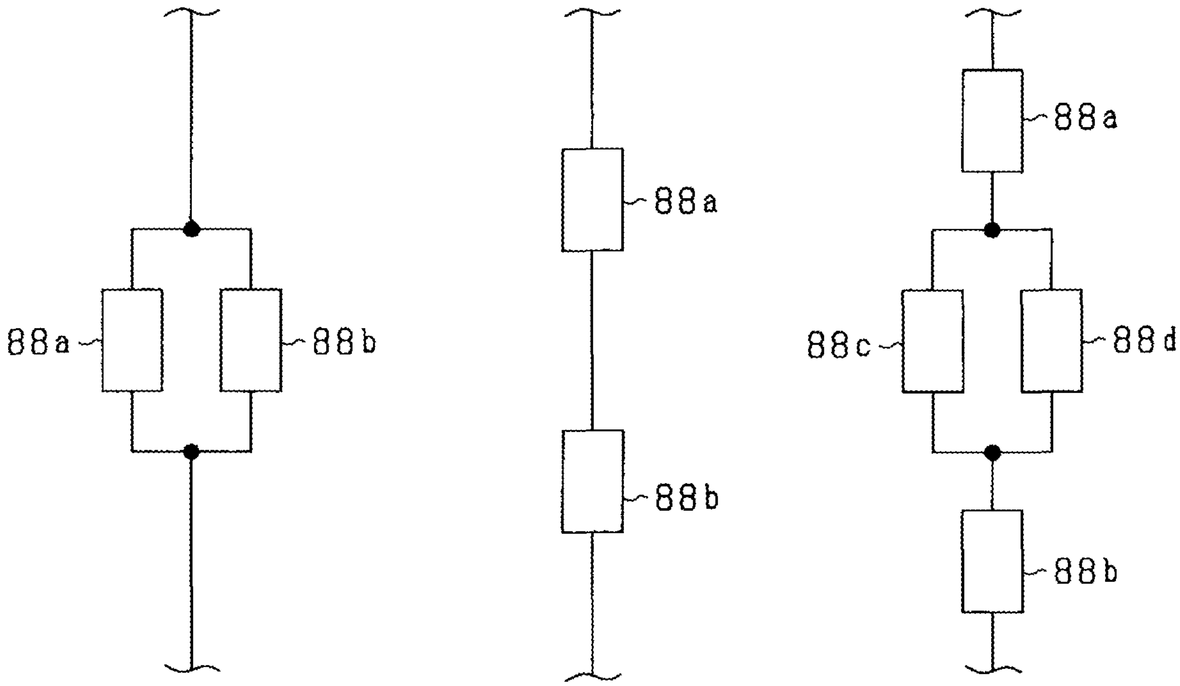


FIG.34

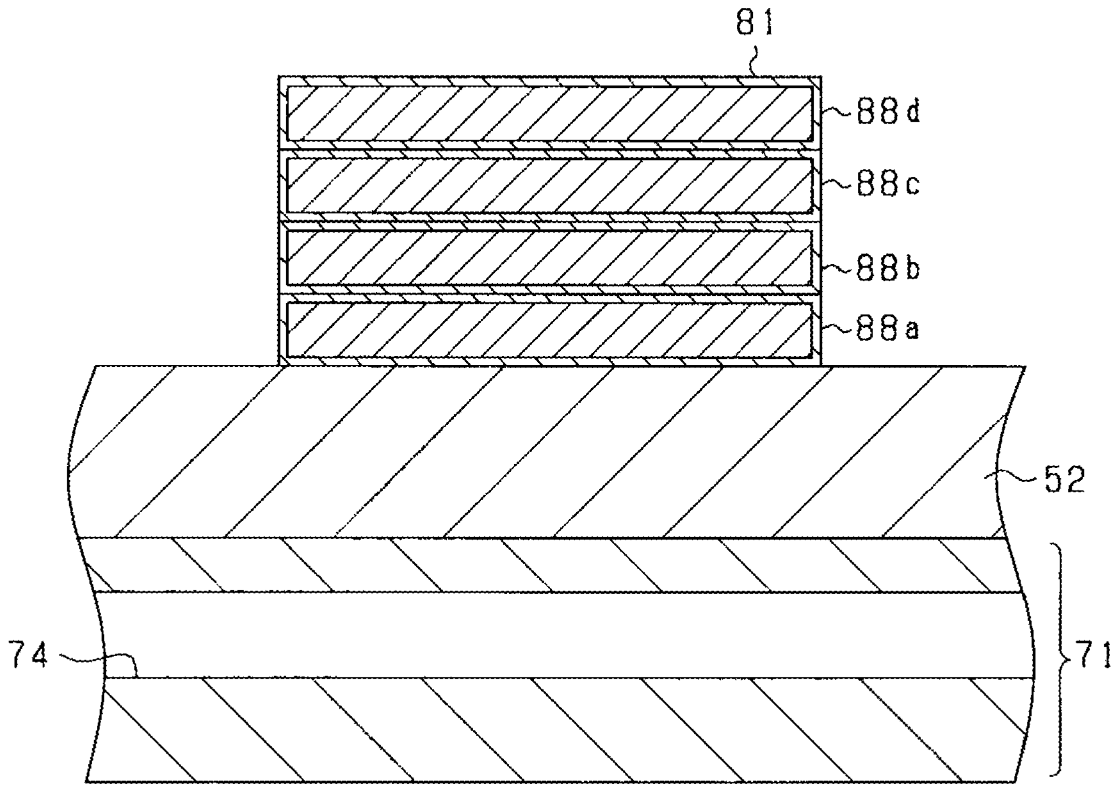


FIG.35

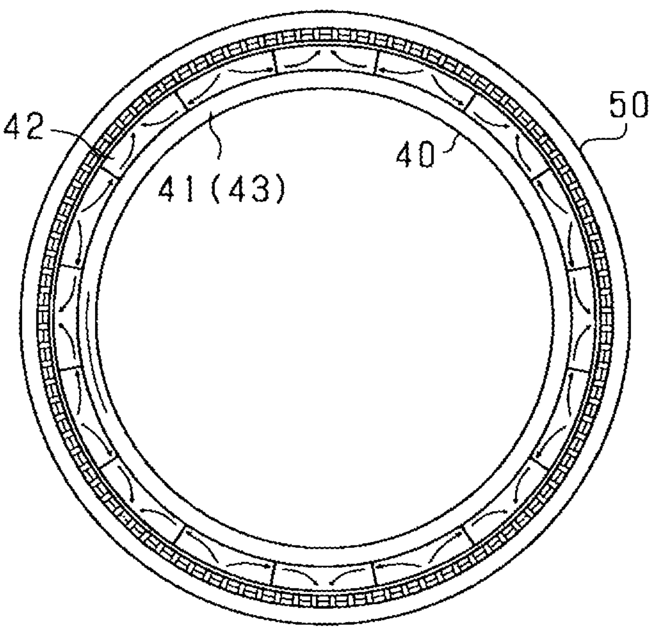


FIG.36

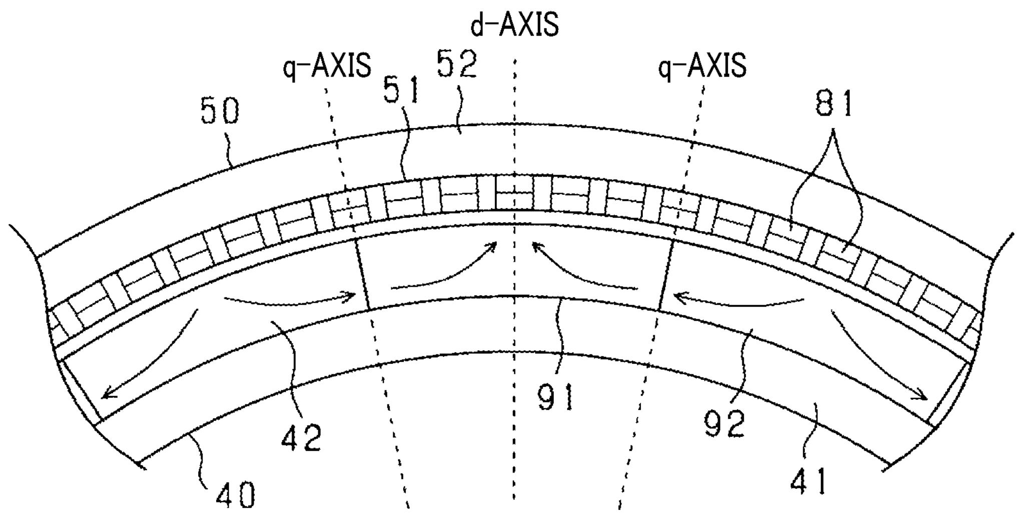


FIG.37

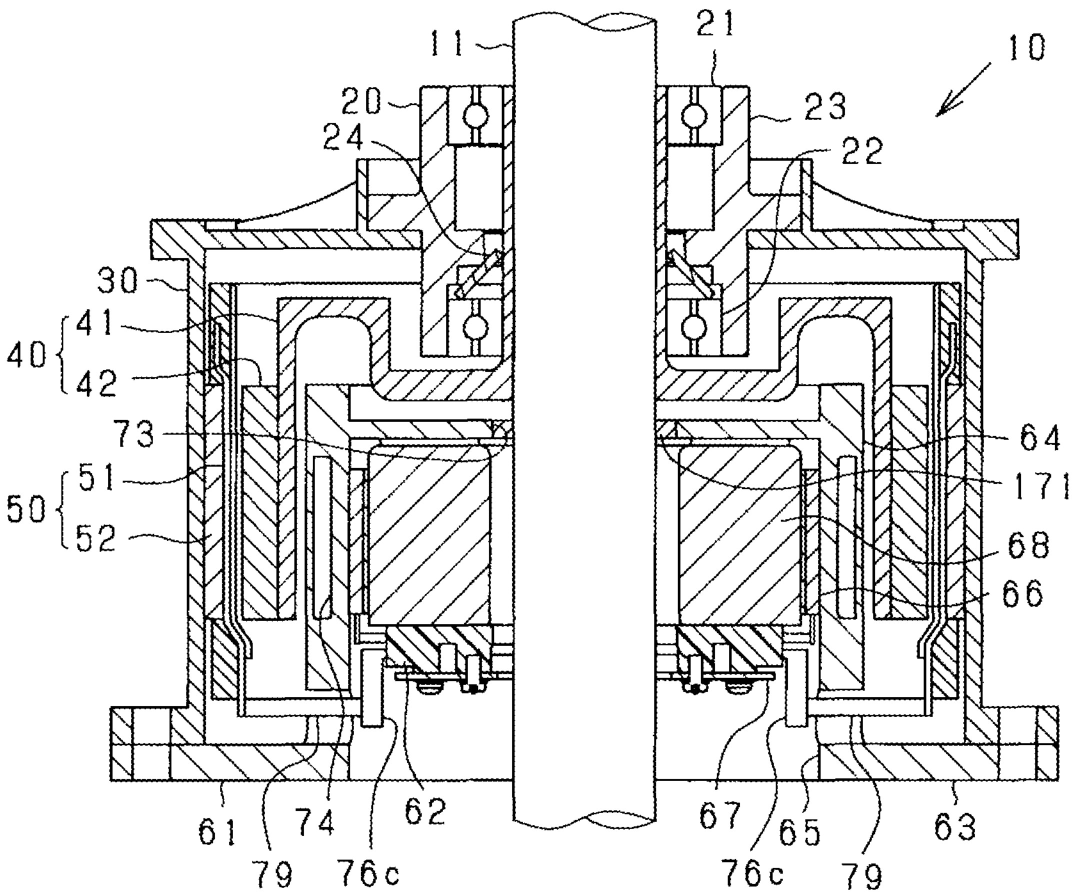

11
21
10
20
23
24
22
30
40
41
42
73
64
50
51
171
52
68
66
61
79
74
76c
62
67
65
76c
79
63

FIG.38

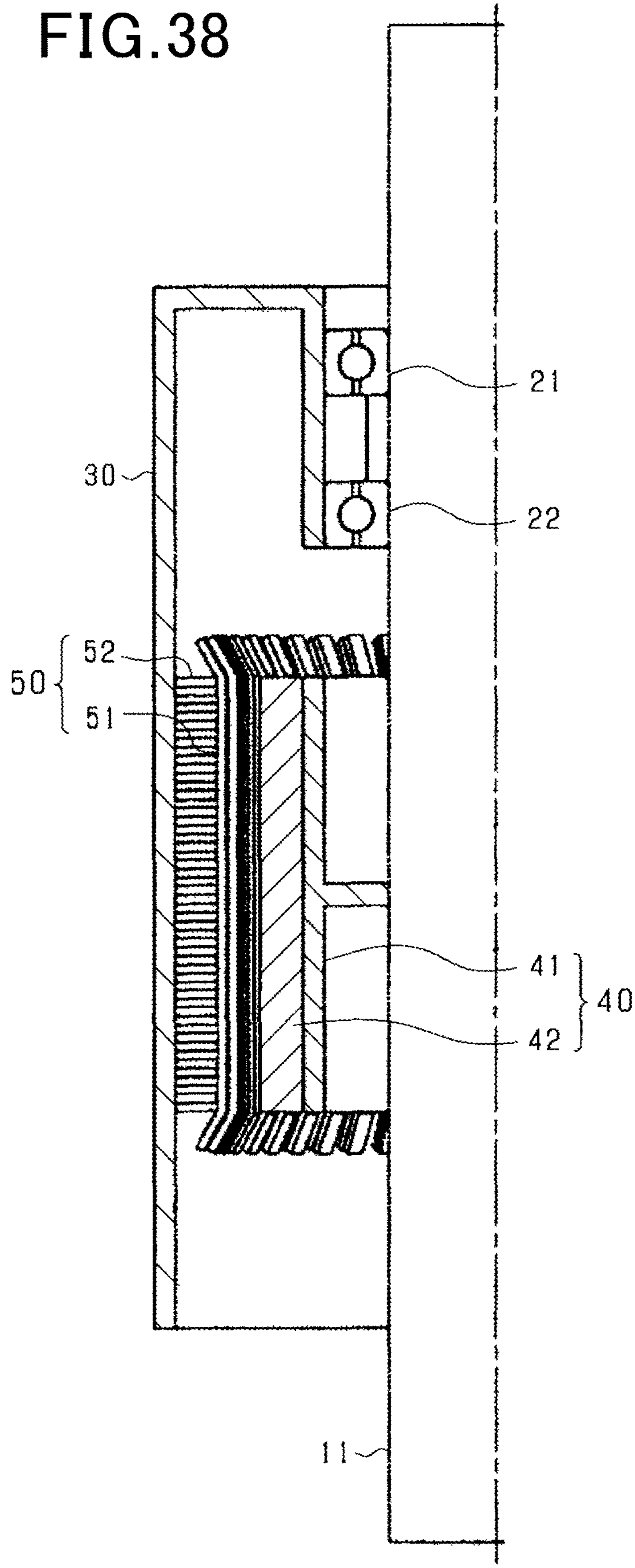


FIG.39

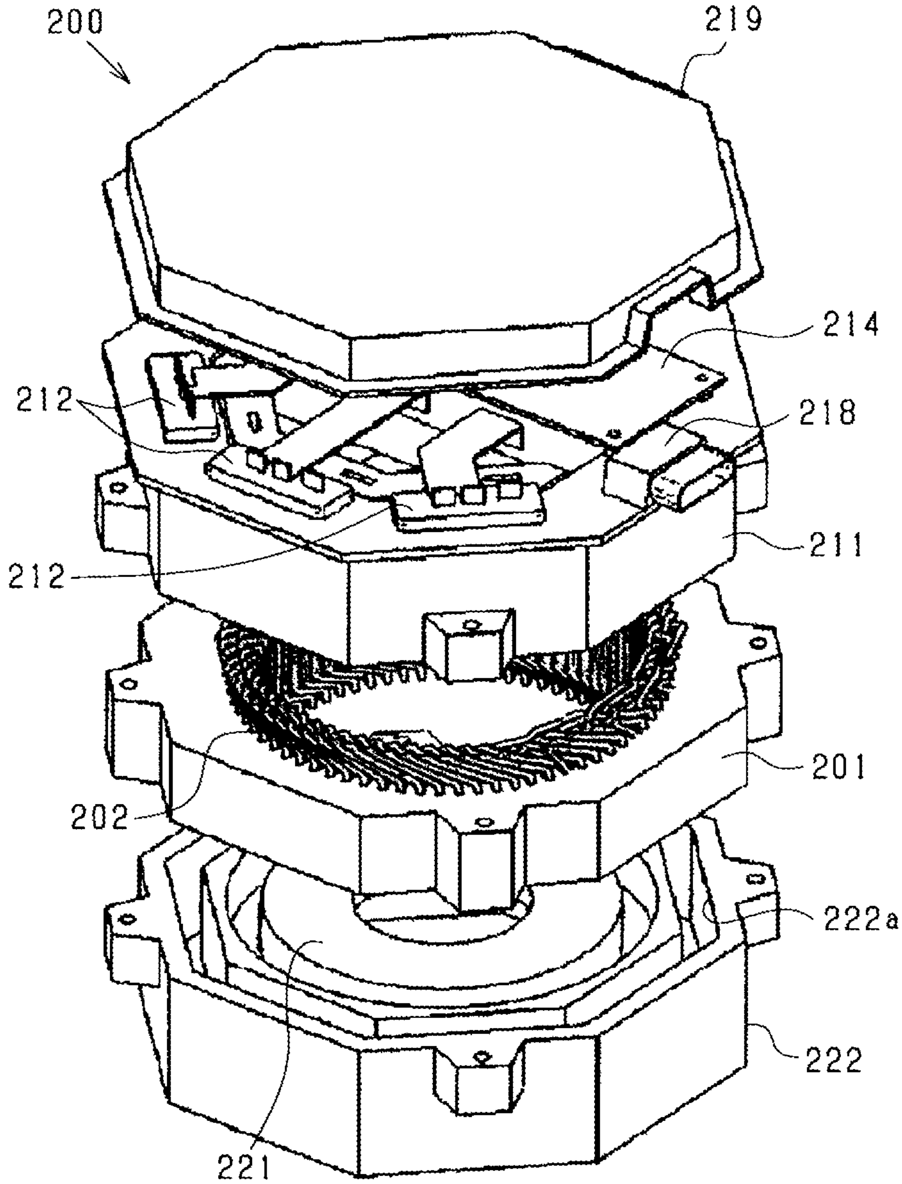
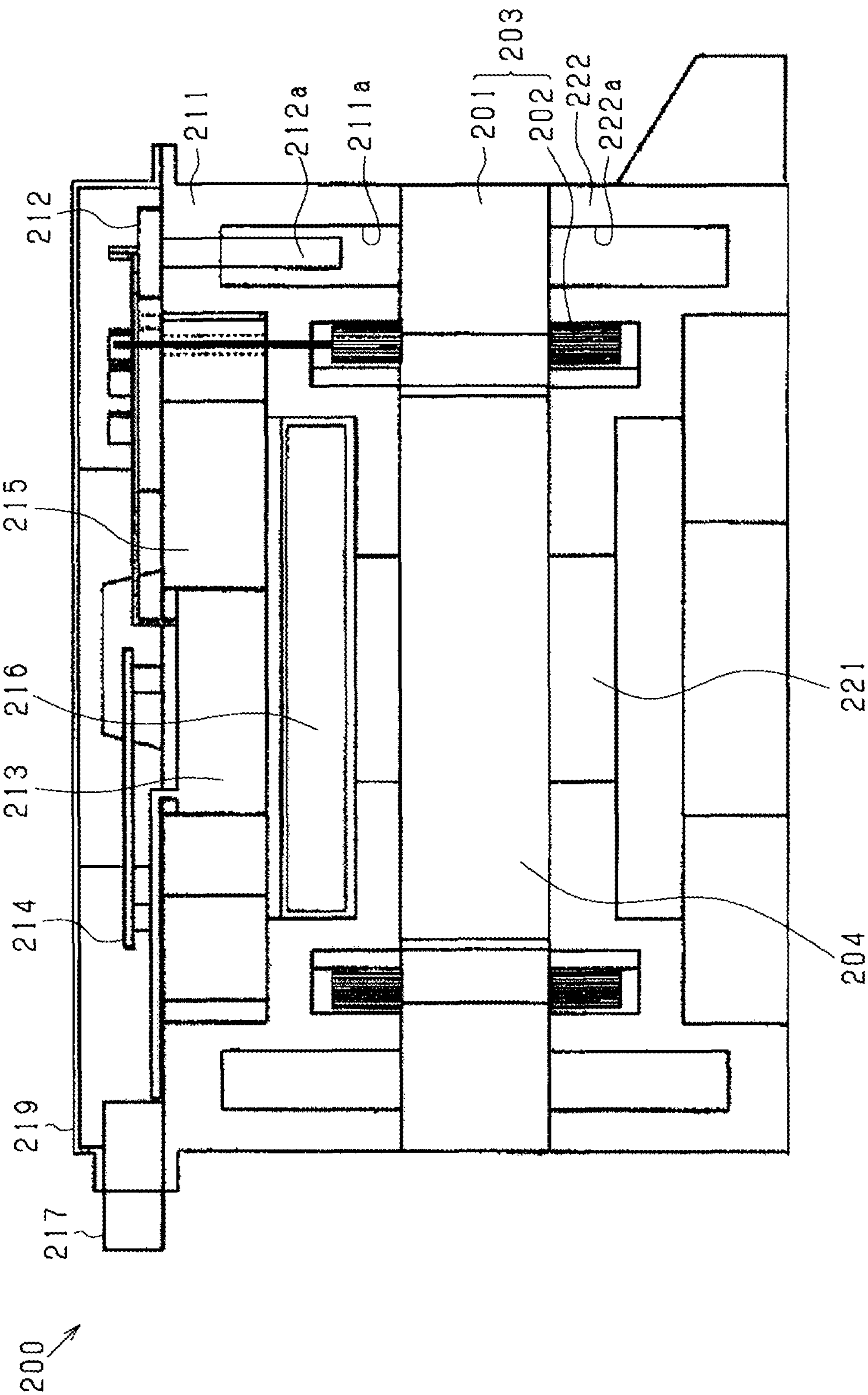


FIG.40



200
211
211a
212
212a
201
202
203
204
213
214
215
216
217
219
221
222
222a

FIG.41

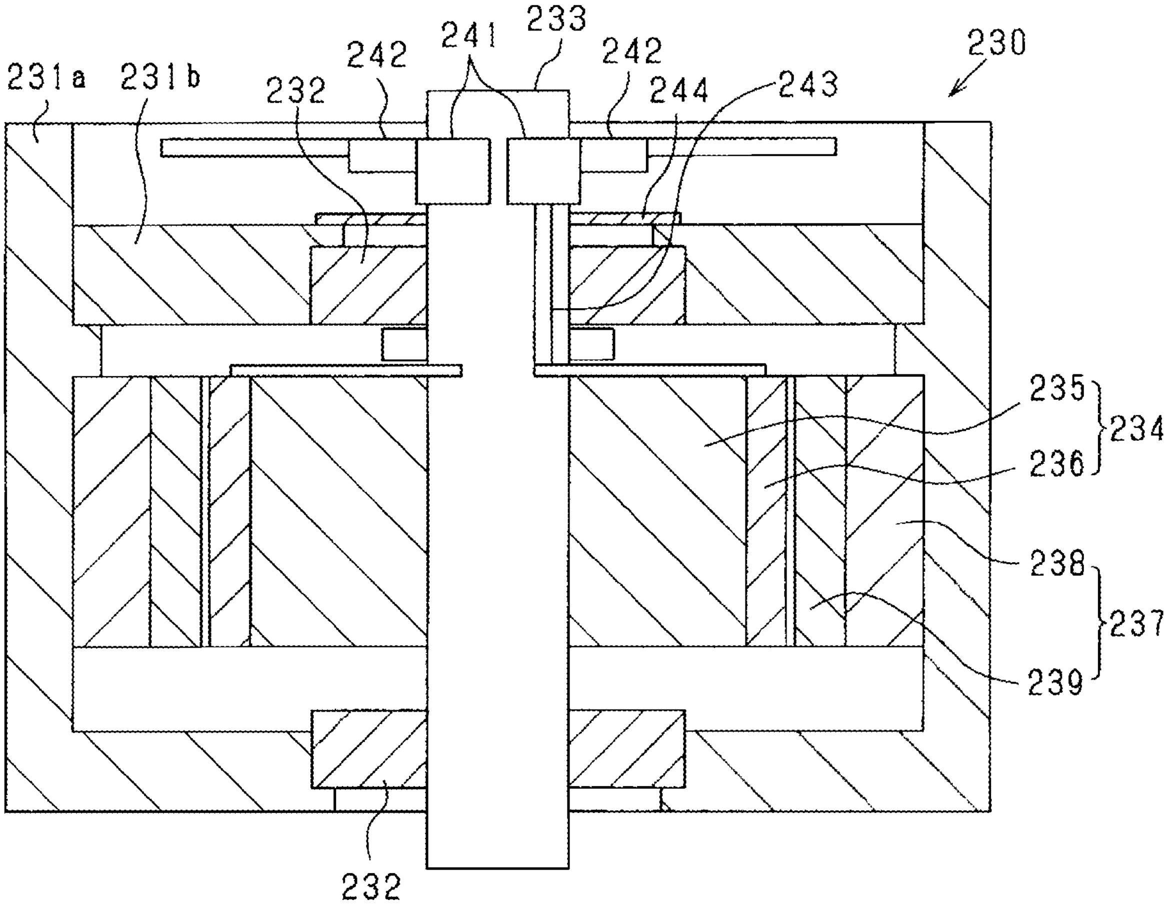

230
231a
231b
232
242
241
233
242
244
243
235
234
236
238
237
239
232

FIG.42

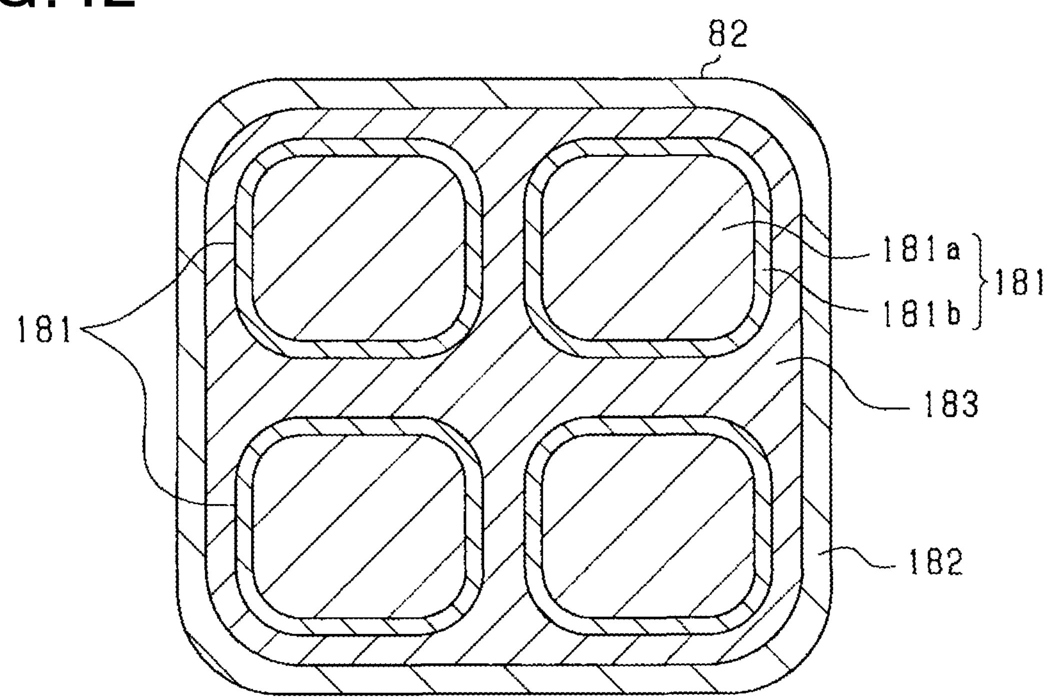

82
181a
181
181b
181
183
182

FIG.43

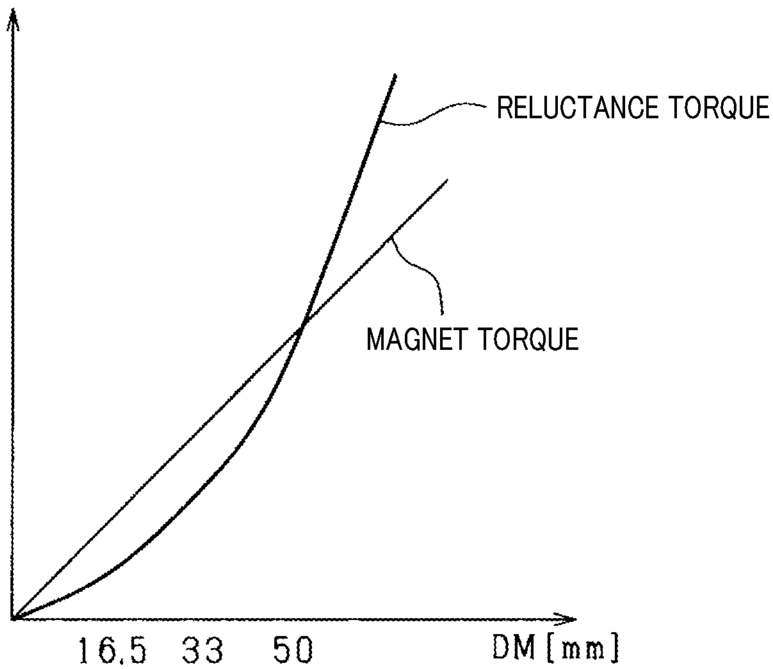


FIG.44

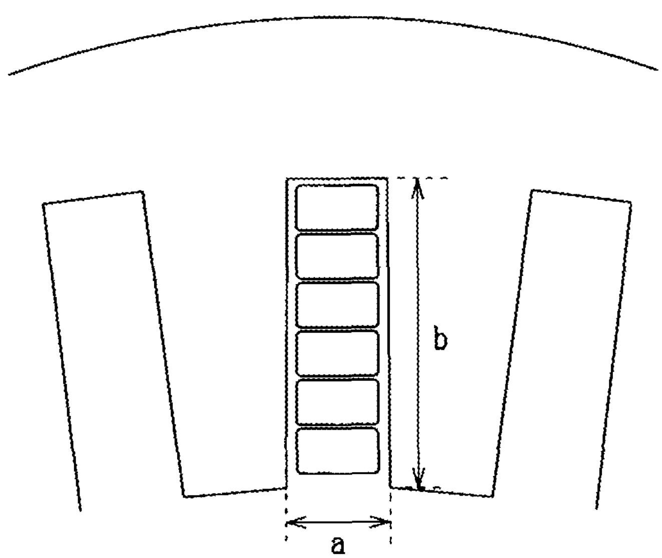


FIG.45

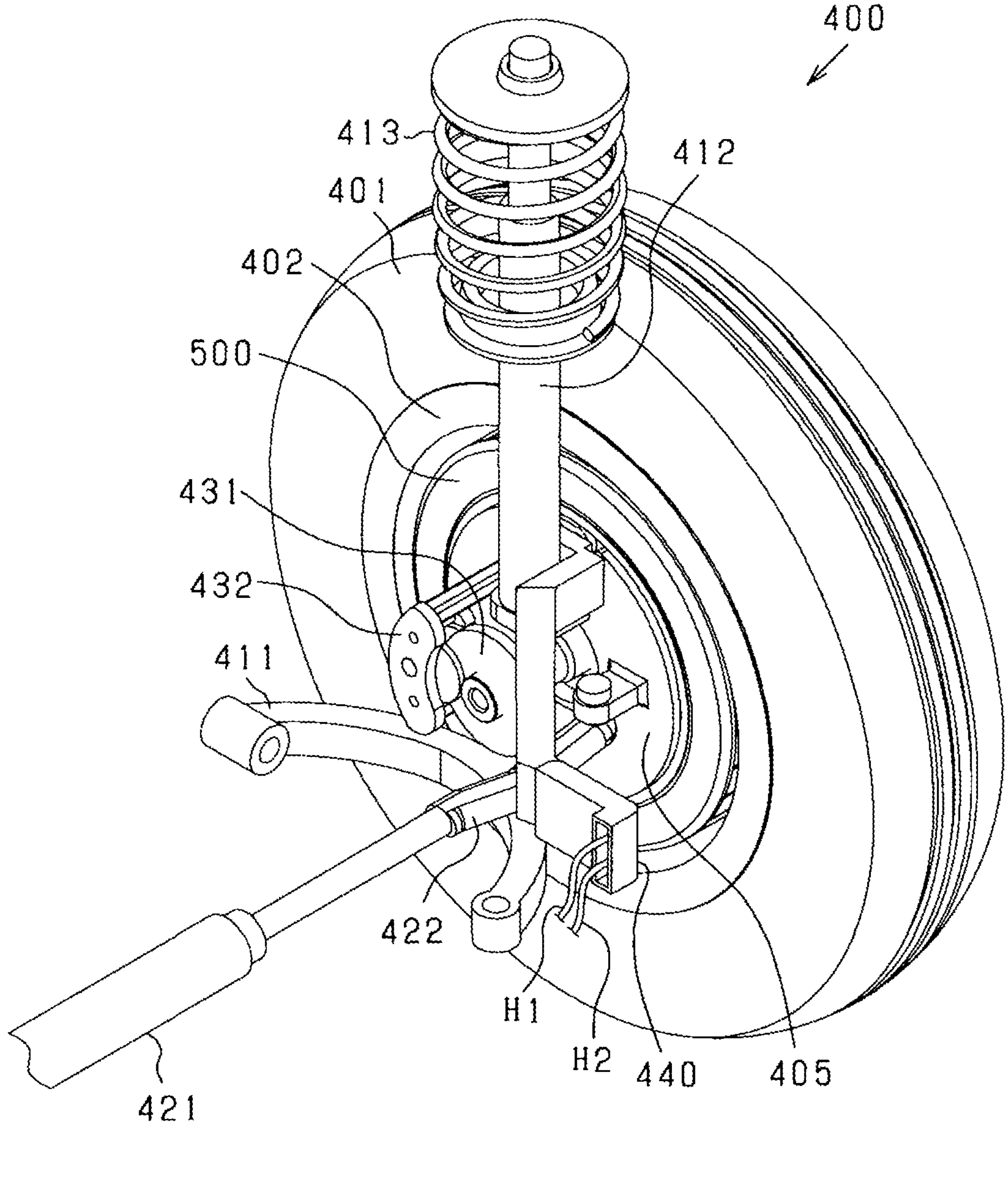


FIG.46

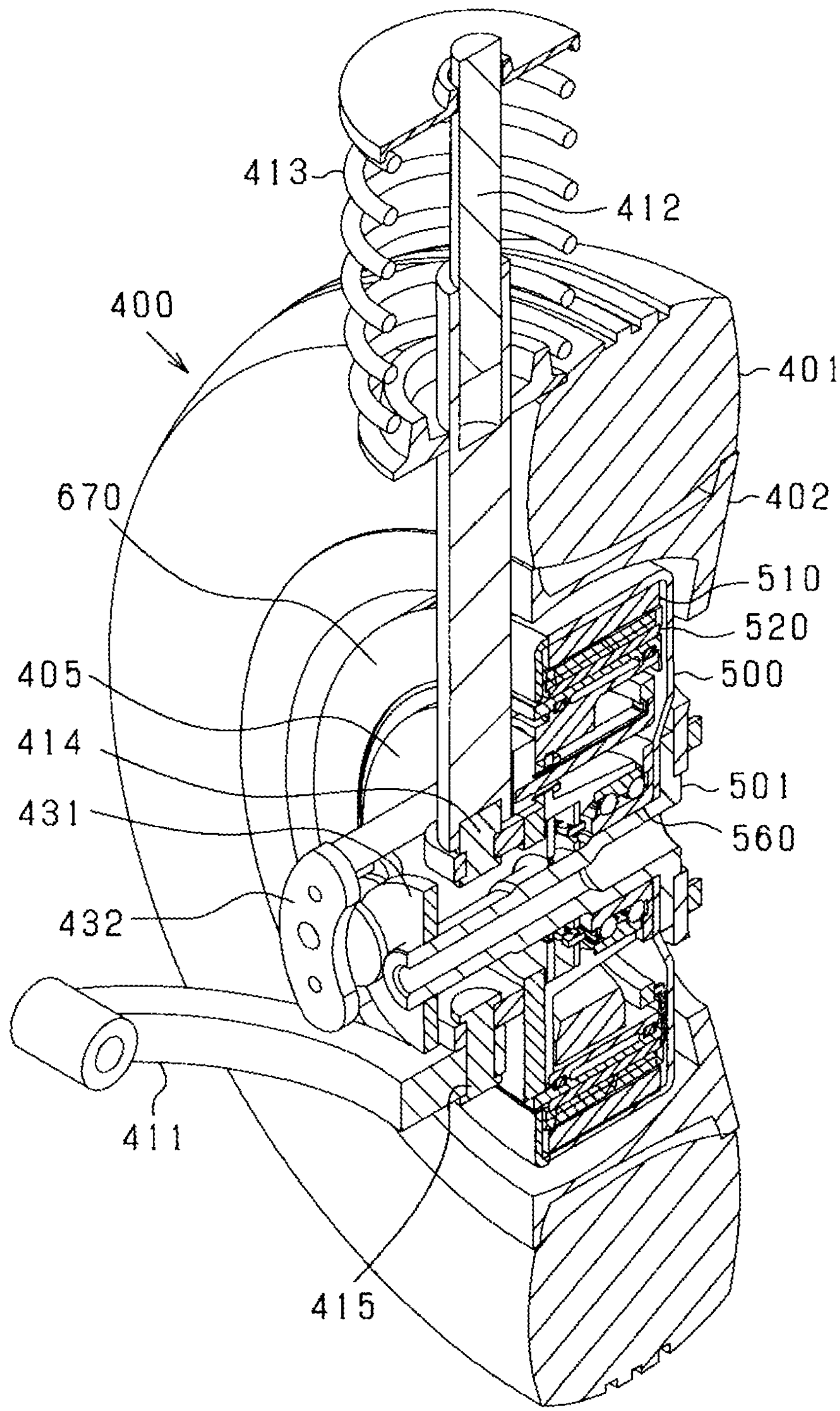

413
412
400
401
402
670
510
520
405
500
414
501
431
560
432
411
415

FIG.47

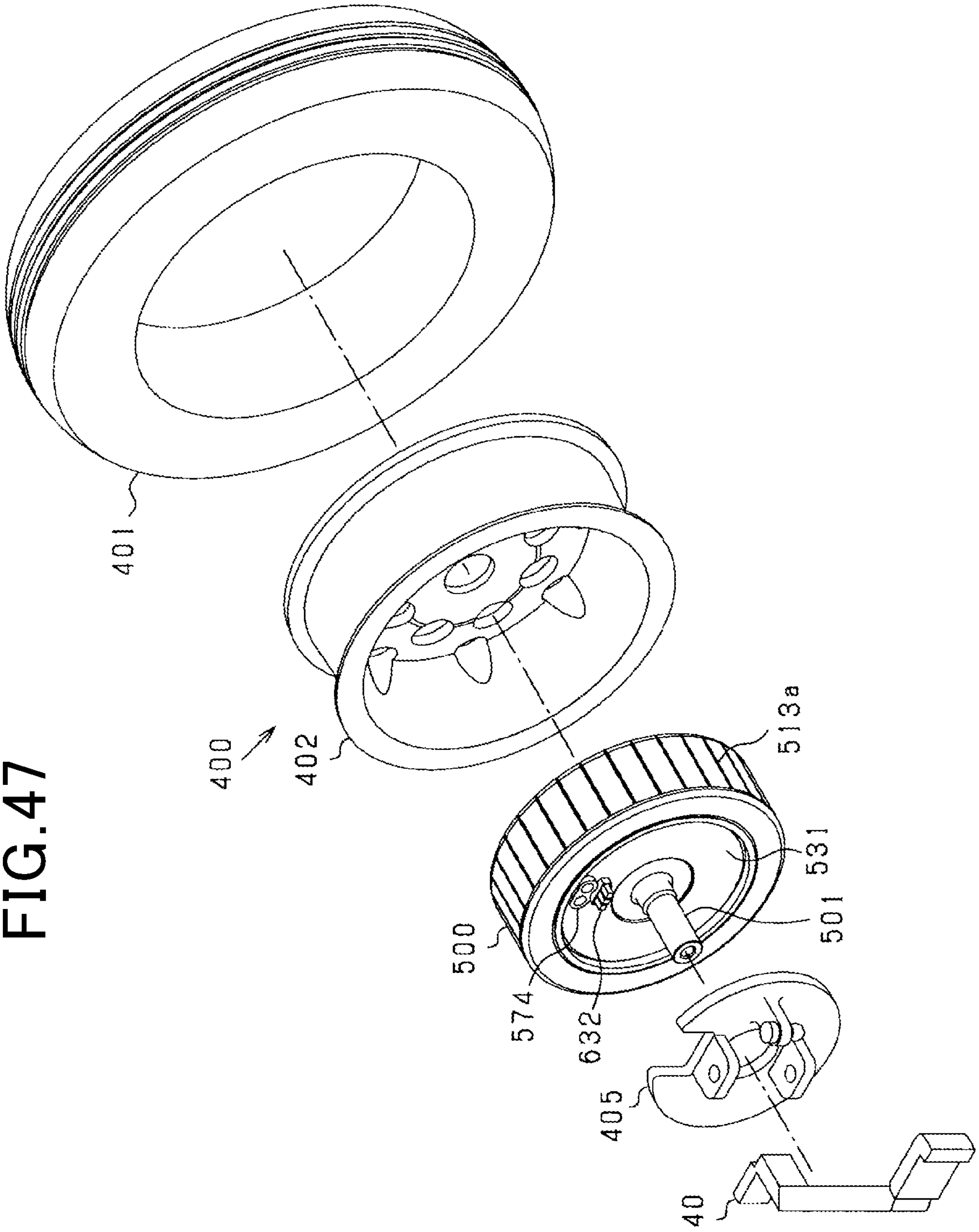
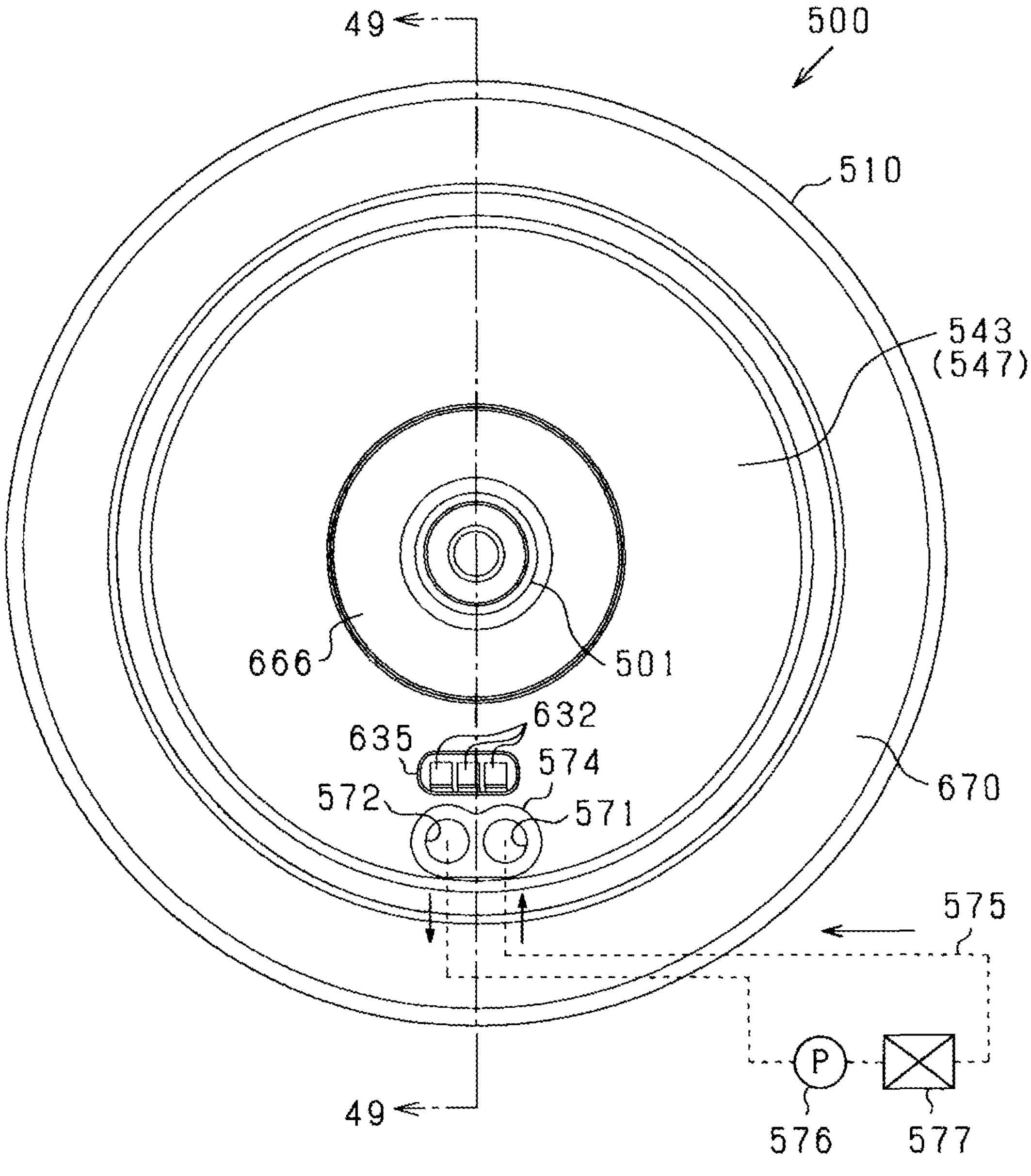


FIG.48



49
500
510
543
(547)
666
501
635
632
574
572
571
670
575
49
P
576
577

FIG.49

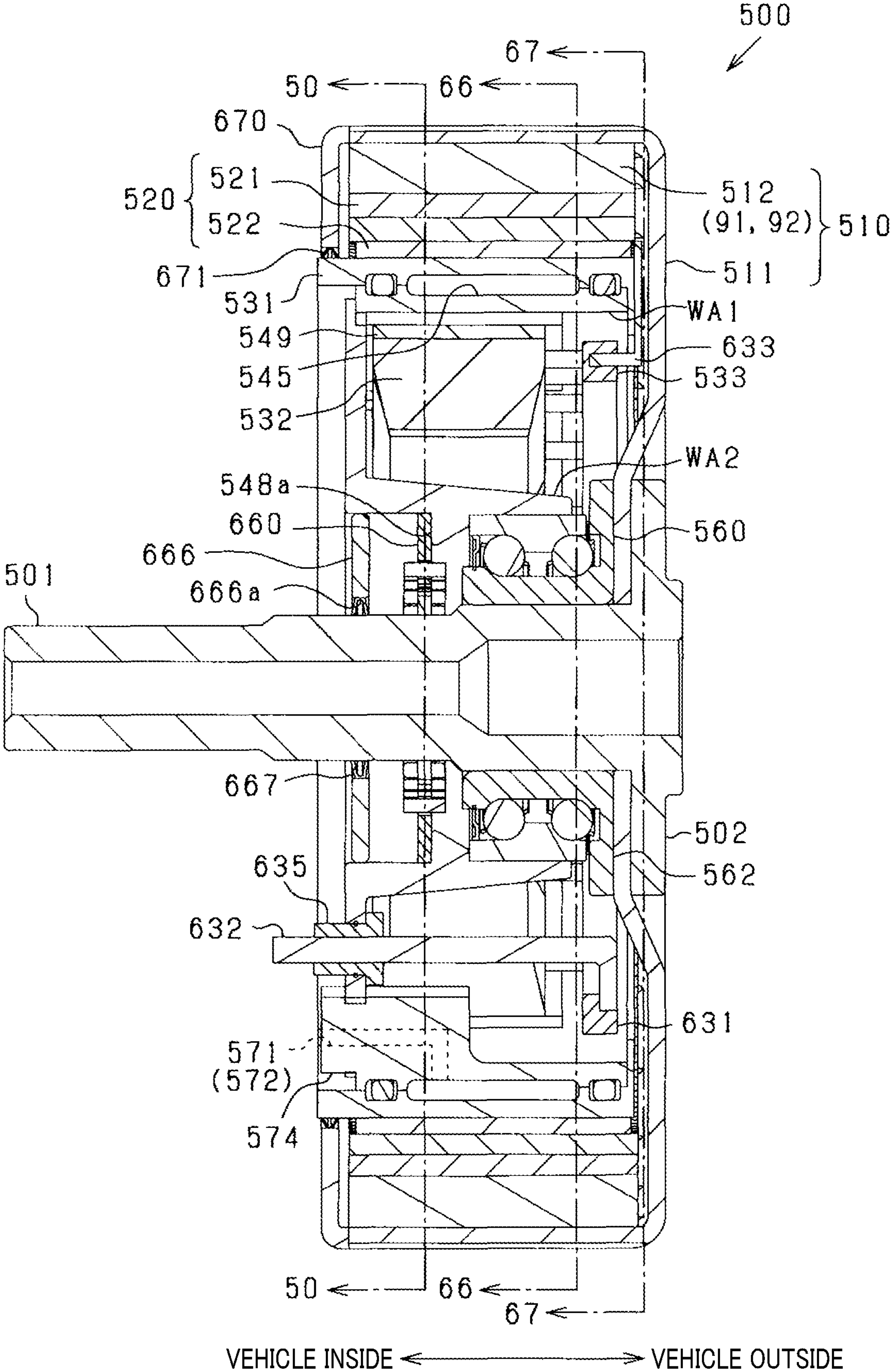

500
67
50
66
670
520
521
522
512
(91, 92)
510
511
671
531
WA1
549
633
545
533
532
WA2
548a
660
560
666
501
666a
667
502
562
635
632
631
571
(572)
574
50
66
67
VEHICLE INSIDE
VEHICLE OUTSIDE

FIG.50

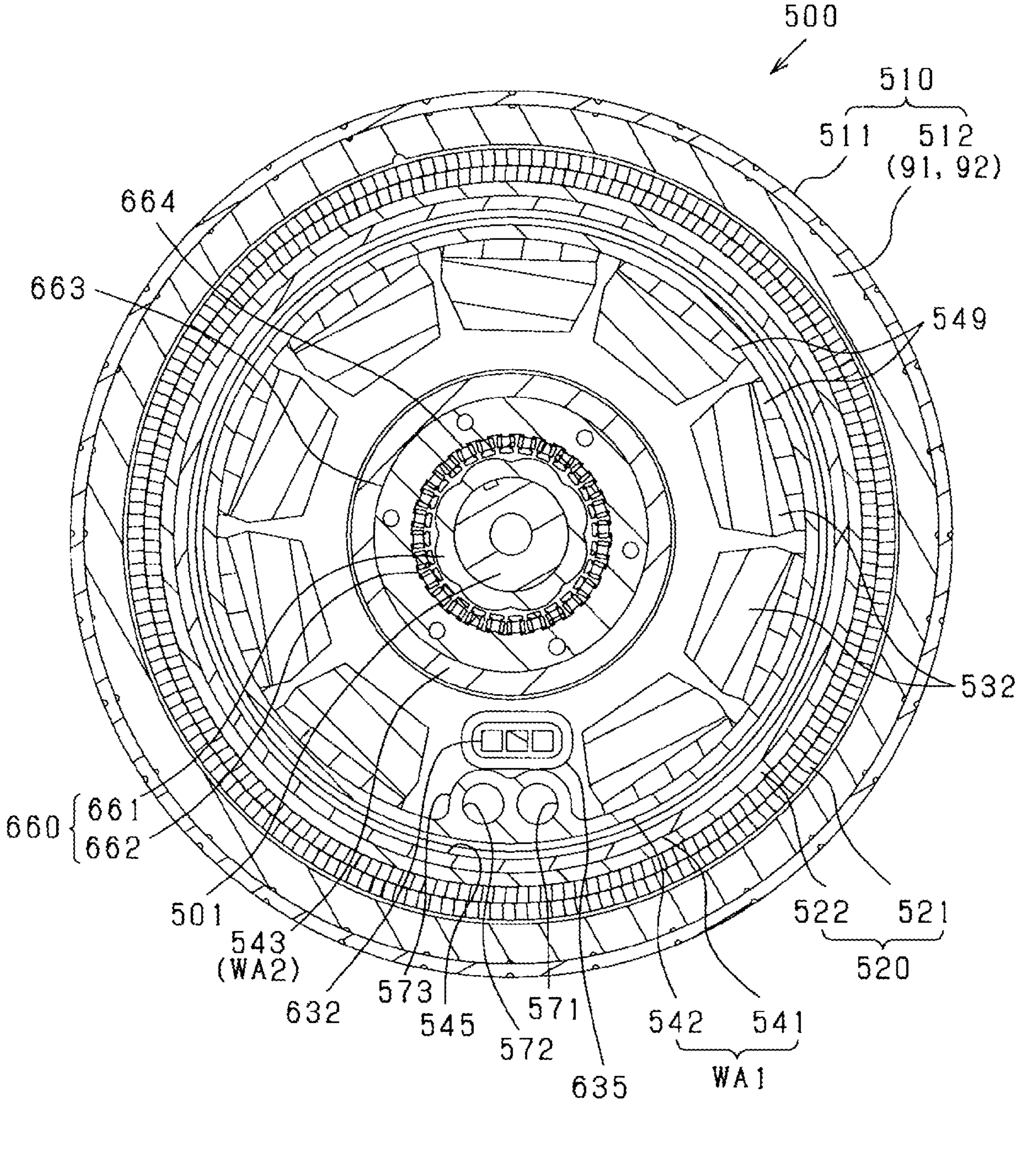

500
510
511
512
(91, 92)
664
663
549
532
660
661
662
501
543
(WA2)
632
573
545
572
571
635
542
541
WA1
522
521
520

FIG.51

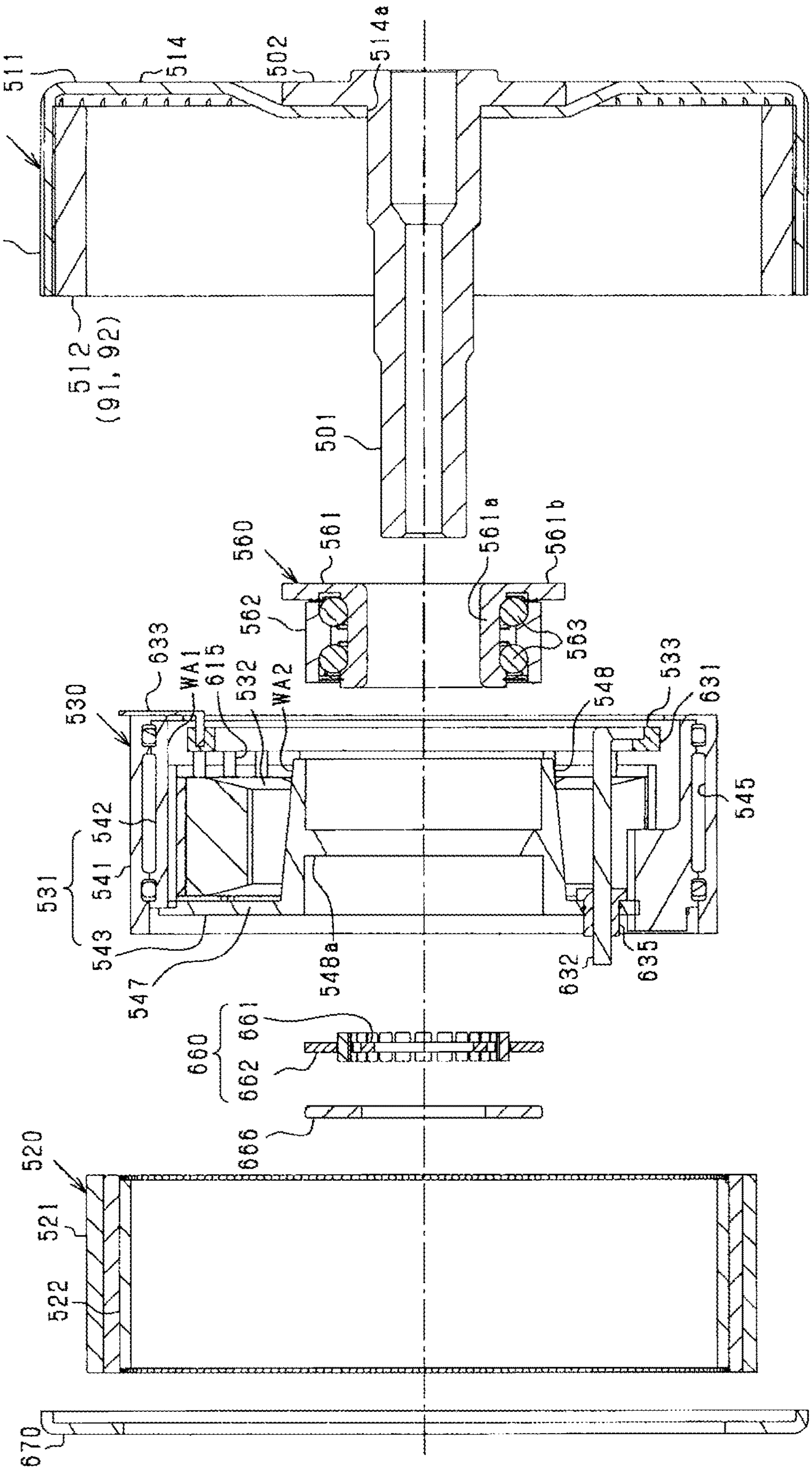

511
514
502
514a
510
513
512
(91, 92)
501
560
561
561a
561b
562
563
530
633
WA1
615
532
WA2
548
533
631
545
531
542
541
543
547
548a
632
635
660
661
662
666
520
521
522
670

FIG.52

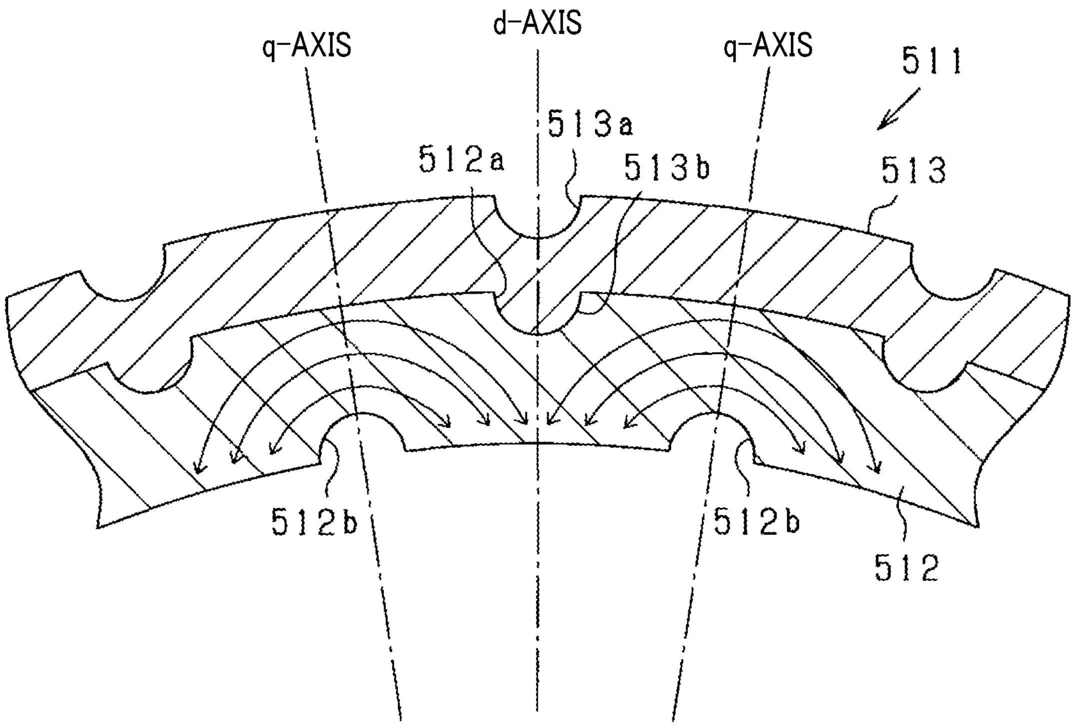


FIG.53

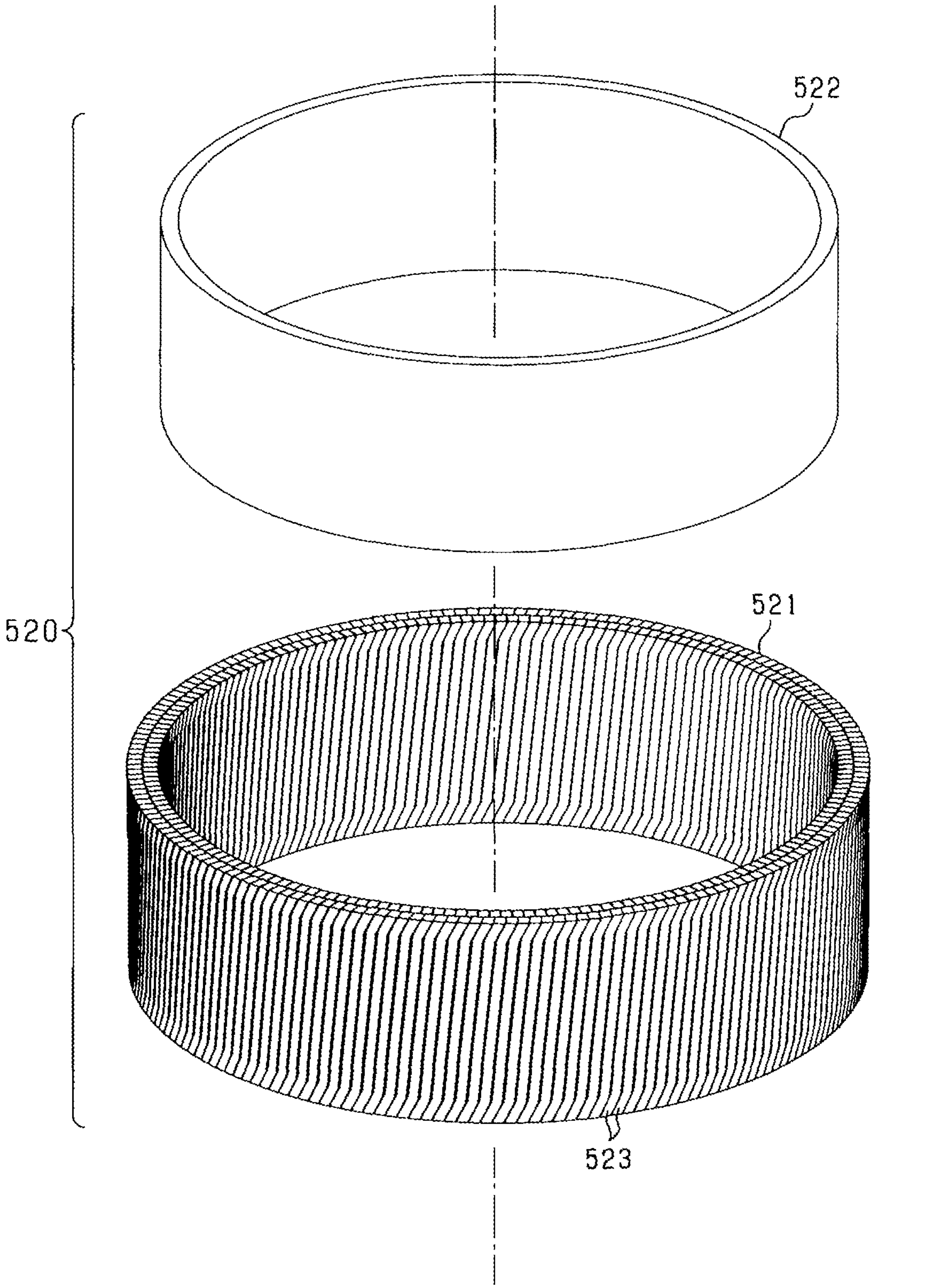


FIG.54(a)

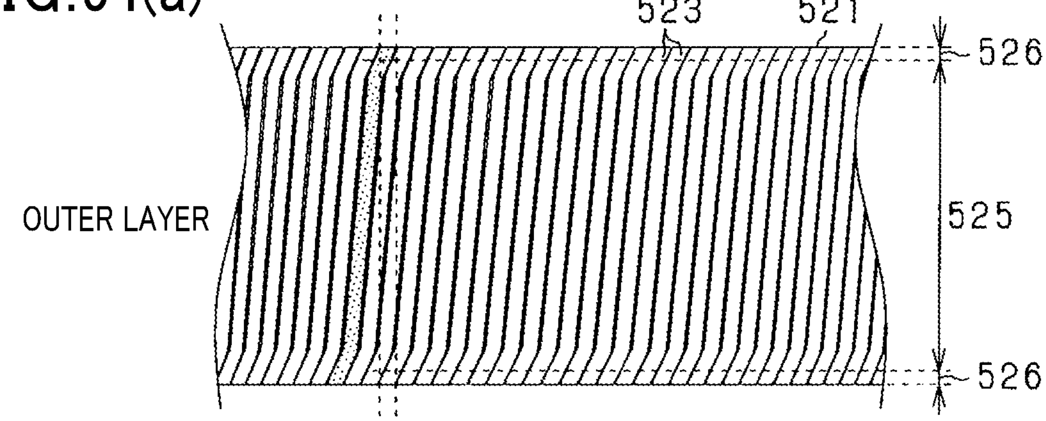


FIG.54(b)

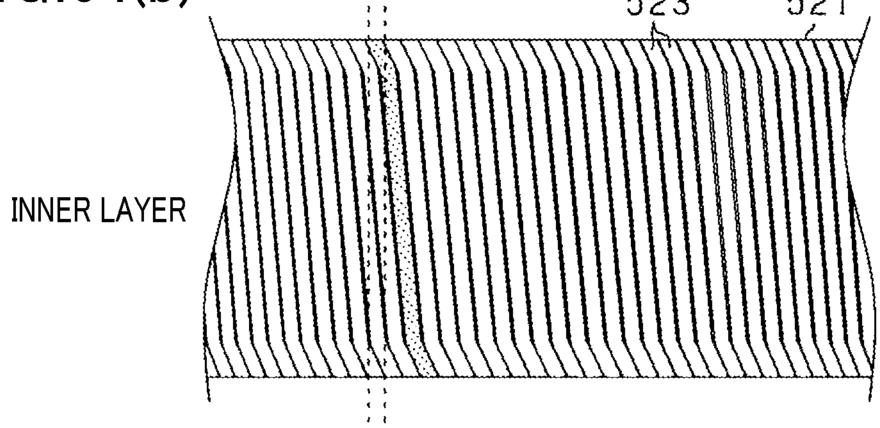


FIG.55

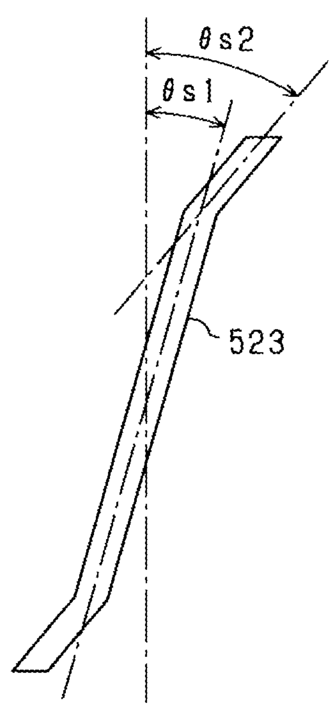
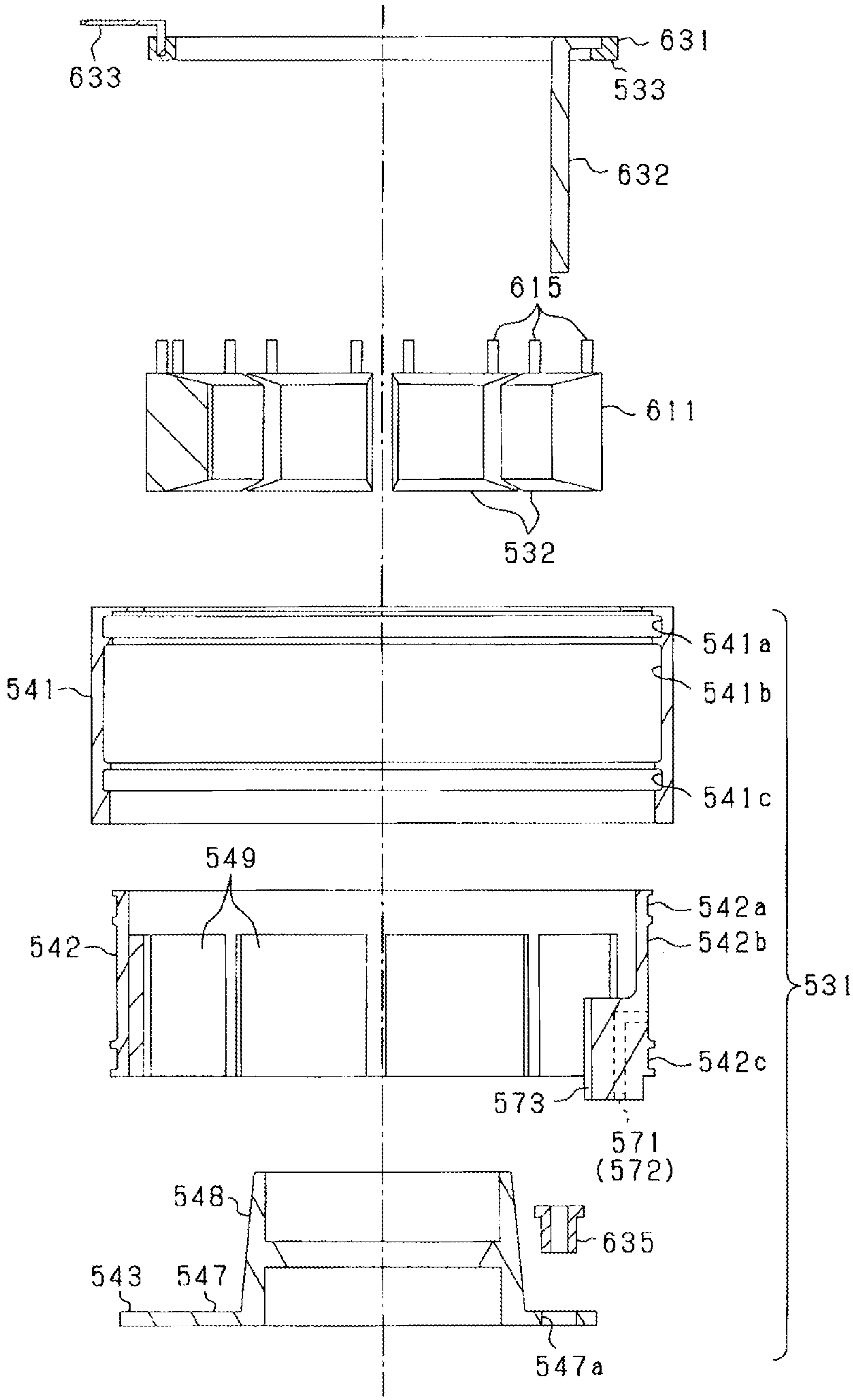


FIG.56



633
631
533
632
615
611
532
541
541a
541b
541c
549
542
542a
542b
542c
573
571
(572)
531
548
635
543
547
547a

FIG.57

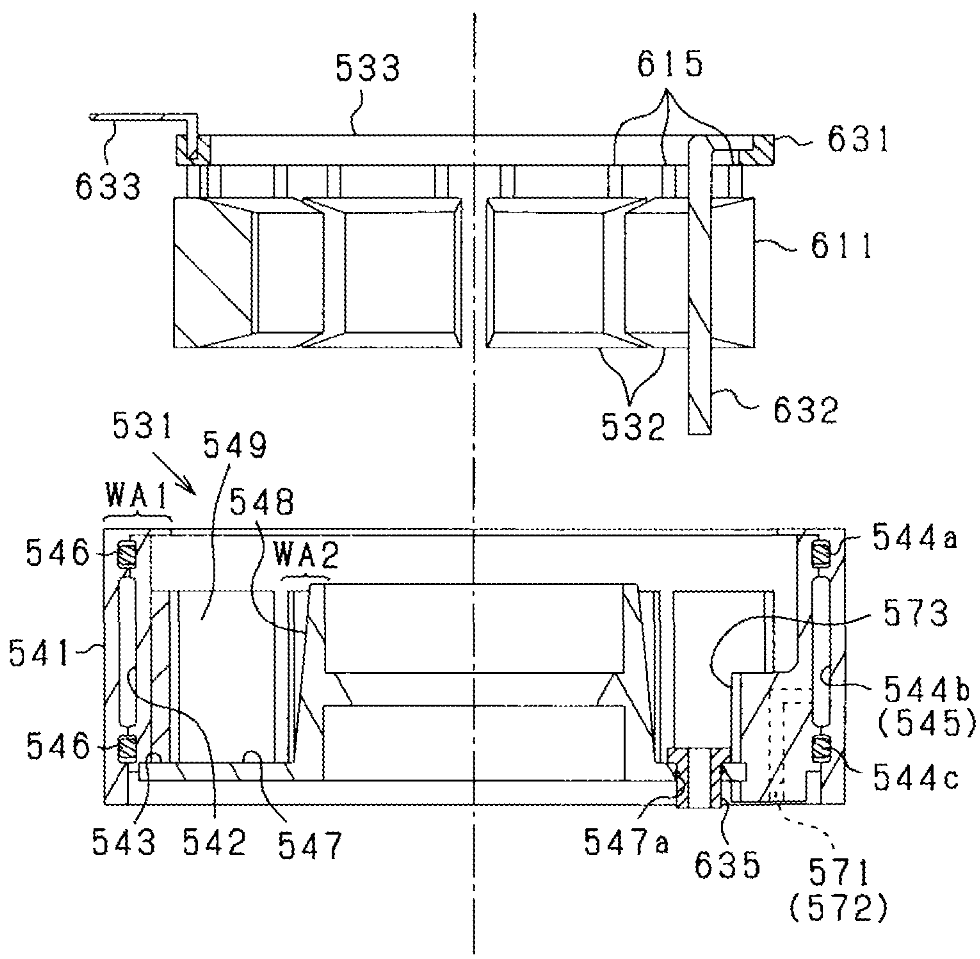

533
615
631
633
611
632
532
531
549
548
WA1
WA2
546
544a
573
541
544b
(545)
546
544c
543
542
547
547a
635
571
(572)

FIG.58

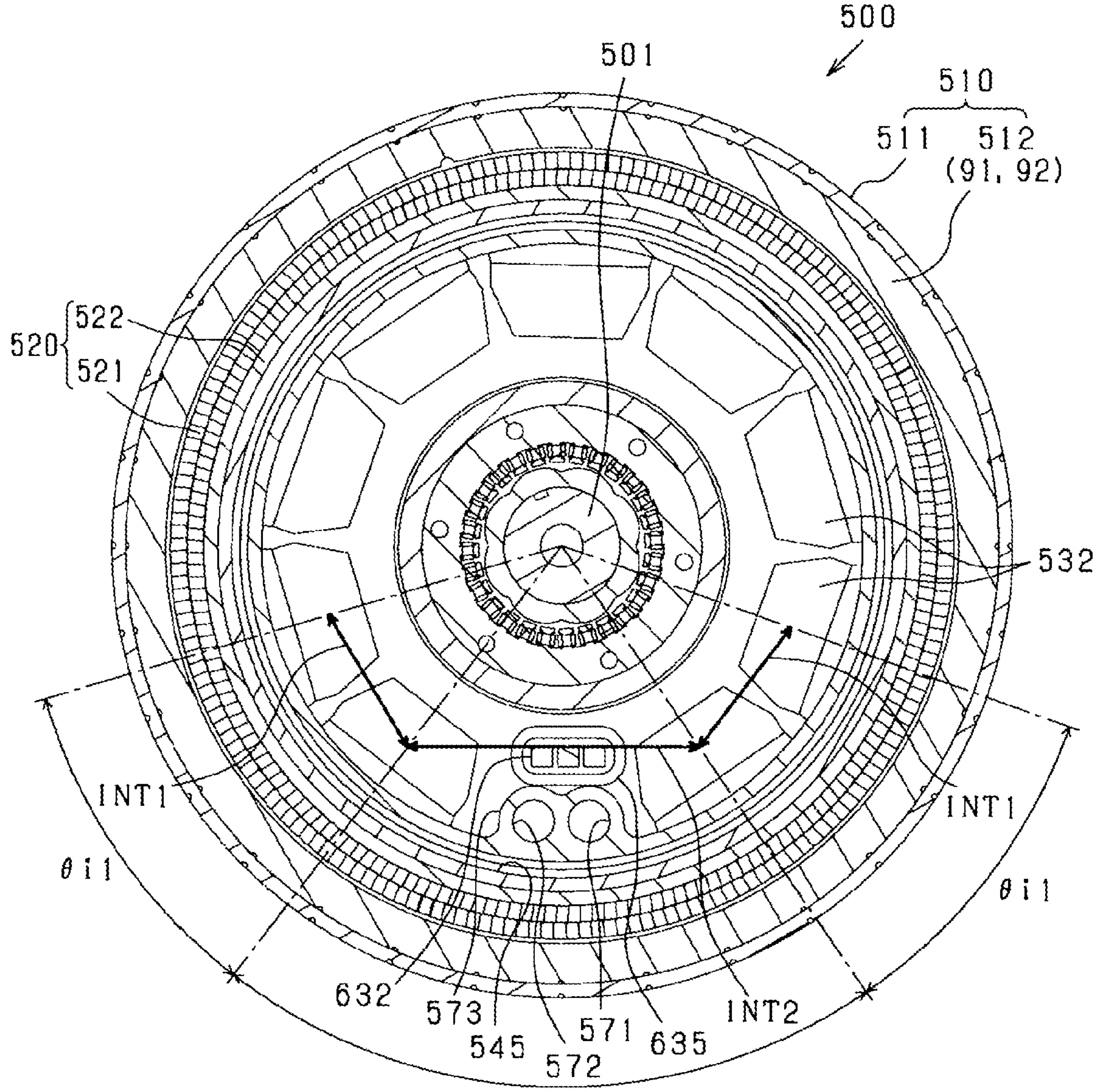

500
501
510
511
512
(91, 92)
520
522
521
532
INT1
INT1
θi1
θi1
632
573
545
572
571
635
INT2
θi2

FIG.59

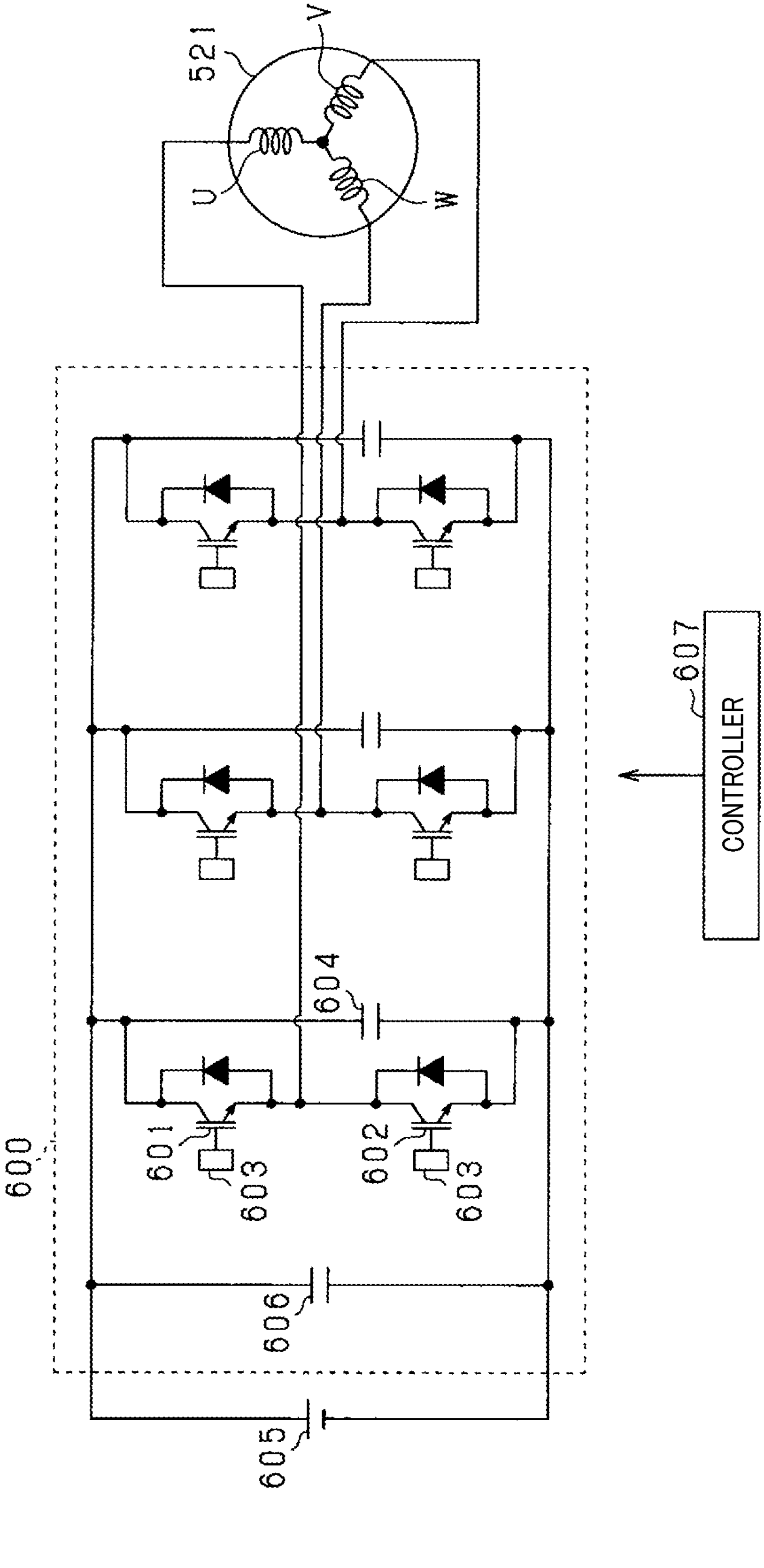


FIG.60

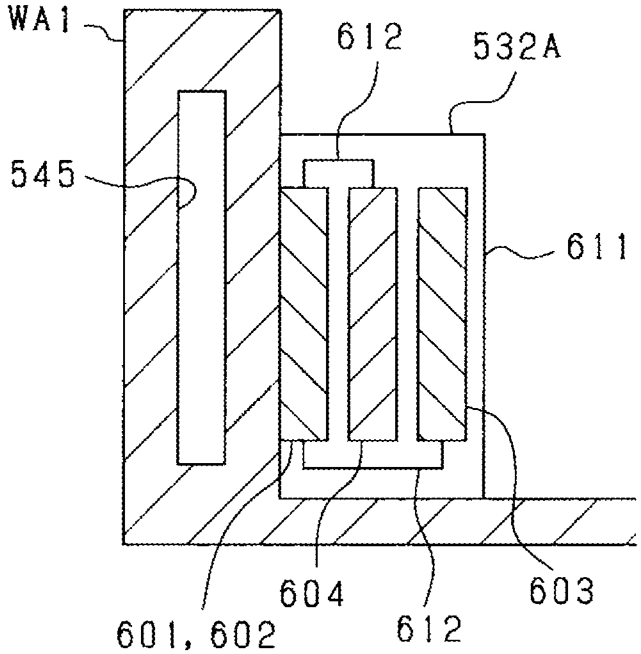


FIG.61(a)

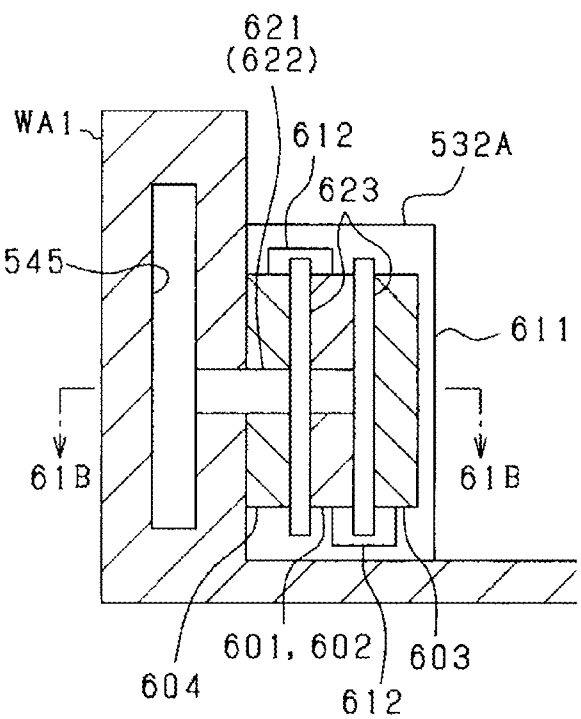


FIG.61(b)

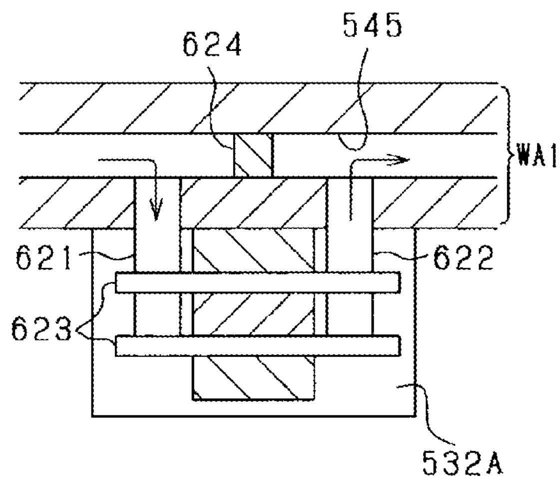


FIG.62(a)

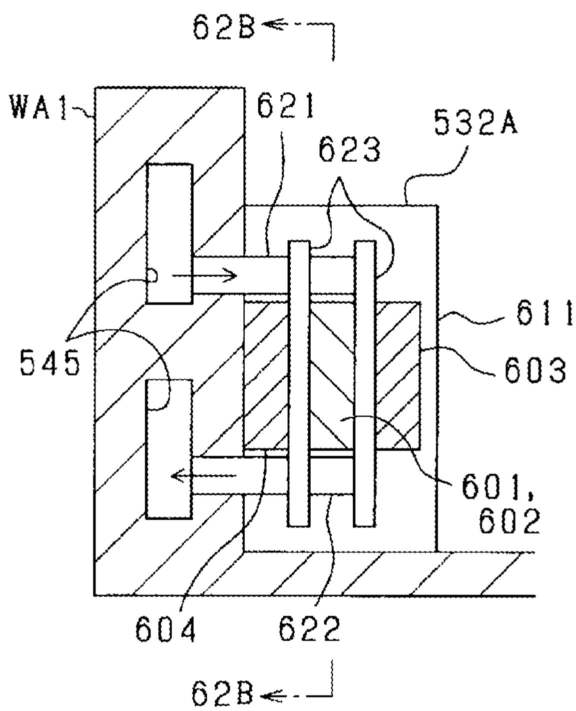


FIG.62(b)

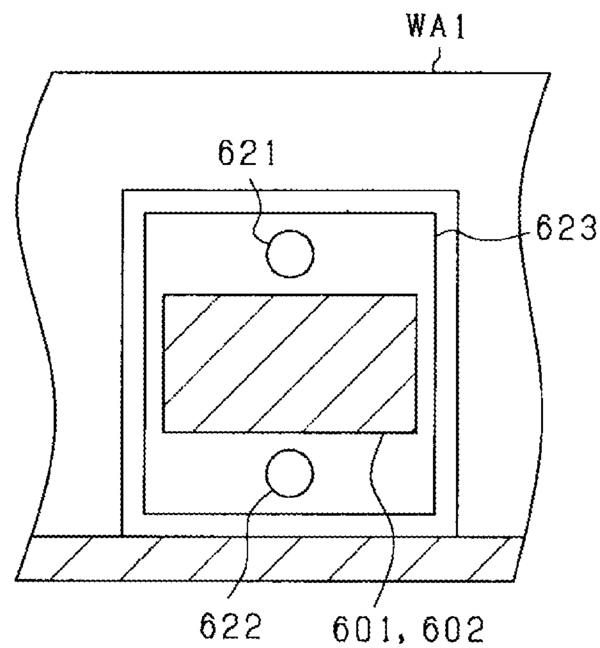


FIG.62(c)

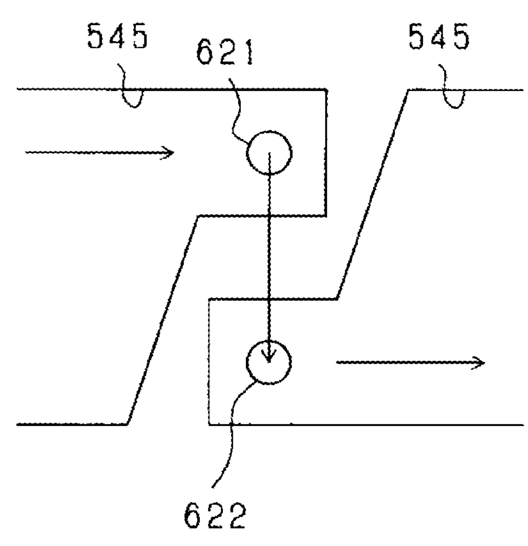


FIG.63(a)

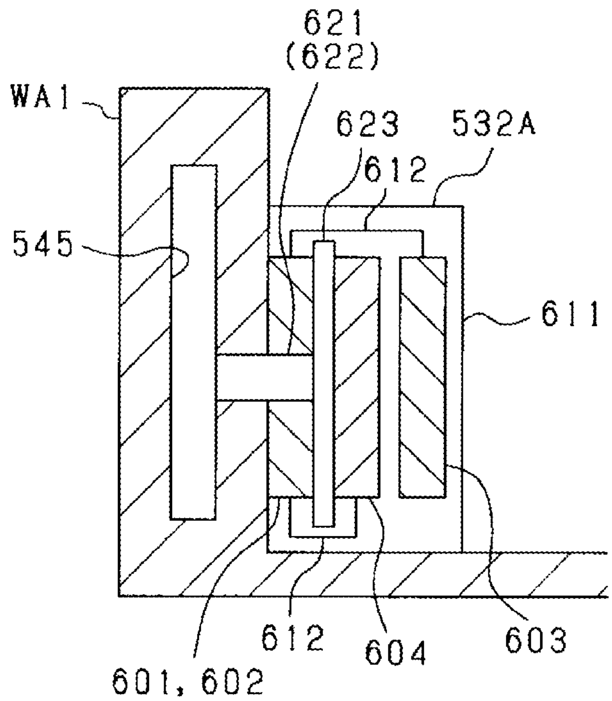


FIG.63(b)

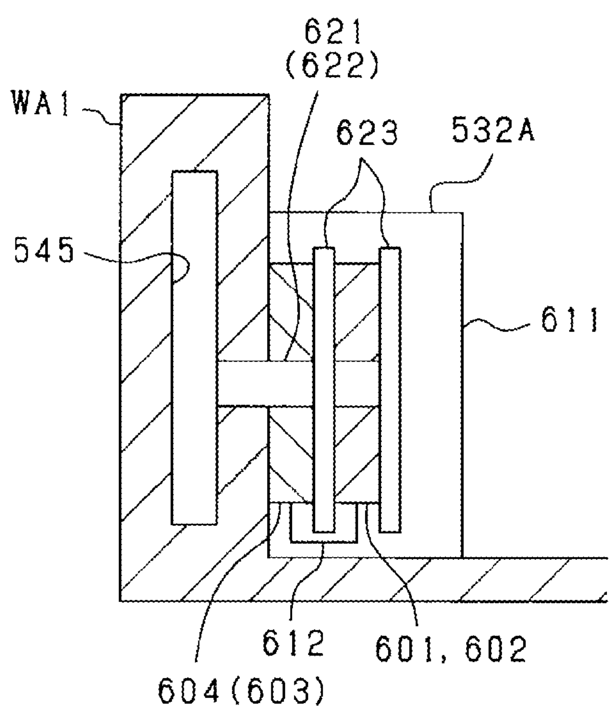


FIG.64

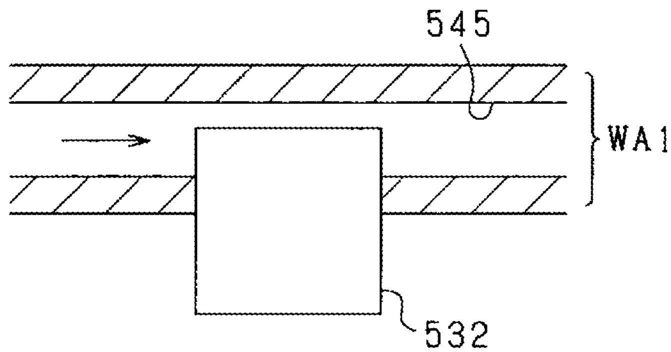


FIG.65

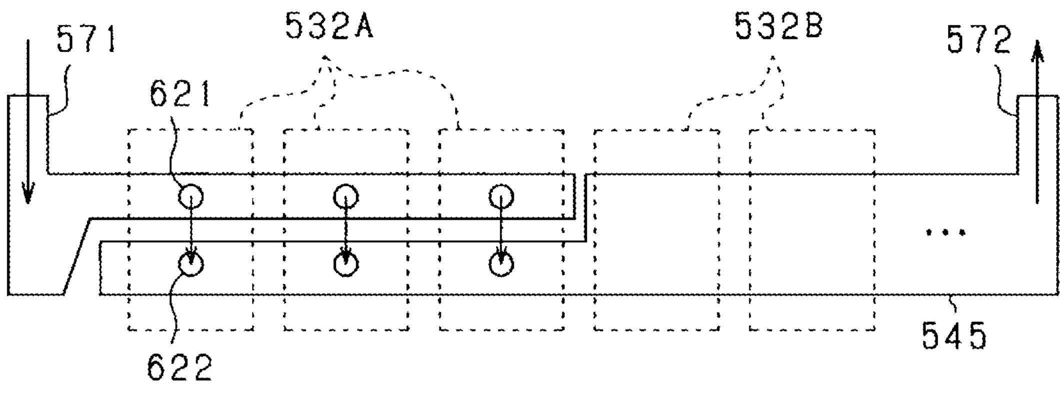
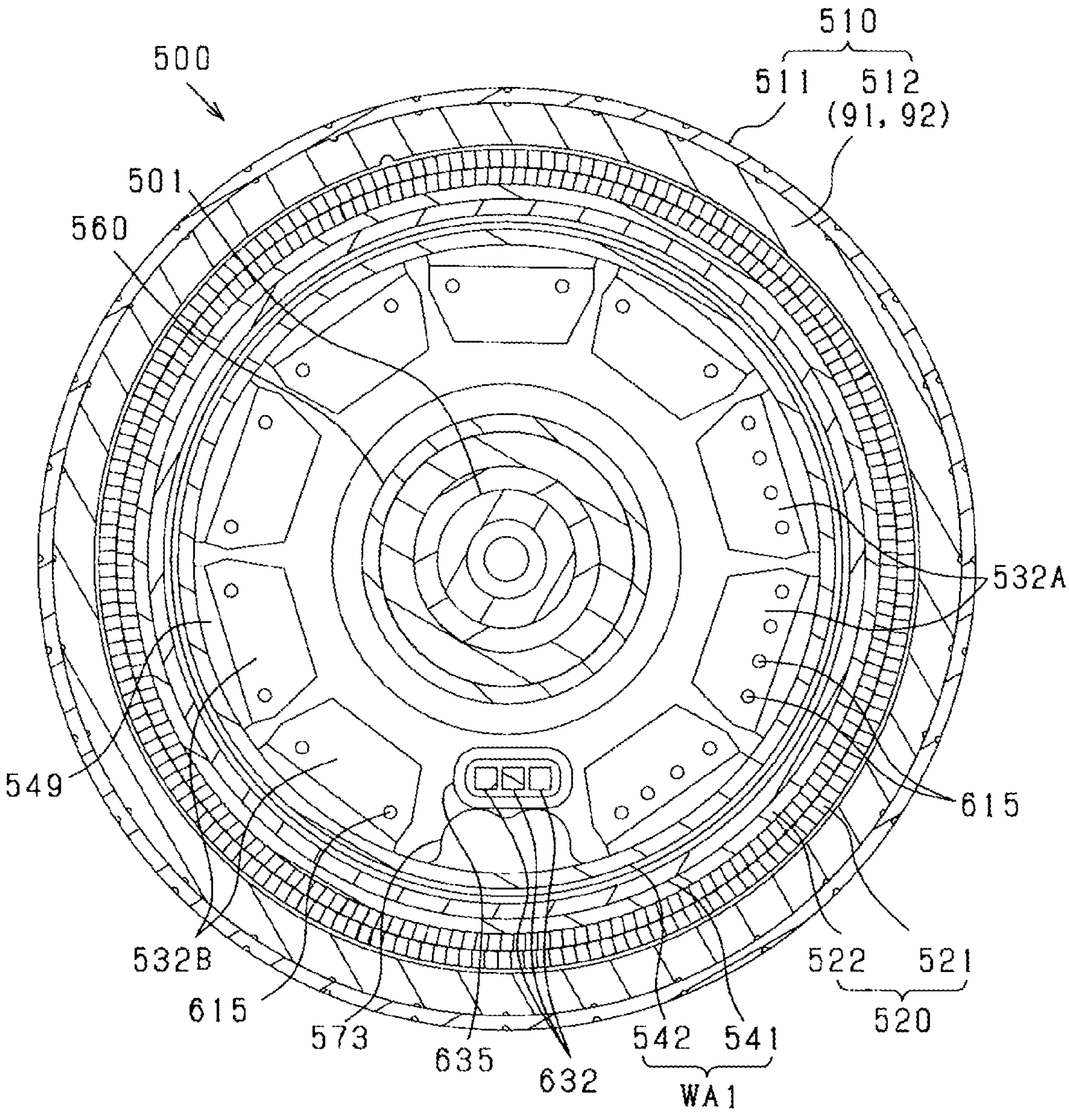


FIG.66



510
500
511
512
(91, 92)
501
560
532A
549
615
532B
615
573
635
632
542
541
WA1
522
521
520

FIG.67

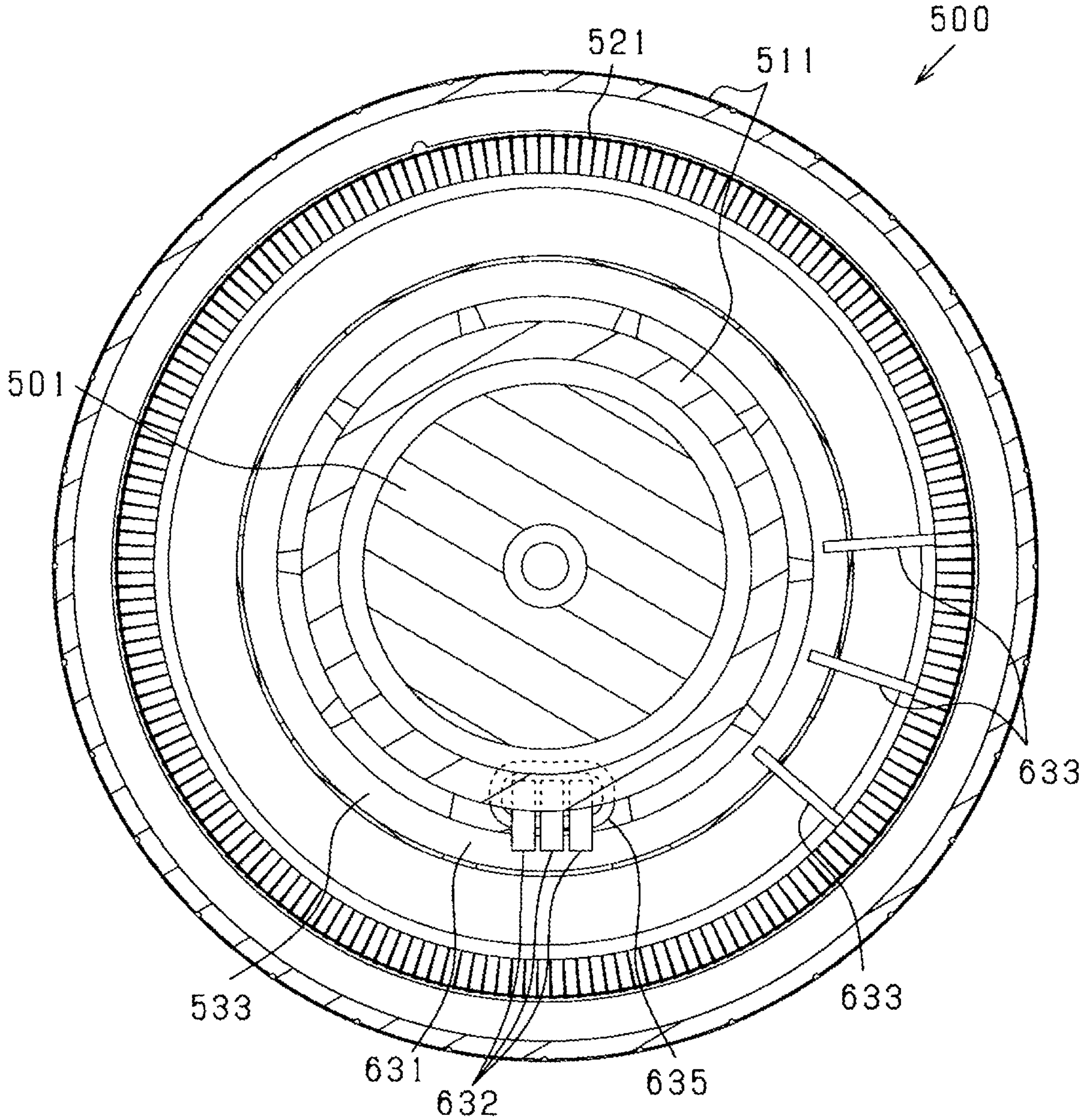


FIG.68

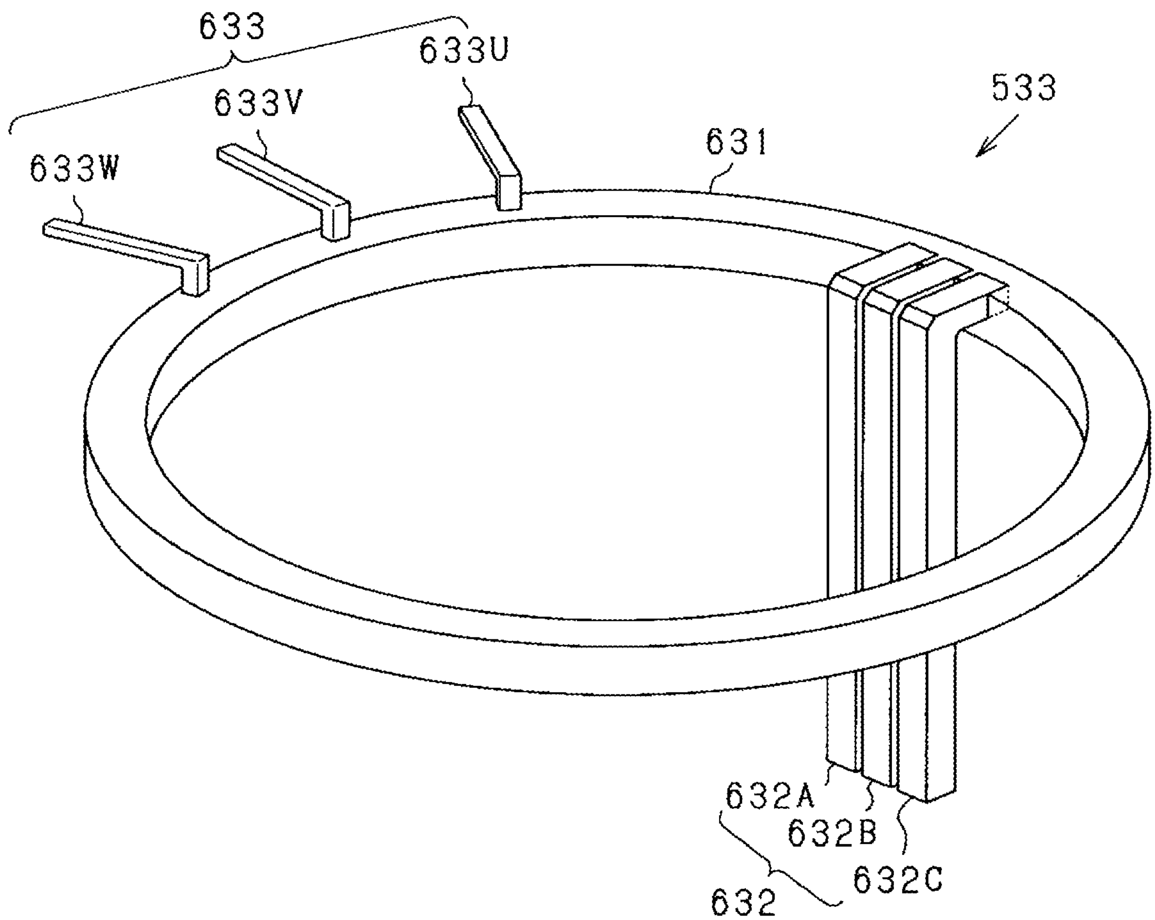


FIG.69

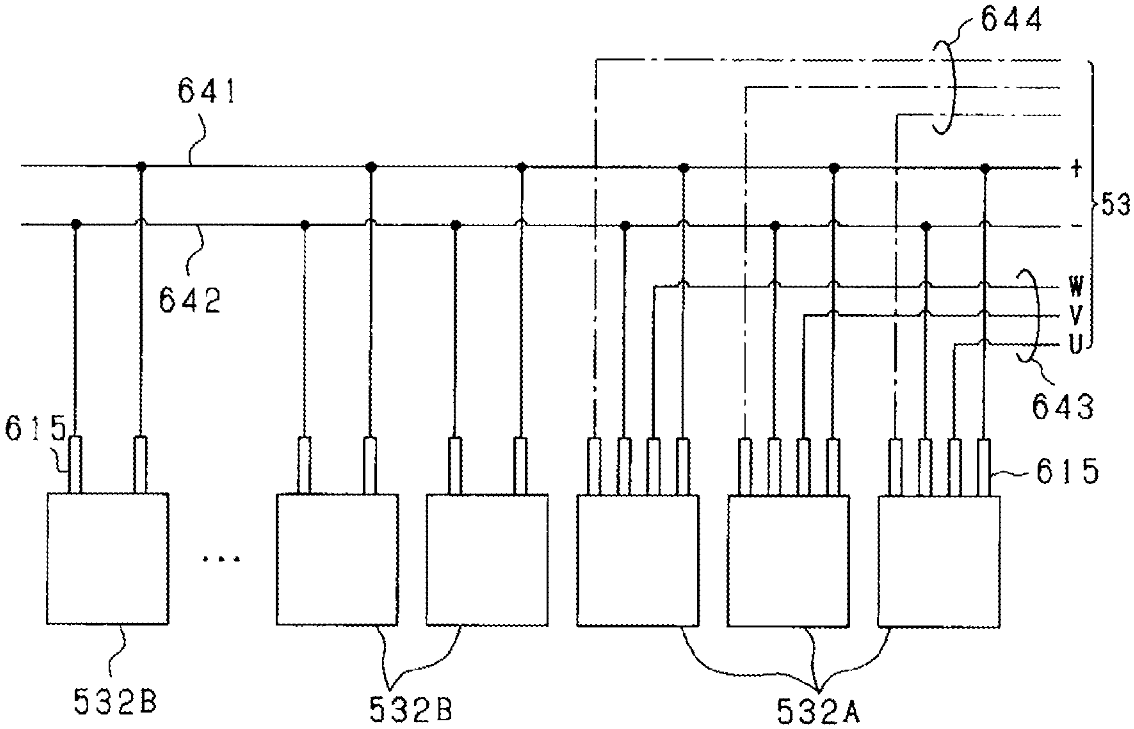

644
641
+
533
642
W
V
U
643
615
615
532B
532B
532A

FIG.70

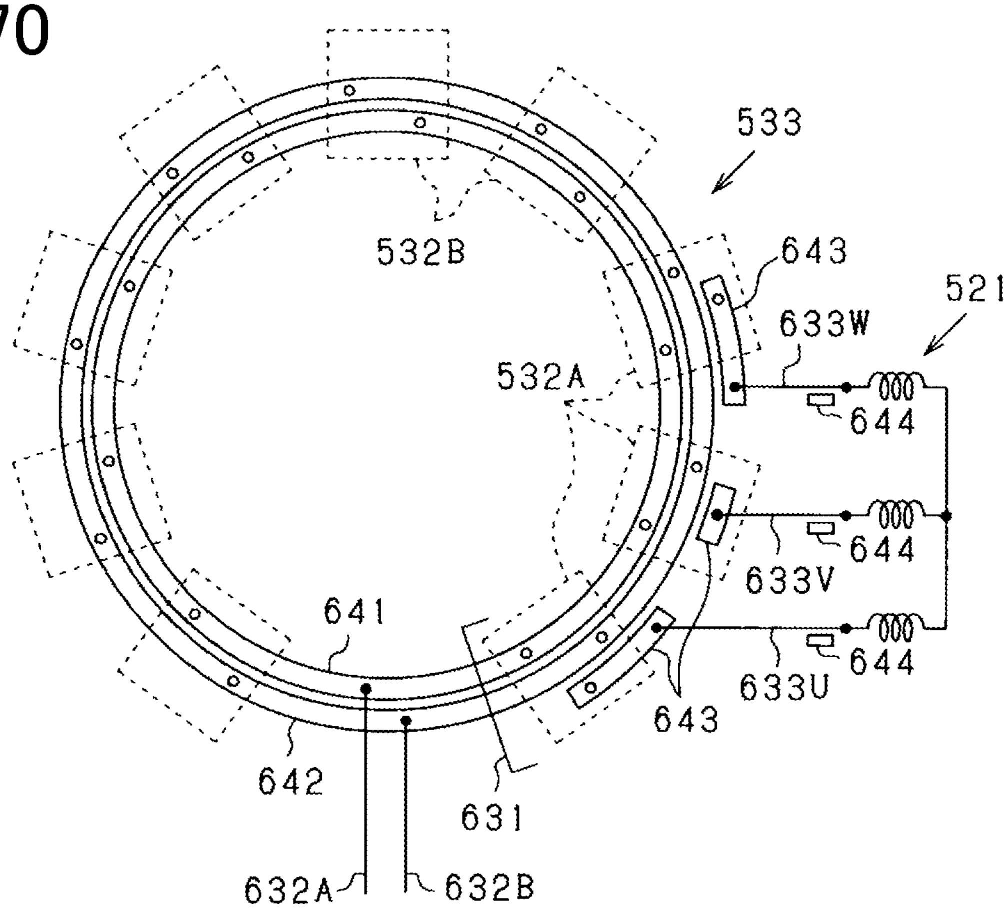
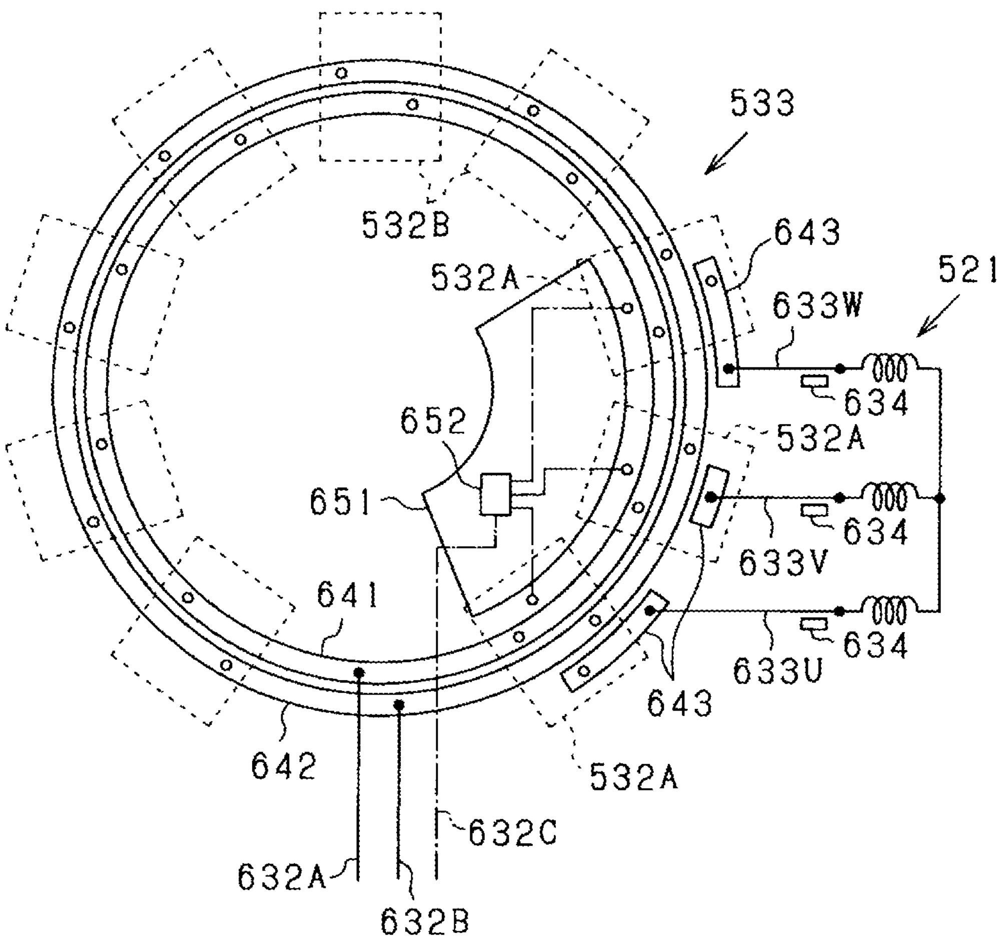

533
532B
643
521
633W
532A
644
644
633V
641
644
633U
643
642
631
632A
632B

FIG.71



533
532B
643
521
532A
633W
634
652
532A
651
634
633V
641
634
633U
643
642
532A
632C
632A
632B

FIG.72(a)

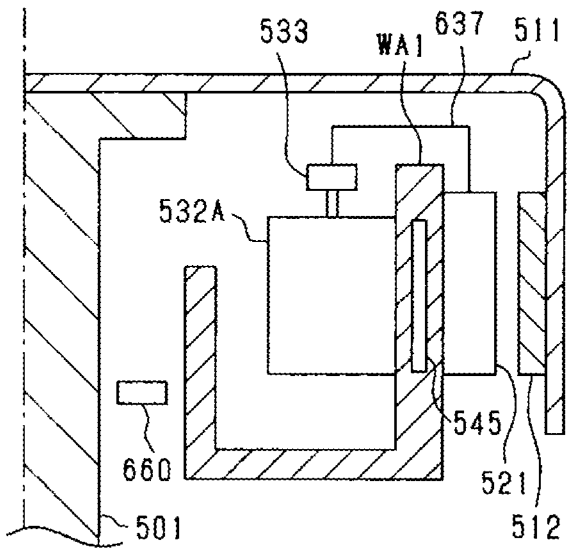


FIG.72(b)

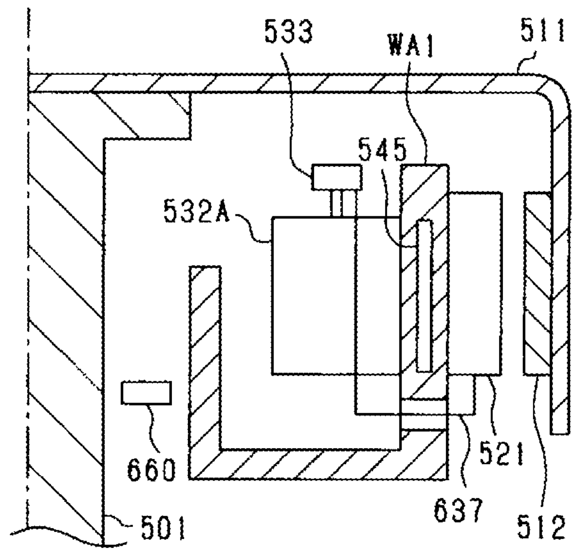


FIG.72(c)

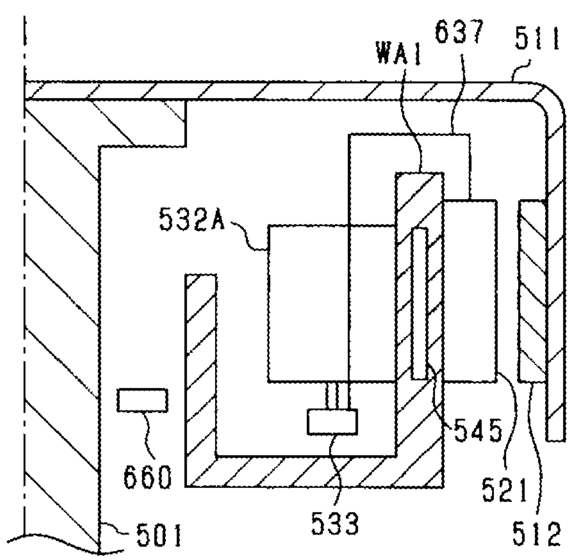


FIG.72(d)

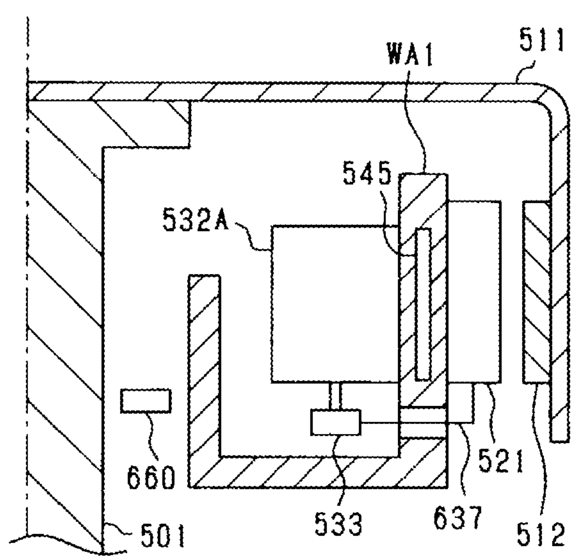


FIG.73(a)

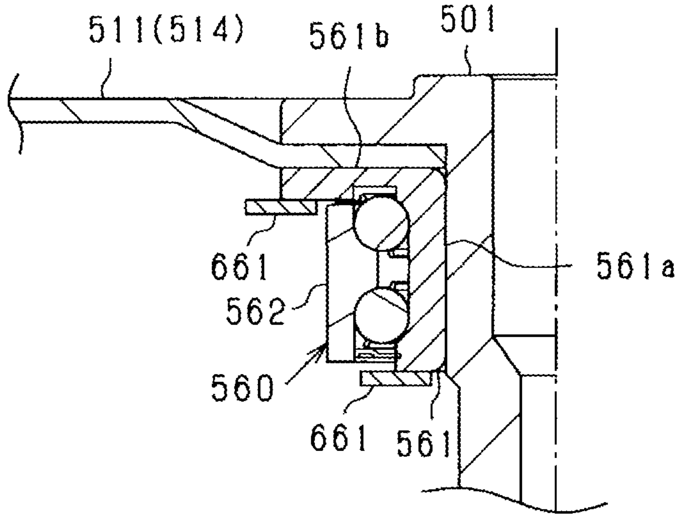


FIG.73(b)

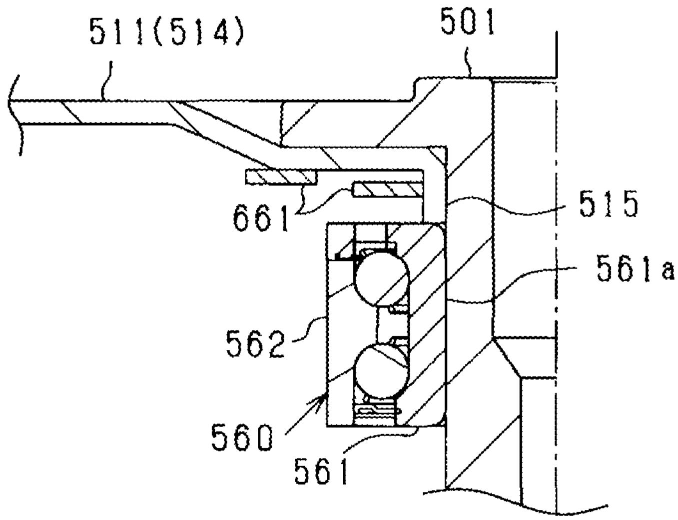


FIG.73(c)

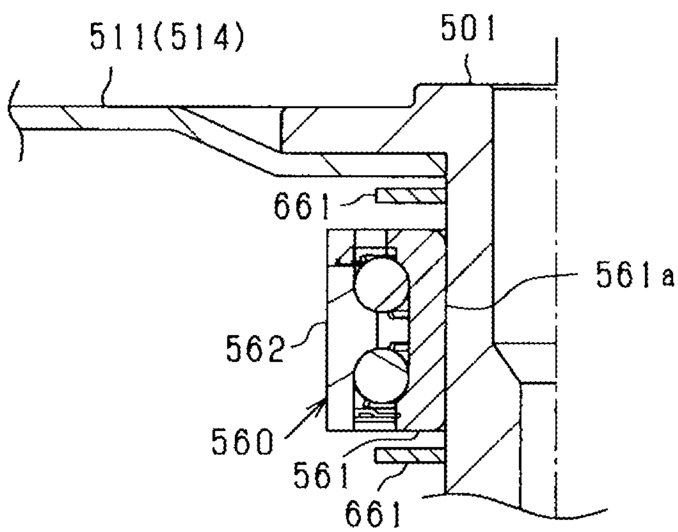


FIG.74(a)

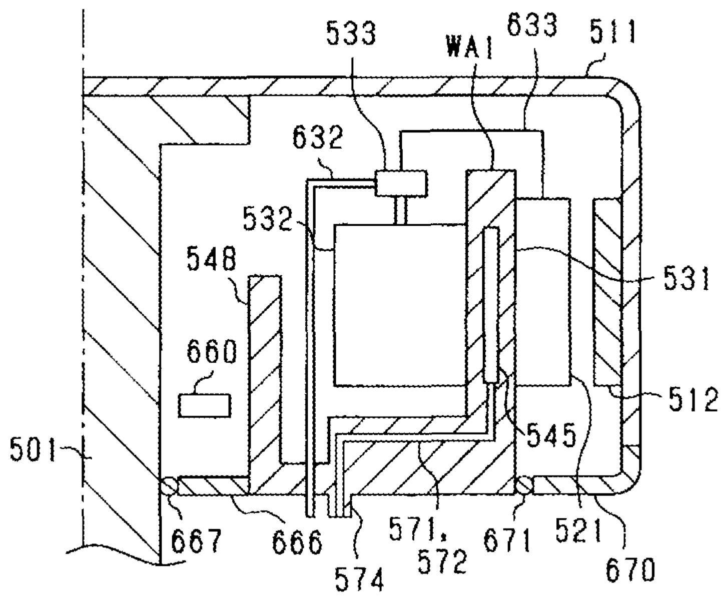


FIG.74(b)

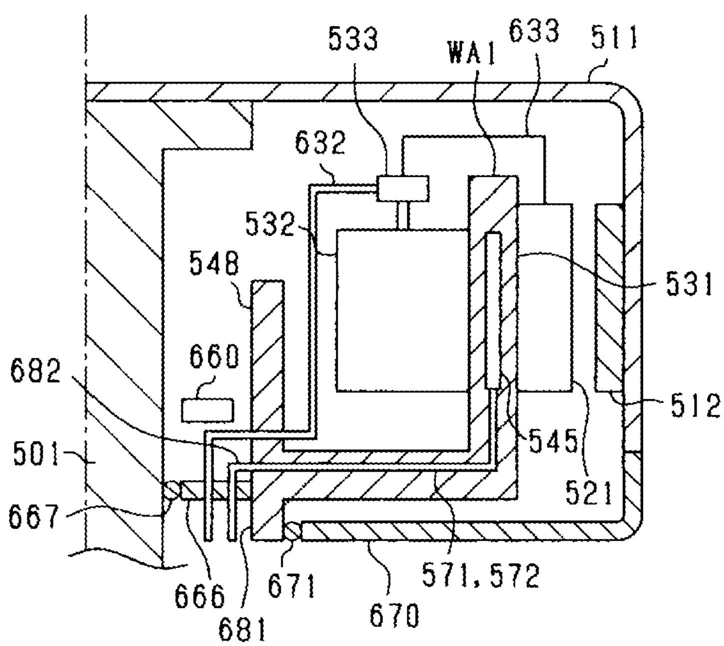


FIG.75

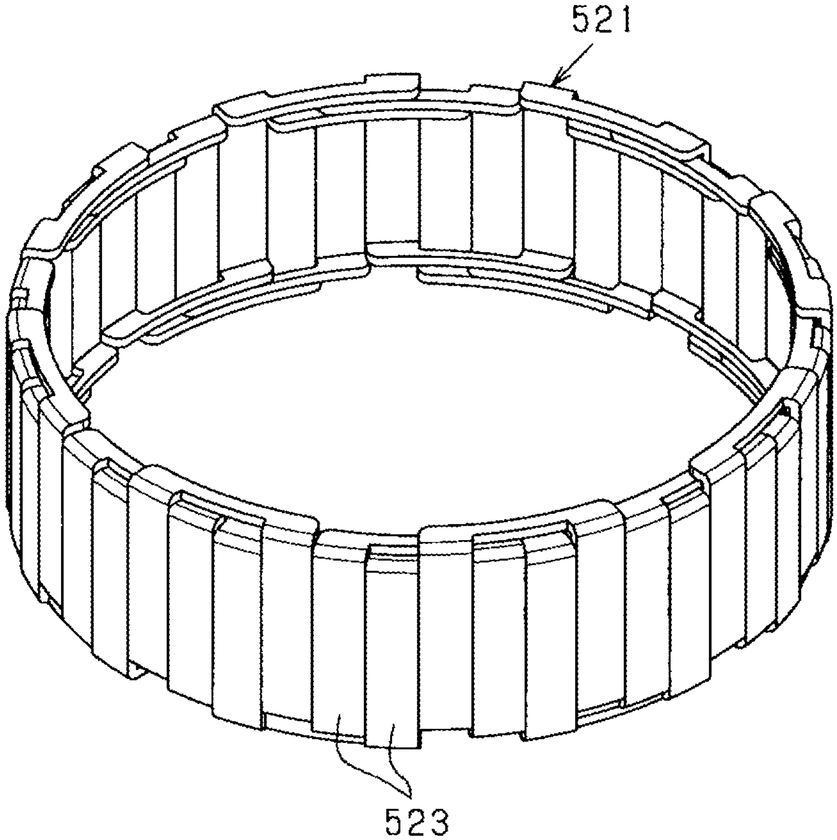


FIG.76

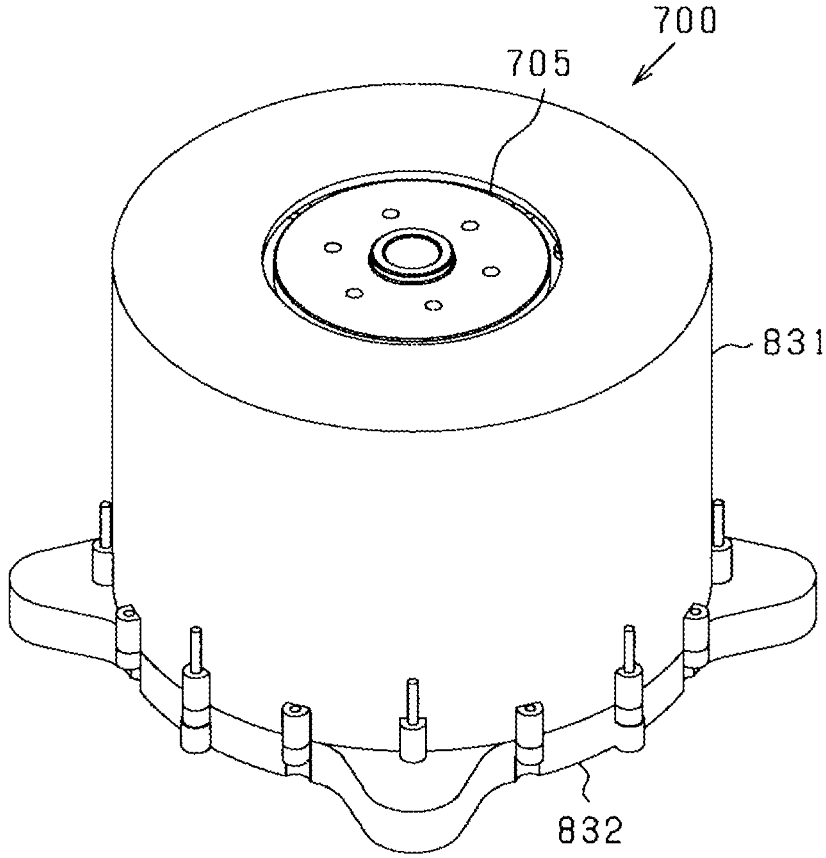
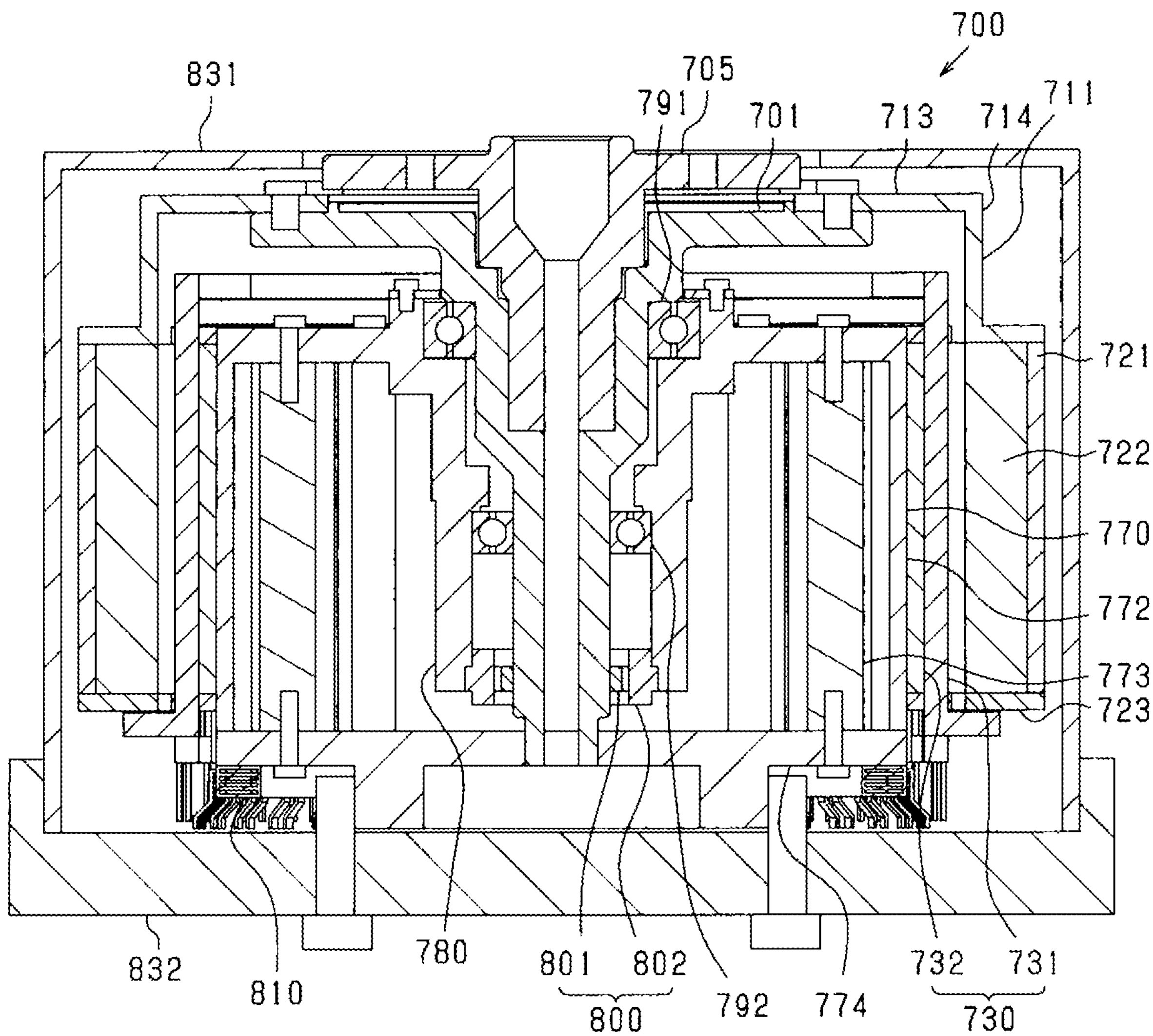


FIG.77



700
831
705
791
701
713
714
711
721
722
770
772
773
723
832
810
780
801
802
800
792
774
732
731
730

FIG.78

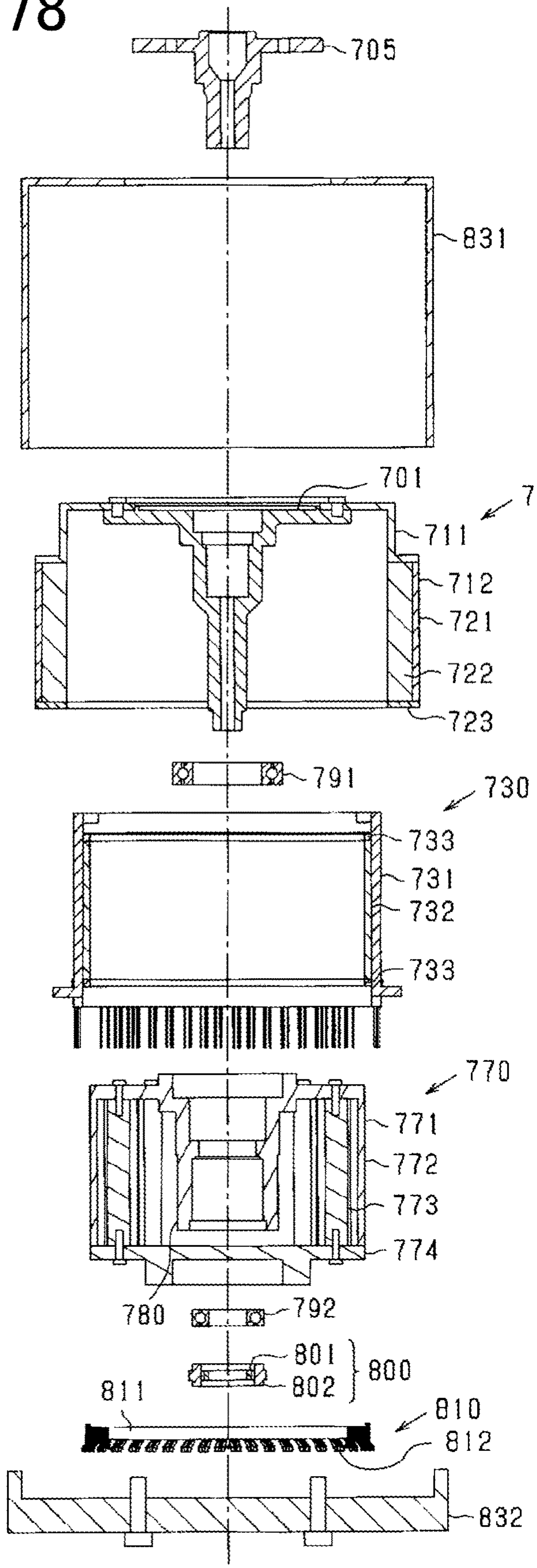

705
831
701
710
711
712
721
722
723
791
730
733
731
732
733
770
771
772
773
774
780
792
801
802
800
811
810
812
832

FIG.79

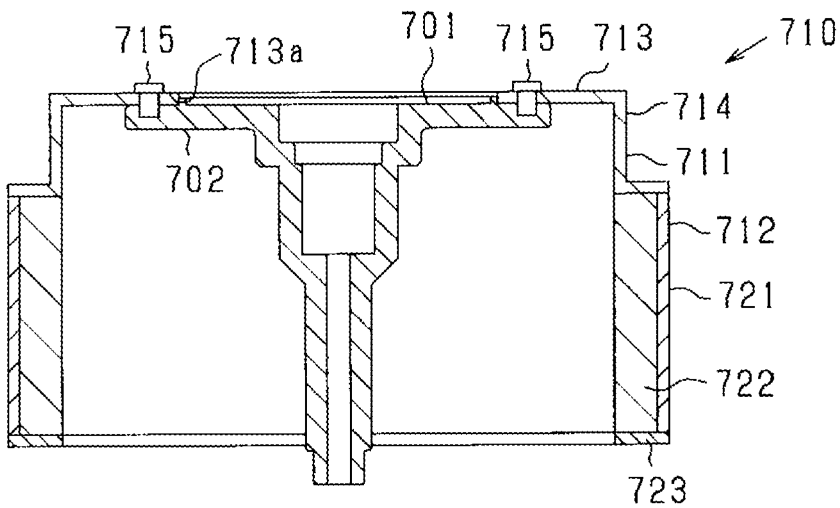


FIG.80

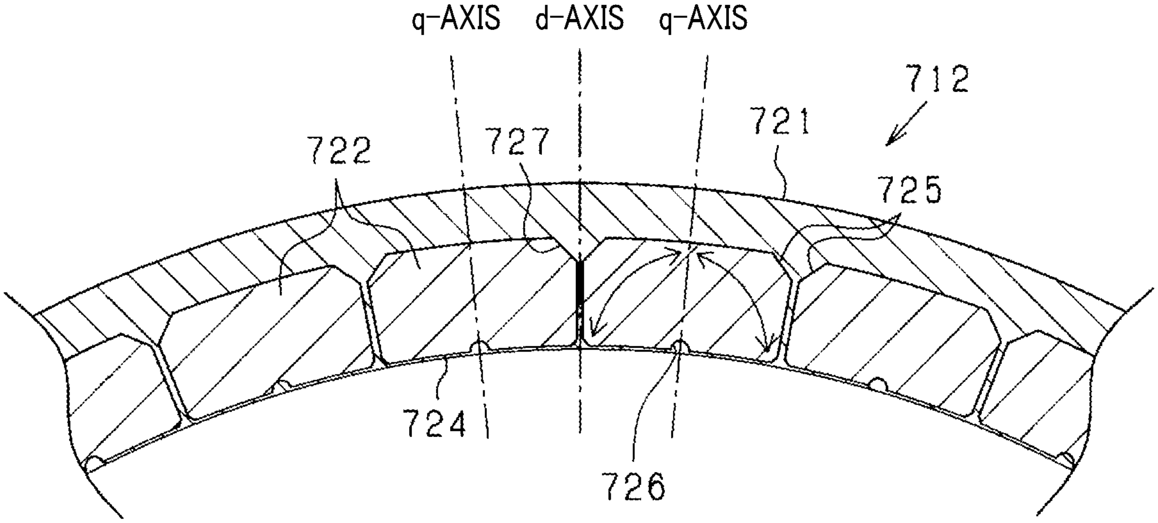

q-AXIS
d-AXIS
q-AXIS
712
721
722
727
725
724
726

FIG.81

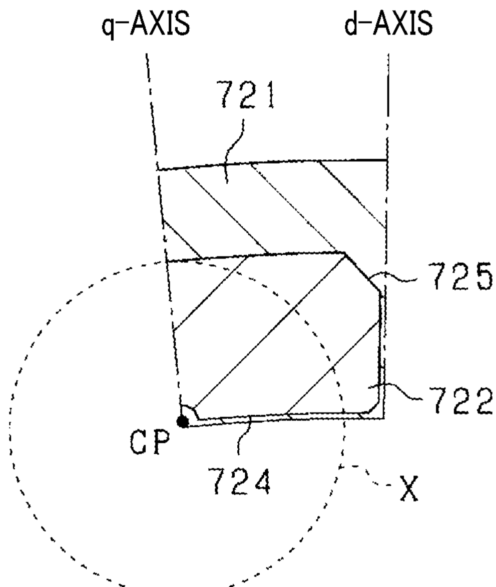

q-AXIS
d-AXIS
721
725
722
CP
724
X

FIG.82

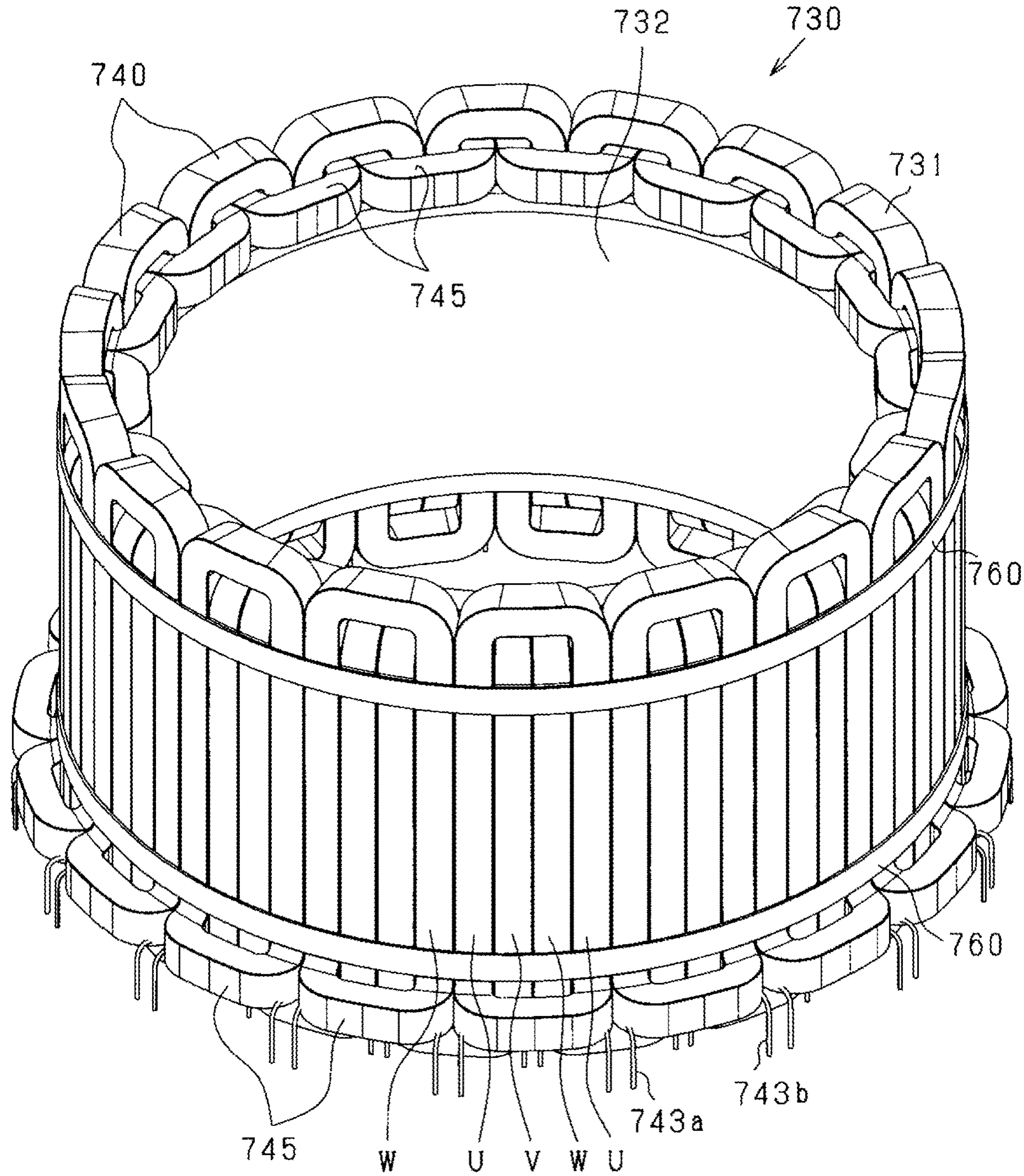


FIG.83

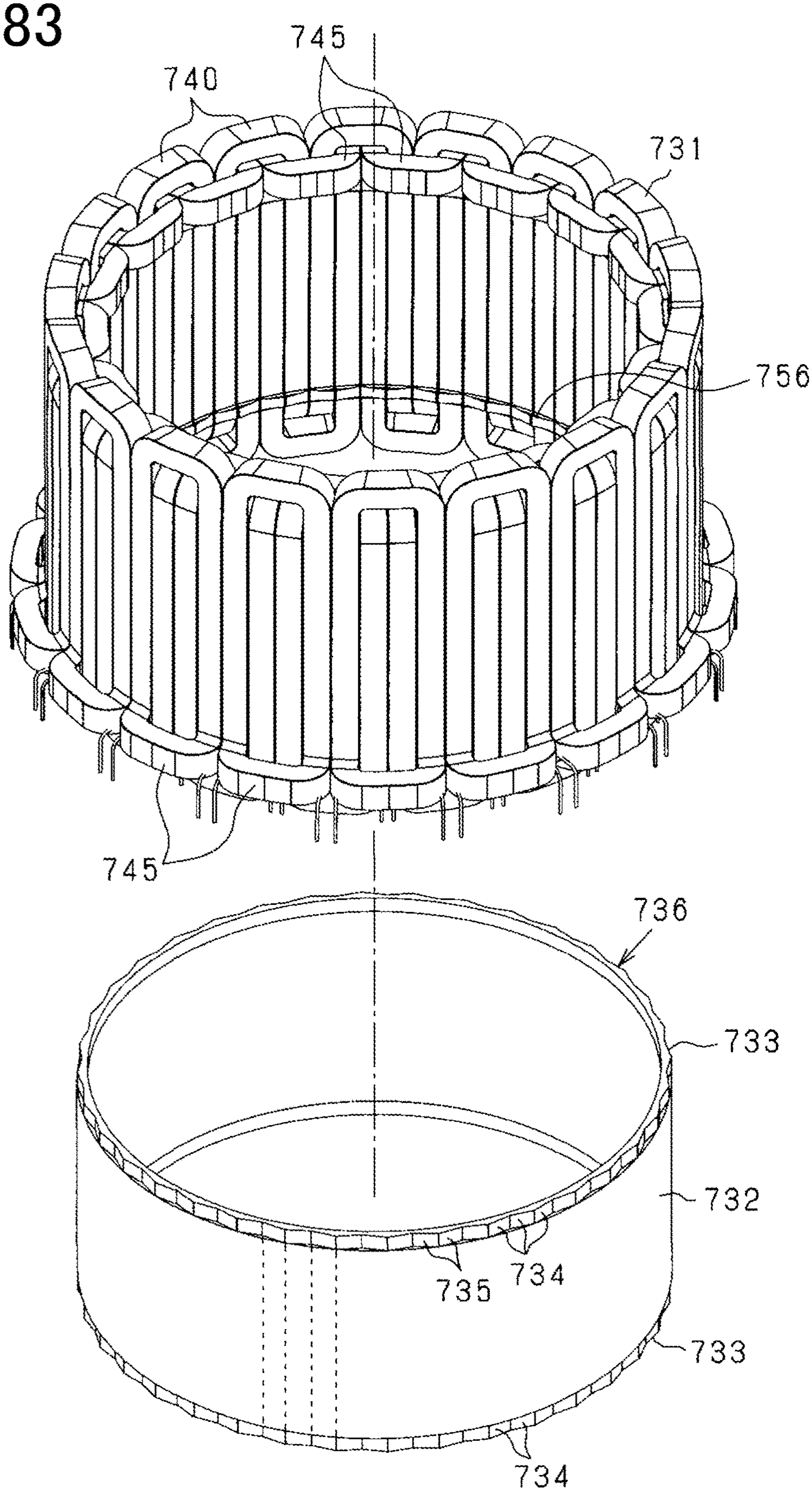


FIG.84

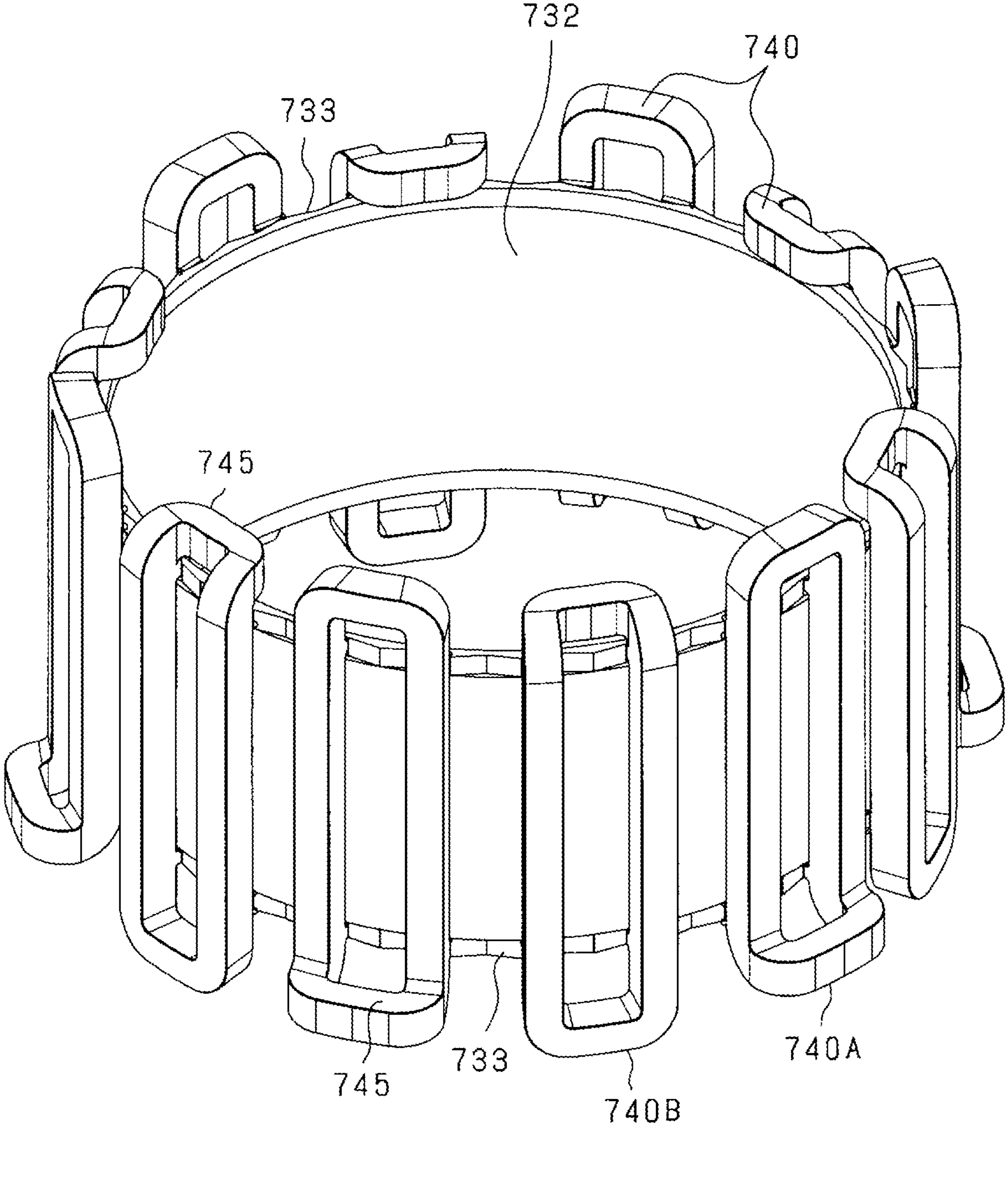


FIG.85

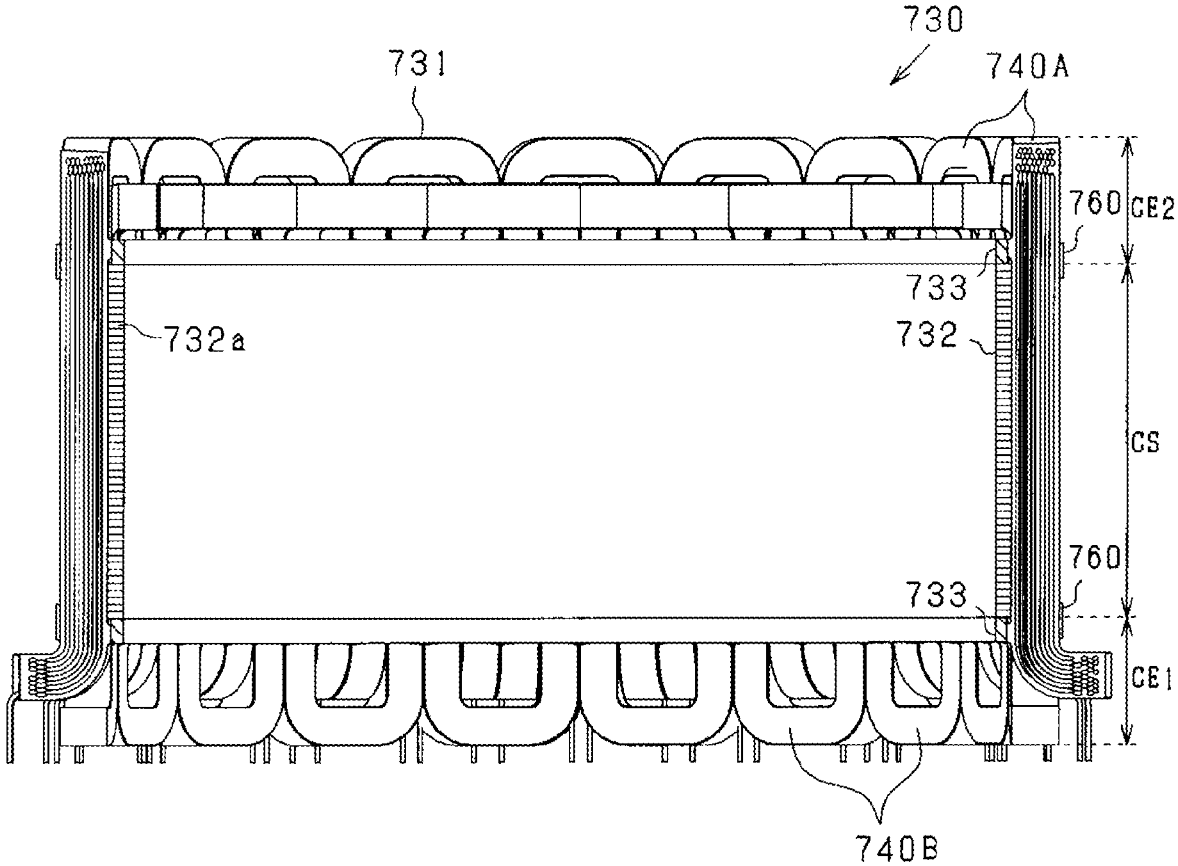

730
731
740A
760
CE2
733
732a
732
CS
760
733
CE1
740B

FIG.86

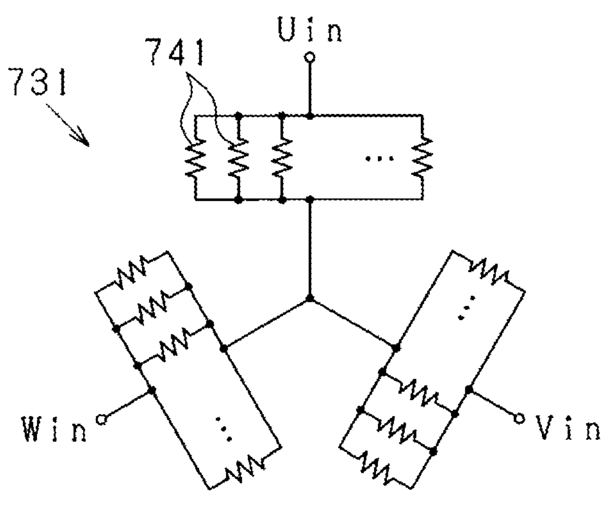

Uin
741
731
...
Win
Vin

FIG.87(d)

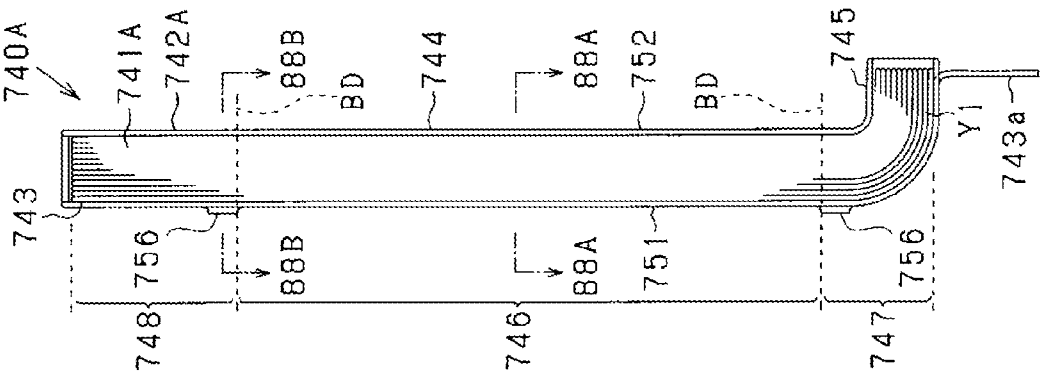


FIG.87(c)

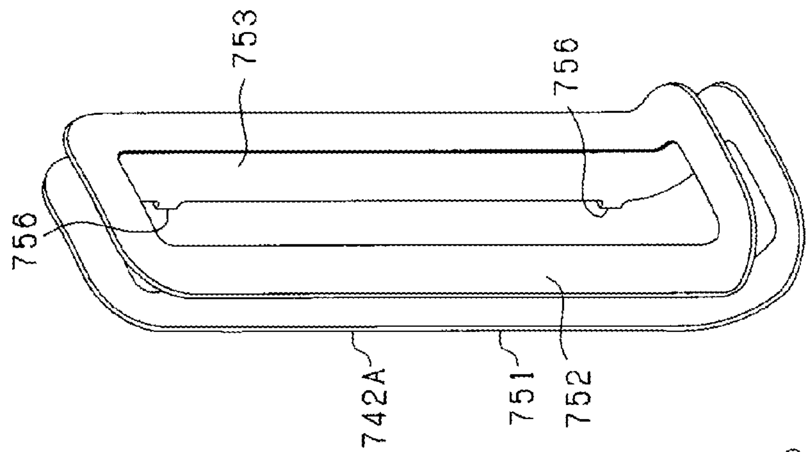


FIG.87(b)

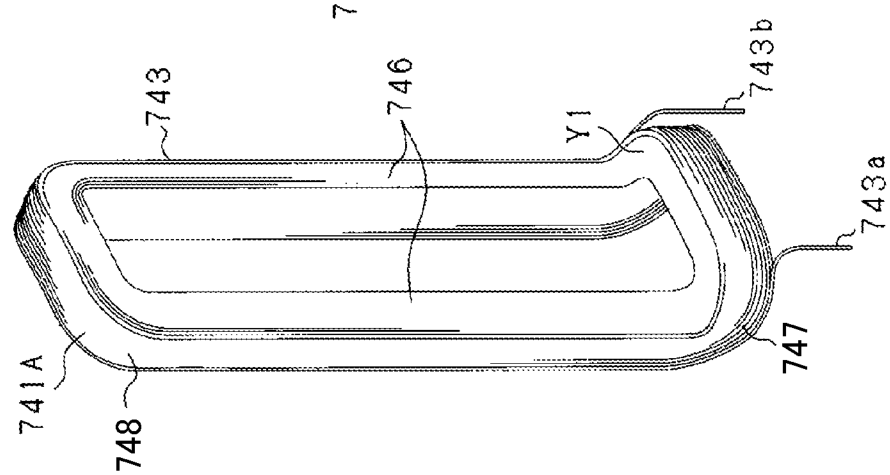


FIG.87(a)

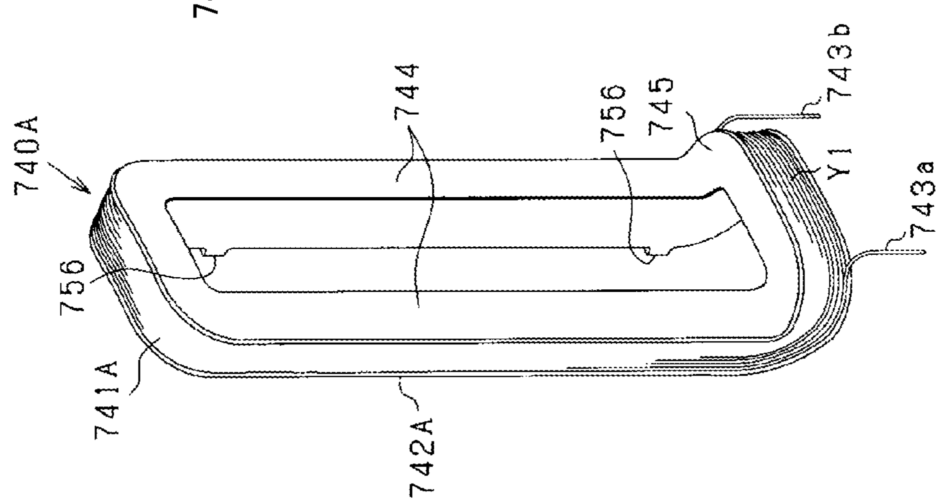


FIG.88(a)

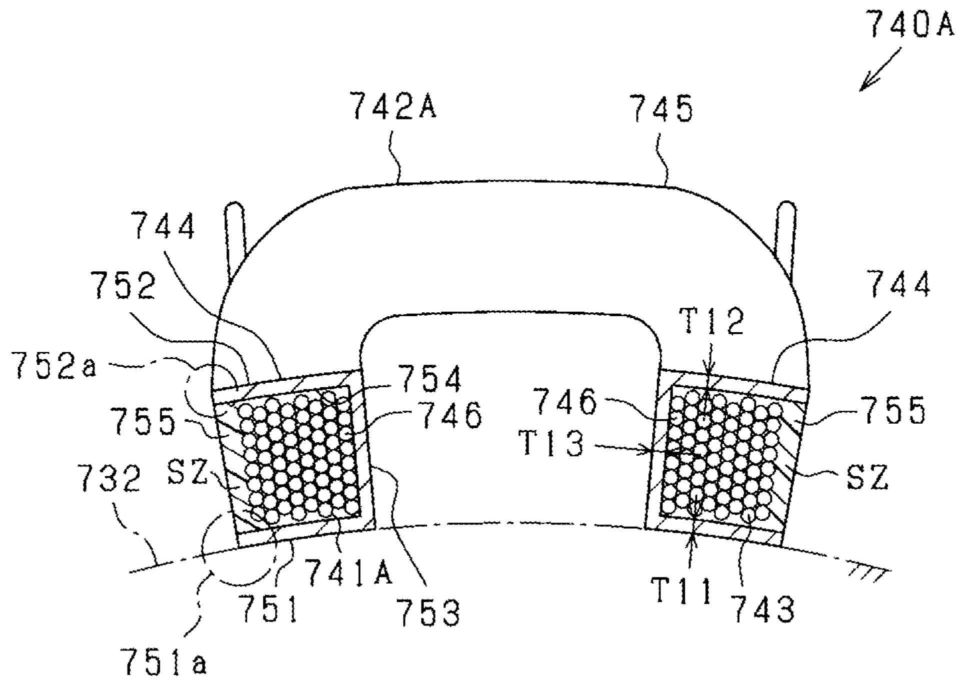


FIG.88(b)

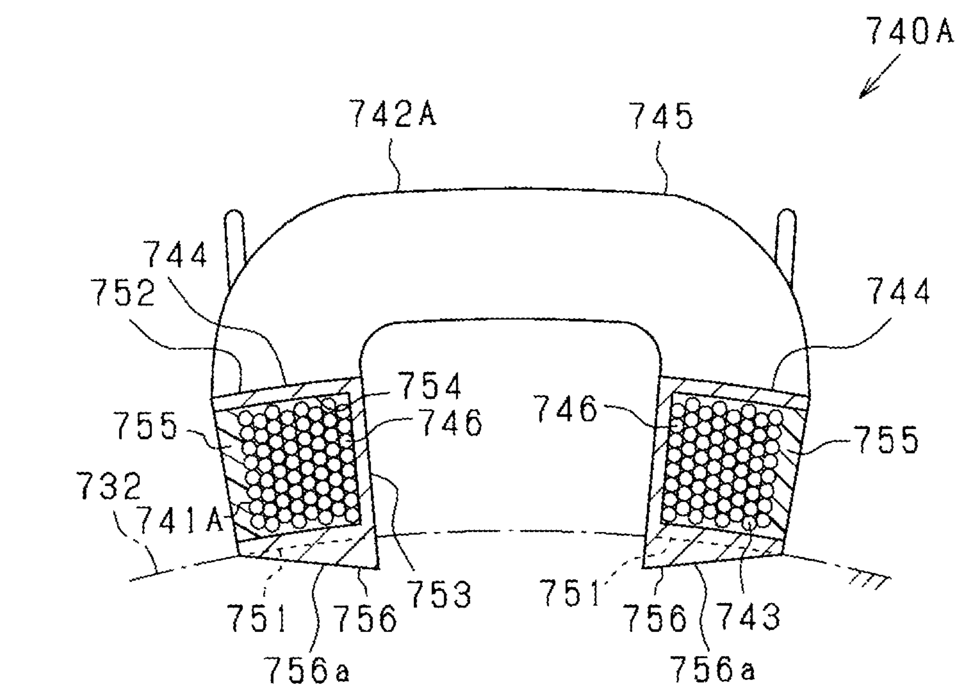


FIG.89(b)

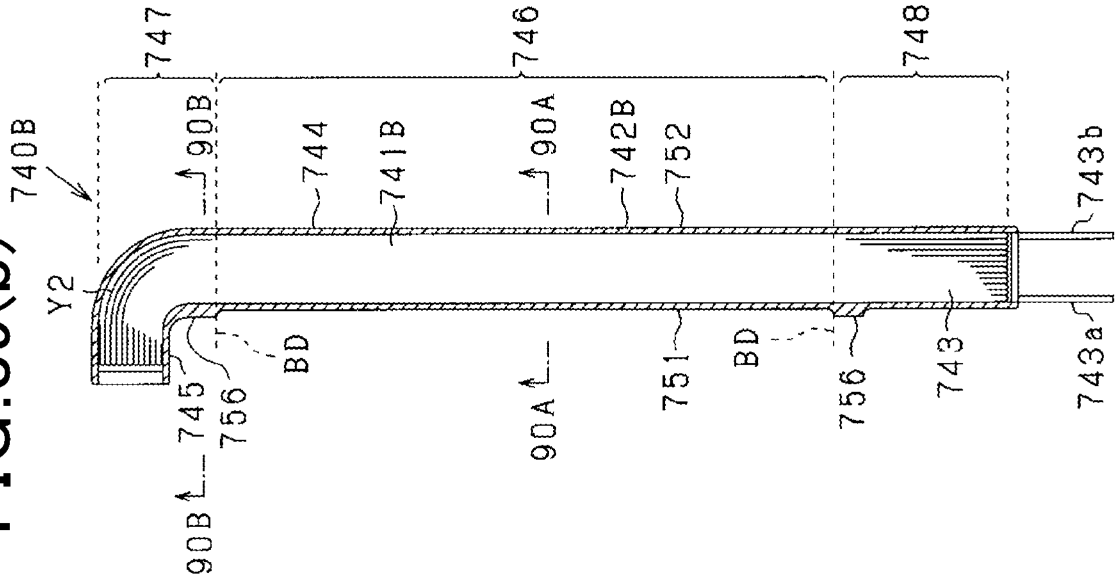


FIG.89(a)

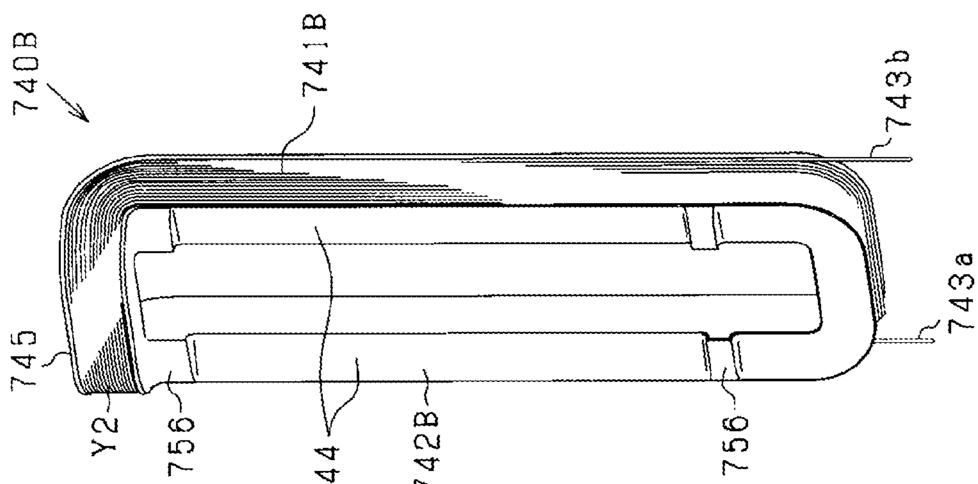


FIG.90(a)

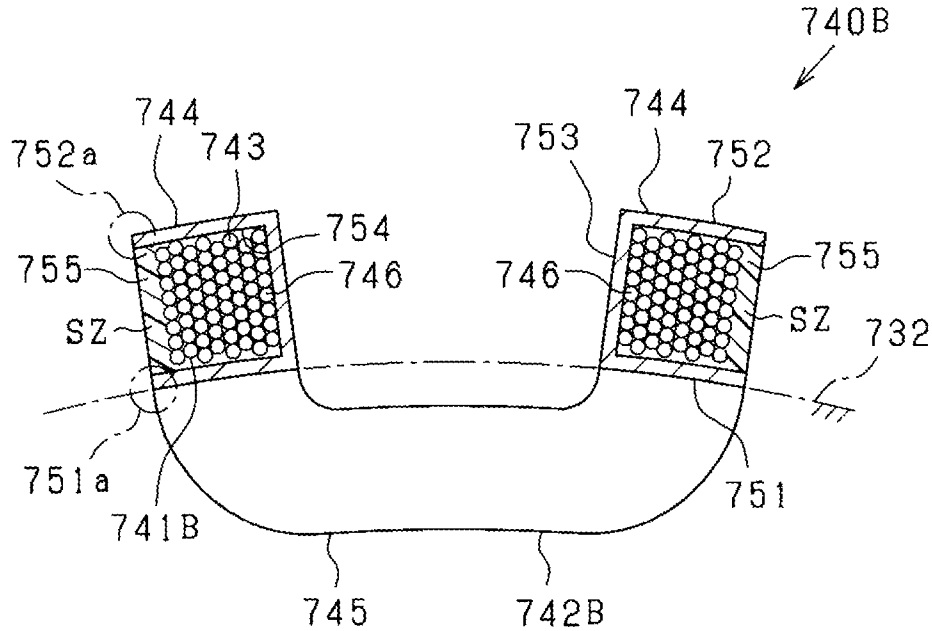


FIG.90(b)

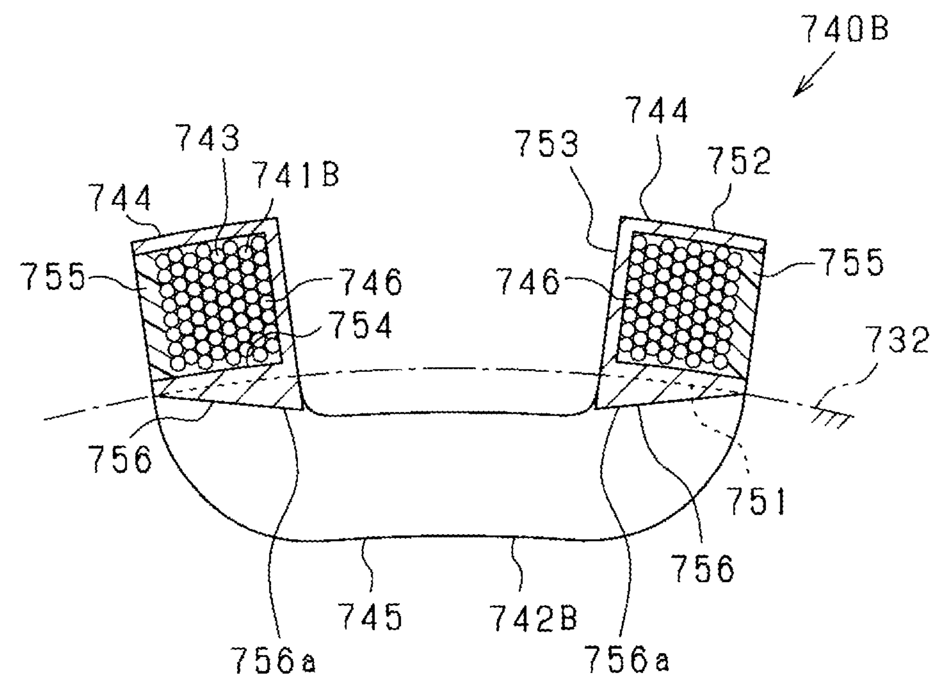


FIG.91

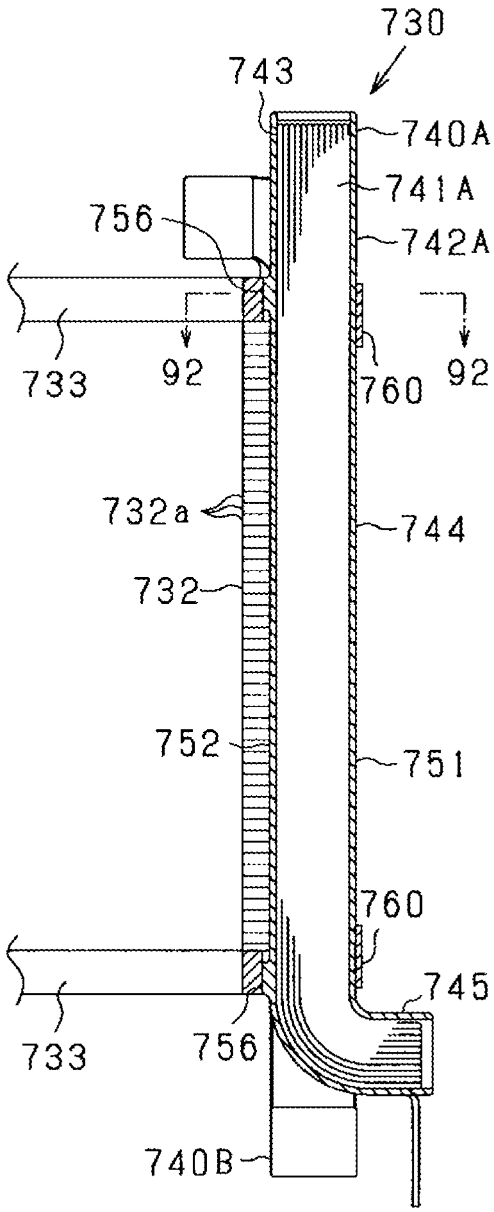

730
743
740A
741A
756
742A
733
92
760
92
732a
744
732
752
751
760
745
733
756
740B

FIG.92

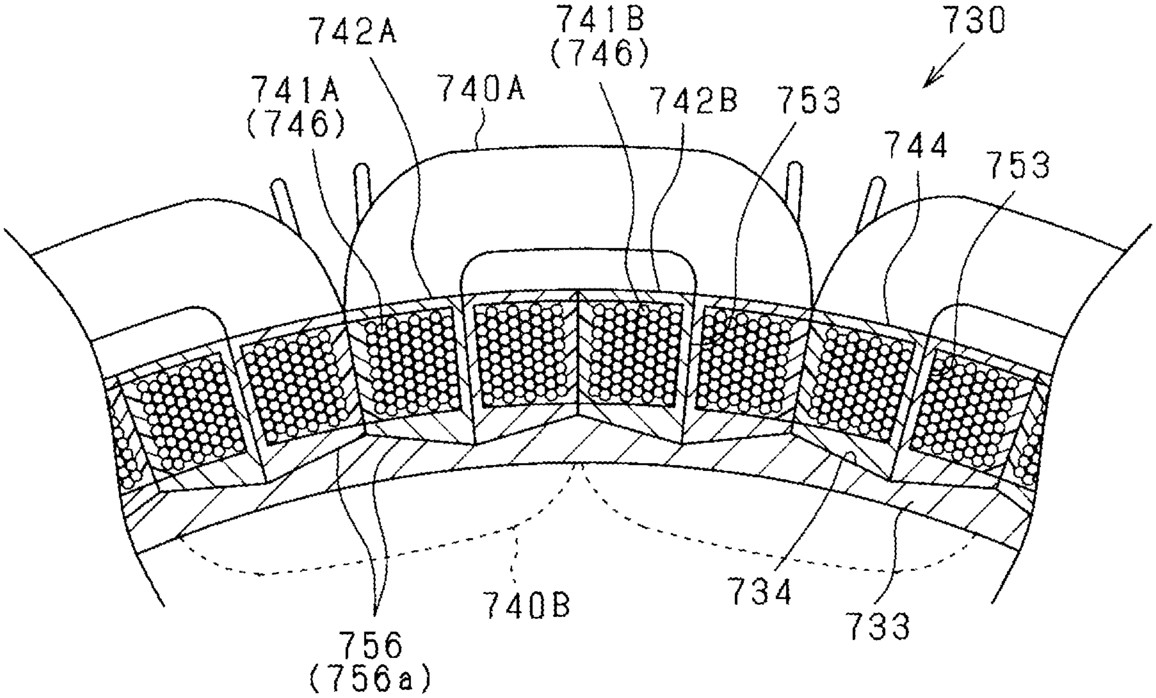

742A
741B
(746)
730
741A
(746)
740A
742B
753
744
753
740B
734
733
756
(756a)

FIG.93

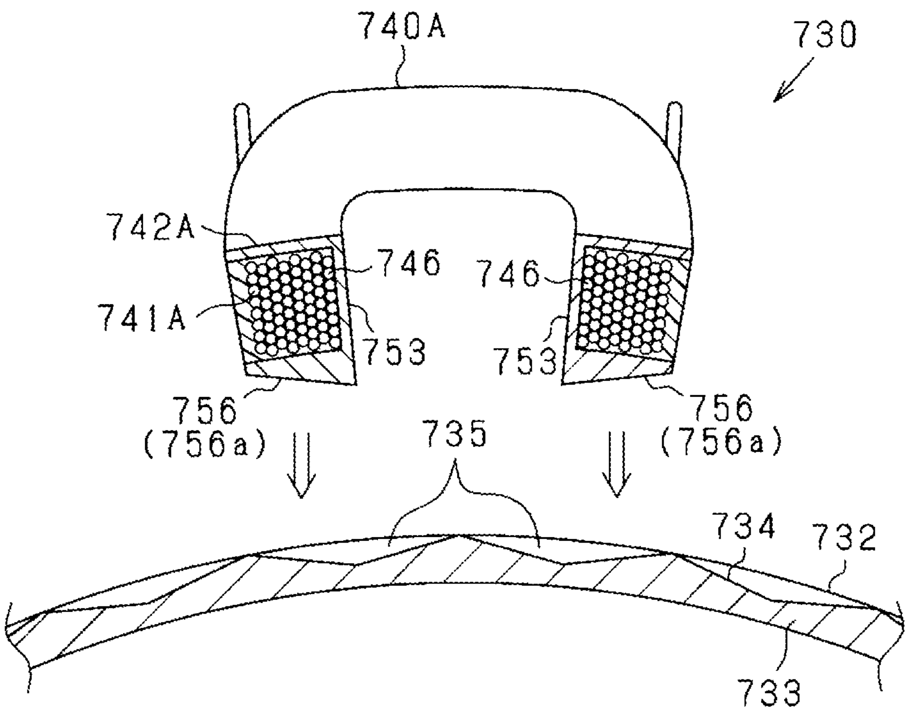

740A
730
742A
746
746
741A
753
753
756
(756a)
756
(756a)
735
734
732
733

FIG.94

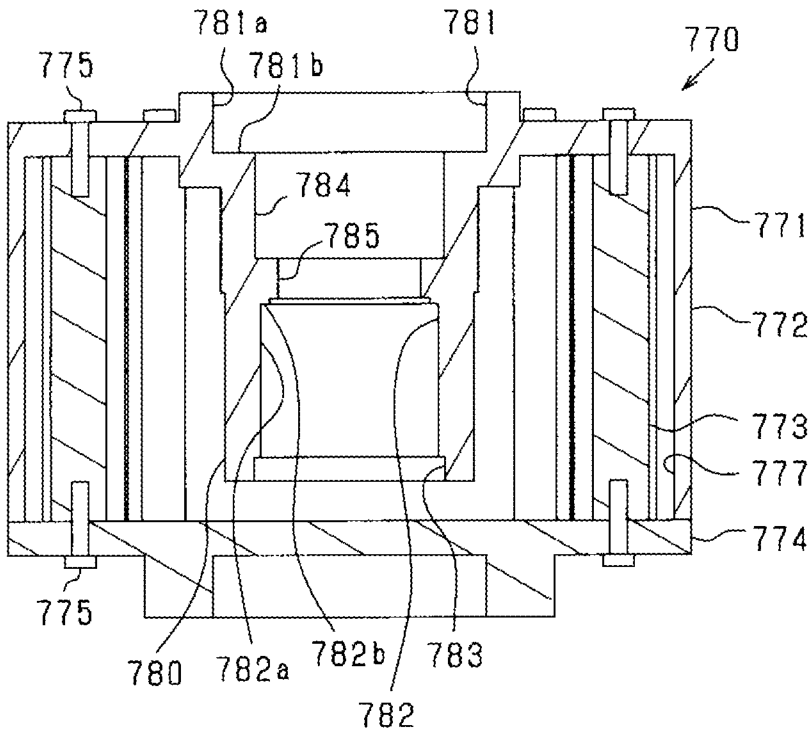

781a
781
770
775
781b
784
785
771
772
773
777
774
775
780
782a
782b
783
782

FIG.95

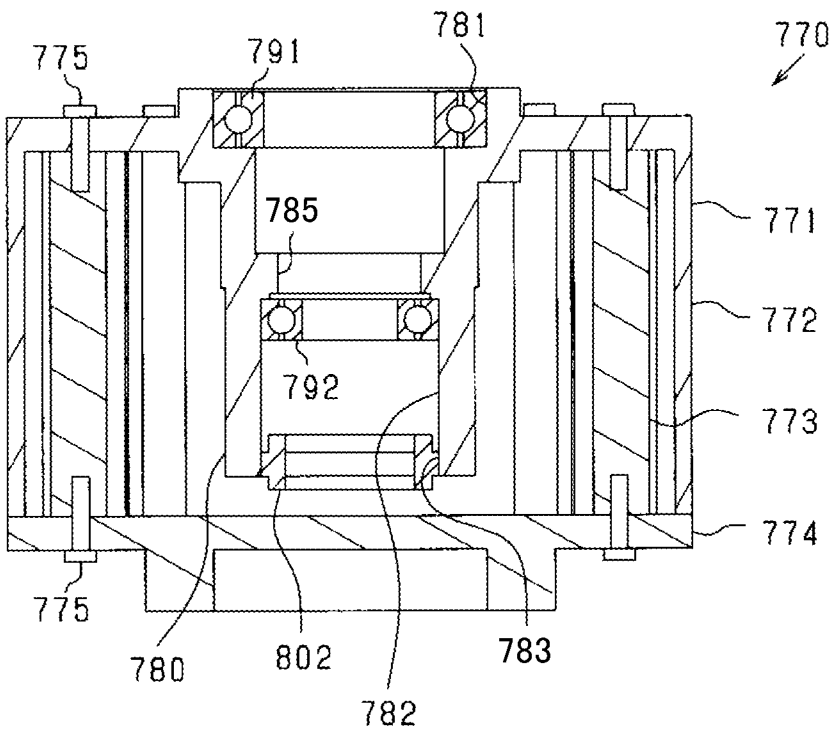

775
791
781
770
785
771
772
792
773
774
775
780
802
783
782

FIG.96

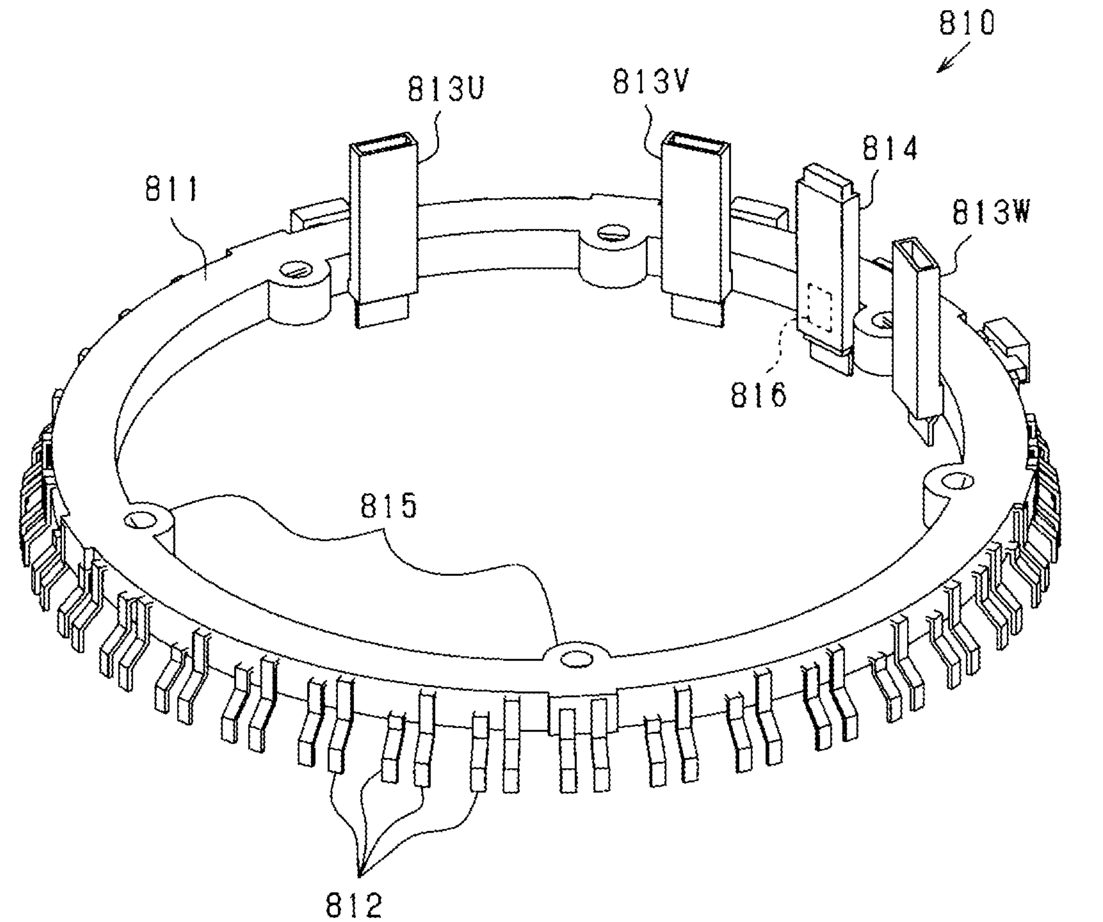


FIG.97

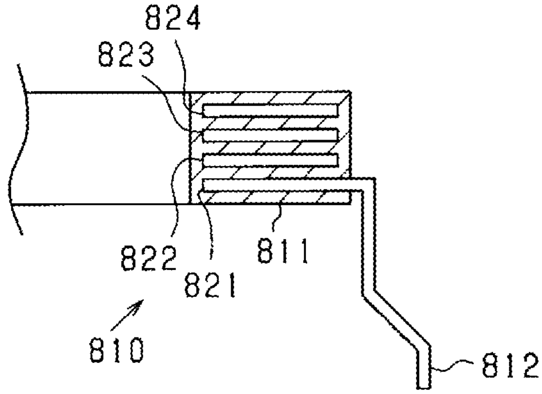

824
823
822
821
811
810
812

FIG.98

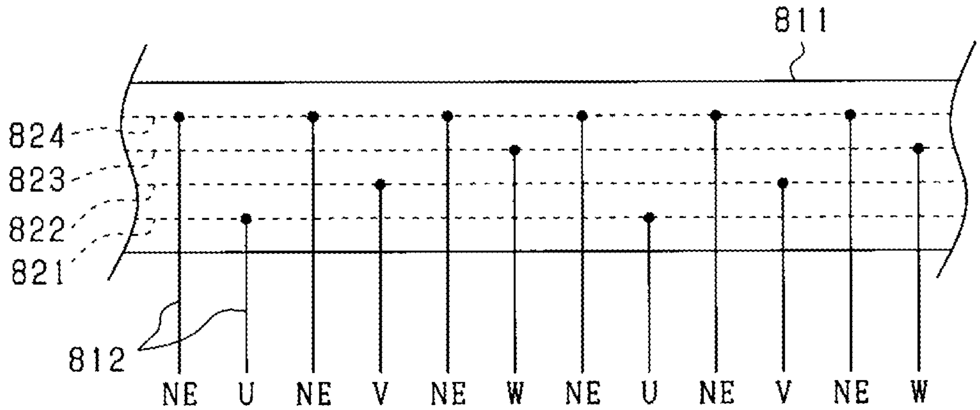

811
824
823
822
821
812
NE
U
NE
V
NE
W
NE
U
NE
V
NE
W

FIG.99

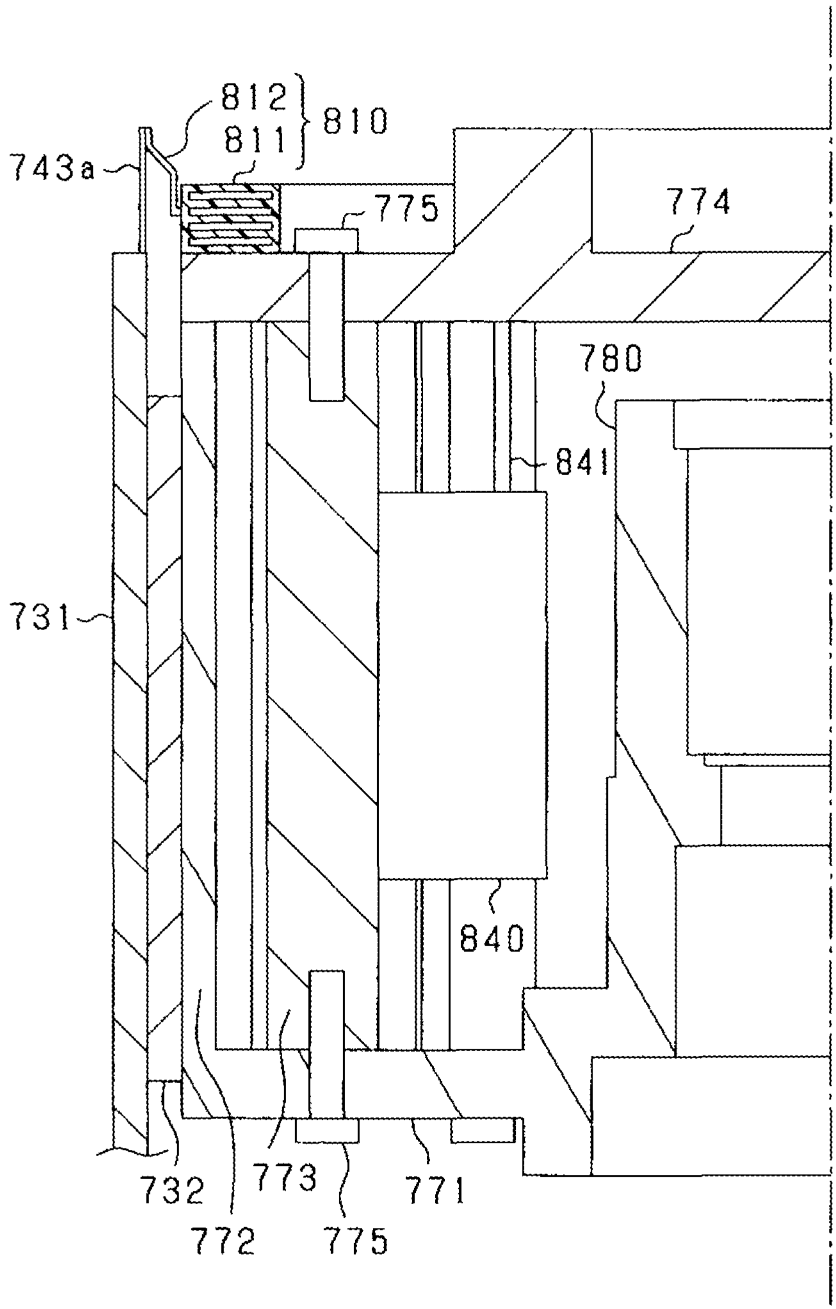


FIG.100

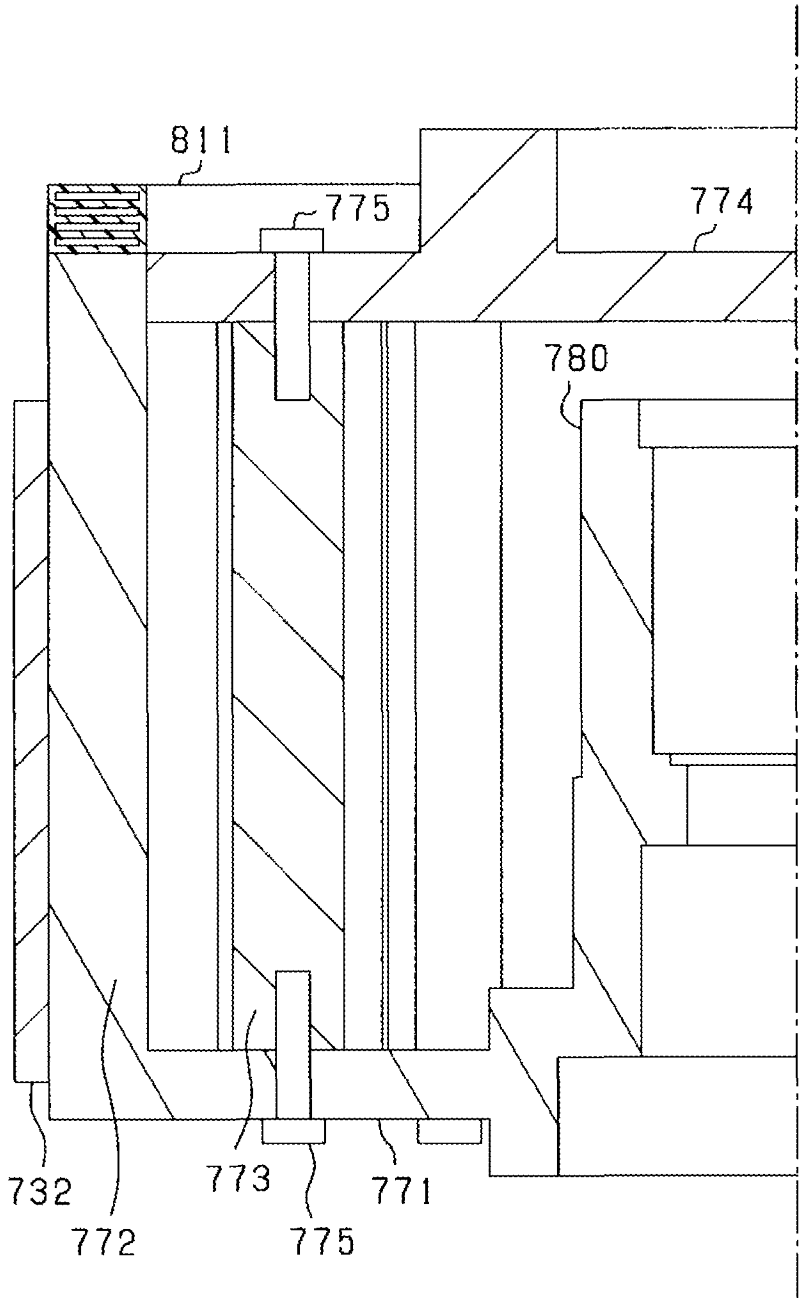


FIG.101

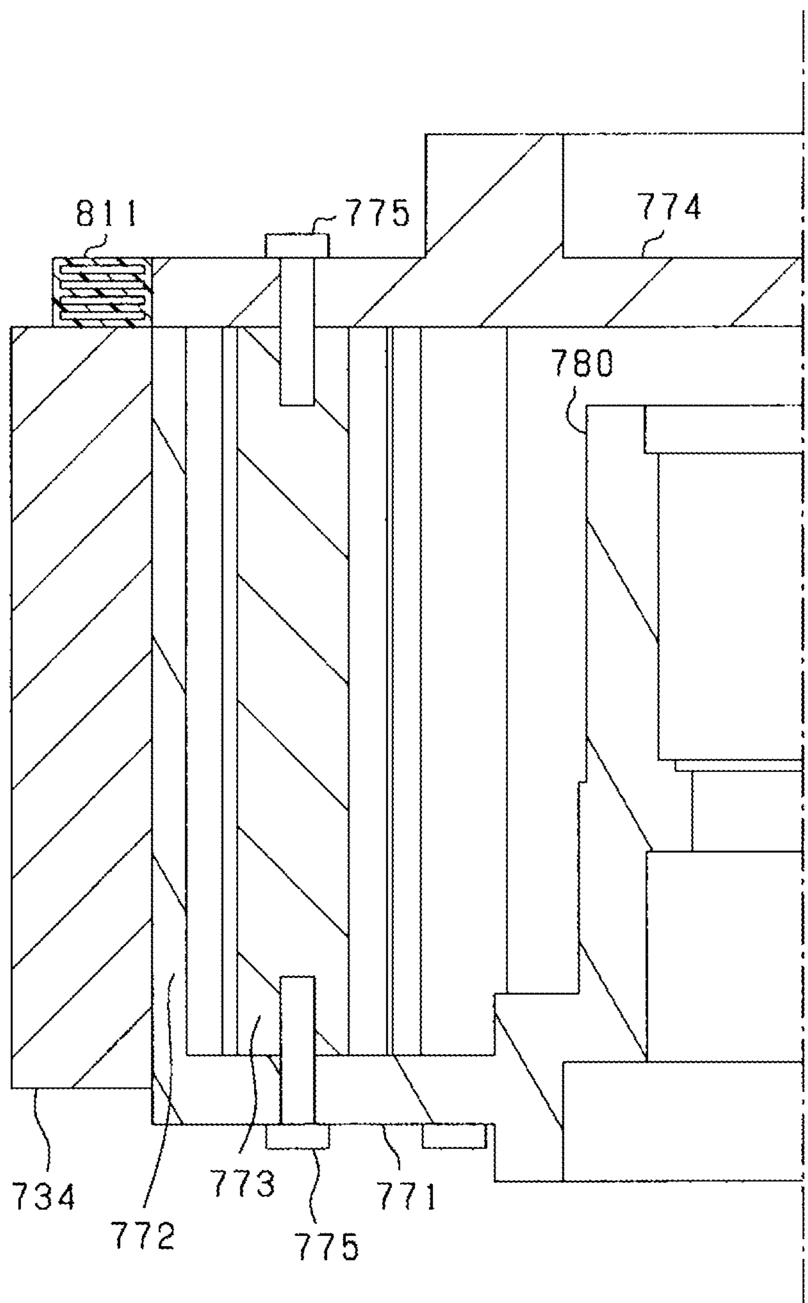


FIG.102

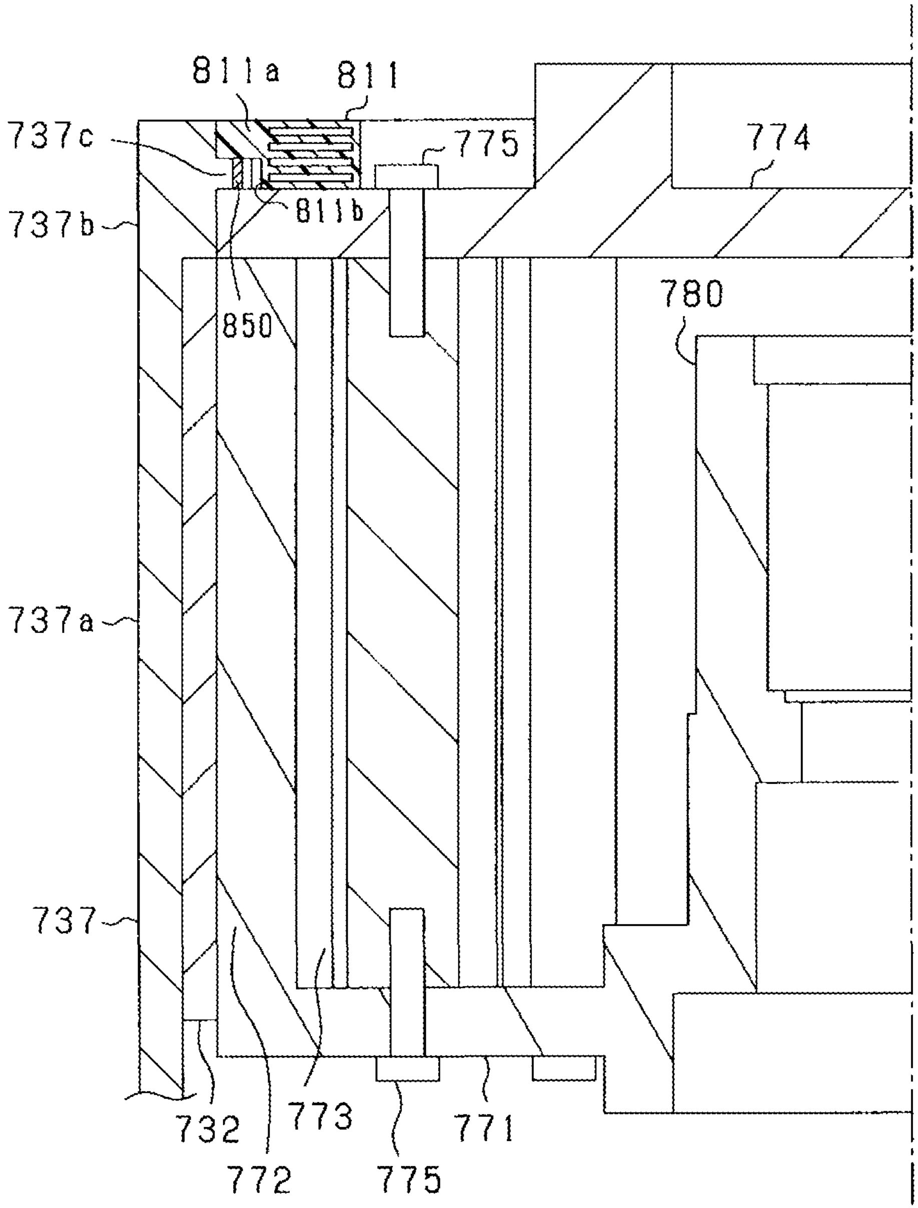
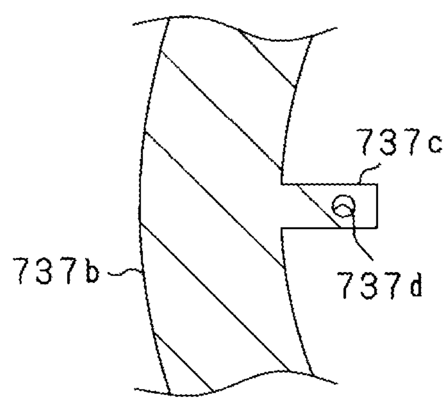


FIG.103



ARMATURE

CROSS REFERENCE TO RELATED DOCUMENT

The present application claims the benefit of priority of Japanese Patent Application No. 2019-032186 filed on Feb. 25, 2019, the disclosure of which is incorporated in its entirety herein by reference.

TECHNICAL FIELD

The present disclosure in this application relates generally to an armature for use in a rotating electrical machine.

BACKGROUND ART

An electrical motor is known which as taught in patent literature 1, includes a cylindrical stator core (i.e., an armature core), air core coils which are arranged adjacent each other in a circumferential direction of the stator core inside an inner peripheral surface of the stator core, a substrate on which a pattern is formed for electrical connections with the air core coils, and an annular-shaped terminal block secured to the substrate. The substrate is of an annular shape and arranged adjacent first ends of the air core coils which are opposed to second ends thereof in an axial direction of the motor.

Each of the air core coils has a coil lead extending in the axial direction to the terminal block. Each of the coil leads has a pin with barbs. The pins of the air core coils are inserted into the terminal block to achieve electrical connections of the air core coils with the pattern on the substrate.

PRIOR ART DOCUMENT

Patent Literature

PATENT LITERATURE 1: Japanese patent first publication No. 2002-101595

SUMMARY OF THE INVENTION

The motor disclosed in the patent literature 1 has the pins of the air core coils which are merely inserted into the terminal block, so that the air core coils are not firmly secured to the terminal block. The structure of the motor, therefore, has a great concern that the motor may not withstand large mechanical vibration.

This disclosure was made in view of the above problems. It is an object of this disclosure to provide an armature having an increased resistance to large mechanical vibrations.

A plurality of embodiments disclosed in this application employ different technical measures to achieve respective objects thereof. The objects, features, and beneficial advantages, as discussed in this application, will be apparent by referring to the following detailed description and accompanying drawings.

According to one aspect of this disclosure, there is provided an armature which radially faces a magnetic field-producing unit equipped with a magnet unit including a plurality of magnetic poles with polarities alternating in a circumferential direction of the magnet unit. The armature comprises: (a) a housing which includes a cylinder and an end plate which is of a disc shape and placed in contact with one of axially opposed ends of the cylinder; (b) an armature core which is of a cylindrical shape and disposed on a portion of the cylinder which radially faces the magnet unit; (c) a multi-phase armature winding which is disposed on a portion of the armature core which radially faces the magnet unit; and (d) a bus bar module which is equipped with bus bars electrically connecting phase windings of the armature winding together and of an annular or a C-shape extending in a circumferential direction of the armature core. The bus bar module is secured to the cylinder, the end plate, or one of axially opposed ends of the armature core.

The bus bar module includes the bus bars electrically connecting the phase windings of the armature winding together. The bus bar module is of the annular or C-shape extending in the circumferential direction of the armature core. The housing or the armature core have an annular axial end to which the annular or C-shaped bus bar module is secured. The bus bar module may alternatively be attached to an axial end of the disc-shaped end plate. This structure achieves a firm joint of the bus bar module to the cylinder, the end plate, or the armature core, thereby enhancing the resistance of the armature to large mechanical vibrations.

The bus bars that are conductive members electrically connect the phase windings together. This reduces the amount of thermal energy generated upon energization of the phase windings and enables a large amount of current to be delivered to the armature winding as compared with the structure, as taught in Patent literature 1, in which the phase windings of the armature winding are connected together using conductive patterns on the substrate.

In the preferred mode, the armature core has a curved peripheral surface which radially faces the magnet unit. The armature winding has an axial end which radially faces the bus bar module. The bus bar module has a retainer formed on an end portion thereof which radially faces the armature winding. The retainer serves to retain the armature winding.

The above preferred mode uses a slot-less structure in which the armature core has the curved peripheral surface which radially faces the magnet unit. In other words, the armature has no teeth radially protruding therefrom, thus requiring a feature to retain the armature winding. To this end, the bus bar module is equipped with the retainer to hold the armature winding. The use of the bus bar module to retain the armature winding results in a decreased number of parts of the armature.

In the second preferred mode, the armature winding has a winding protrusion formed on one of axially opposed ends thereof, the winding protrusion protruding radially toward the bus bar module. The retainer includes a recess formed on a portion of the bus bar module which radially faces the winding protrusion. The recess is hollowed away from the armature winding in a radial direction of the bus bar module. The winding protrusion is fit on the recess.

The second preferred mode uses the bus bar module to firmly keep the armature winding at desired axial position.

In the third preferred mode, the retainer includes an axial protrusion which is formed in the recess and protrudes in an axial direction of the armature. The winding protrusion has formed therein a fitting hole which extends in the axial direction. The axial protrusion is fit in the fitting hole.

The third preferred mode uses the bus bar module to firmly hold the armature winding at desired circumferential position.

In the fourth preferred mode which is a modification of one of the first to third preferred modes, the annular portion has an axial outer end which does not protrude outside an axial outer end of the armature winding in the axial direction of the armature.

The fourth preferred mode minimizes an undesirable increase in dimension of the armature in the axial direction thereof.

In the fifth preferred mode, the armature further comprises a power converter which is disposed on a portion of the cylinder which is located away from the magnet unit in a radial direction of the armature and electrically connected to the armature winding. The armature also comprises winding connecting terminals which electrically connect between the bus bars and the armature winding and device connecting terminals which electrically connect between the bus bars and the power converter.

The fifth preferred mode achieves electrical connections between the armature winding and the power converter using the single bus bar module, thereby resulting in a decrease in number of parts of the armature.

In the sixth preferred mode that is a modification of the fifth preferred mode, the bus bar module includes an annular portion which is of a circular shape and made from an electrically insulating material. The bus bars are embedded in the annular portion and located away from each other.

The sixth preferred mode ensures electrical insulation between the phase windings to eliminate a risk of short-circuit between the phase windings.

In the seventh preferred mode, the armature is arranged inside the magnetic field-producing unit in the radial direction of the armature. An outer diameter of the annular portion is smaller than an inner diameter of the armature winding.

The seventh preferred mode enables the size of the bus bar module to be reduced.

In the eighth preferred mode that is a modification of the seventh preferred mode, the winding connecting terminals protrude radially outside the annular portion and connect with the bus bars. The device connecting terminals protrude radially outside the annular portion and connect with the bus bars.

The eighth preferred mode enables the winding connecting terminals to be arranged close to the armature winding and also enables the device connecting terminals to be arranged close to the power converter, thereby resulting in a decrease in length of electrical paths connecting between the armature winding and the winding connecting terminals and between the power converter and the device connecting terminals.

BRIEF DESCRIPTION OF THE DRAWINGS

The above described object, and other objects, features, or beneficial advantages in this disclosure will be apparent from the appended drawings or the following detailed discussion.

In the drawings:

FIG. **1** is a perspective longitudinal sectional view of a rotating electrical machine;

FIG. **2** is a longitudinal sectional view of a rotating electrical machine;

FIG. **3** is a sectional view taken along the line III-III in FIG. **2**;

FIG. **4** is a partially enlarged sectional view of FIG. **3**;

FIG. **5** is an exploded view of a rotating electrical machine;

FIG. **6** is an exploded view of an inverter unit;

FIG. **7** is a torque diagrammatic view which demonstrates a relationship between ampere-turns and torque density in a stator winding;

FIG. **8** is a transverse sectional view of a rotor and a stator;

FIG. **9** is an enlarged view of part of FIG. **8**;

FIG. **10** is a transverse sectional view of a stator;

FIG. **11** is a longitudinal sectional view of a stator;

FIG. **12** is a perspective view of a stator winding;

FIG. **13** is a perspective view of a conductor;

FIG. **14** is a schematic view illustrating a structure of wire;

FIGS. **15**(*a*) and **15**(*b*) are views showing the layout of conductors at the n^{th} layer position;

FIG. **16** is a side view showing conductors at the n^{th} layer position and the $(n+1)^{th}$ layer position;

FIG. **17** is a view representing a relation between an electrical angle and a magnetic flux density in magnets of an embodiment;

FIG. **18** is a view which represents a relation between an electrical angle and a magnetic flux density in a comparative example of magnet arrangement;

FIG. **19** is an electrical circuit diagram of a control system for a rotating electrical machine;

FIG. **20** is a functional block diagram which shows a current feedback control operation of a control device;

FIG. **21** is a functional block diagram which shows a torque feedback control operation of a control device;

FIG. **22** is a transverse sectional view of a rotor and a stator in the second embodiment;

FIG. **23** is a partially enlarged view of FIG. **22**;

FIGS. **24**(*a*) and **24**(*b*) are views demonstrating flows of magnetic flux in a magnet unit;

FIG. **25** is a sectional view of a stator in the first modification;

FIG. **26** is a sectional view of a stator in the first modification;

FIG. **27** is a sectional view of a stator in the second modification;

FIG. **28** is a sectional view of a stator in the third modification;

FIG. **29** is a sectional view of a stator in the fourth modification;

FIG. **30** is a sectional view of a stator in the seventh modification;

FIG. **31** is a functional block diagram which illustrates a portion of operations of an operation signal generator in the eighth modification **8**;

FIG. **32** is a flowchart representing a sequence of steps to execute a carrier frequency altering operation;

FIGS. **33**(*a*), **33**(*b*), and **33**(*c*) are views which illustrate connections of conductors constituting a conductor group in the ninth modification;

FIG. **34** is a view which illustrates a stack of four conductors in the ninth modification;

FIG. **35** is a transverse sectional view of an inner rotor type rotor and a stator in the tenth modification;

FIG. **36** is a partially enlarged view of FIG. **35**;

FIG. **37** is a longitudinal sectional view of an inner rotor type rotating electrical machine;

FIG. **38** is a longitudinal sectional view which schematically illustrates a structure of an inner rotor type rotating electrical machine;

FIG. **39** is a view which illustrates a structure of an inner rotor type rotating electrical machine in the eleventh modification;

FIG. **40** is a view which illustrates a structure of an inner rotor type rotating electrical machine in the eleventh modification;

FIG. **41** is a view which illustrates a structure of a revolving armature type of rotating electrical machine in the twelfth modification;

FIG. **42** is a sectional view which illustrates a structure of a conductor in the fourteenth modification;

FIG. **43** is a view which illustrates a relation among reluctance torque, magnet torque, and distance DM;

FIG. **44** is a view which illustrates teeth;

FIG. **45** is a perspective view which illustrates a structure of a wheel assembly with an in-wheel motor and a peripheral structure;

FIG. **46** is a longitudinal sectional view which illustrates a wheel assembly and a peripheral structure;

FIG. **47** is an exploded view of a wheel assembly;

FIG. **48** is a side view which illustrates a rotating electrical machine, as viewed from a protruding portion of a rotating shaft;

FIG. **49** is a sectional view taken along the line **49-49** in FIG. **48**;

FIG. **50** is a sectional view taken along the line **50-50** in FIG. **49**;

FIG. **51** is an exploded sectional view of a rotating electrical machine;

FIG. **52** is a partially sectional view of a rotor;

FIG. **53** is a perspective view of a stator winding and a stator core;

FIGS. **54**(*a*) and **54**(*b*) are front views which illustrate a development of a stator winding;

FIG. **55** is a view which demonstrates skew of a conductor;

FIG. **56** is an exploded sectional view of an inverter unit;

FIG. **57** is an exploded sectional view of an inverter unit;

FIG. **58** is a view which demonstrates layout of electrical modules in an inverter housing;

FIG. **59** is a circuit diagram which illustrates an electrical structure of a power converter;

FIG. **60** is a sectional view which illustrates a cooling structure of a switch module;

FIGS. **61**(*a*) and **61**(*b*) are sectional views which illustrate a cooling structure of a switch module;

FIGS. **62**(*a*), **62**(*b*), and **62**(*c*) are partial views which illustrate a cooling structure of a switch module;

FIGS. **63**(*a*) and **63**(*b*) are partially sectional views each of which illustrates a cooling structure of a switch module;

FIG. **64** is a partial view which illustrates a cooling structure of a switch module;

FIG. **65** is a view which illustrates layout of electrical modules and a coolant path;

FIG. **66** is a sectional view taken along the line **66-66** in FIG. **49**;

FIG. **67** is a sectional view taken along the line **67-67** in FIG. **49**;

FIG. **68** is a perspective view which illustrates a bus bar module;

FIG. **69** is a circuit diagram which illustrates a relation in electrical connection between electrical modules and a bus bar module;

FIG. **70** is a view which illustrates electrical connections between electrical modules and a bus bar module;

FIG. **71** is a view which illustrates electrical connections between electrical modules and a bus bar module;

FIGS. **72**(*a*), **72**(*b*), **72**(*c*), and **72**(*d*) are structural views of the first modified form of an in-wheel motor;

FIGS. **73**(*a*), **73**(*b*), and **73**(*c*) are structural views of the second modified form of an in-wheel motor;

FIGS. **74**(*a*) and **74**(*b*) are structural views of the third modified form of an in-wheel motor;

FIG. **75** is a structural view of the fourth modified form of an in-wheel motor;

FIG. **76** is a perspective view illustrating the overall structure of a rotating electrical machine according to the fifteenth modification;

FIG. **77** is a longitudinal sectional view of the rotating electrical machine;

FIG. **78** is an exploded sectional view of the rotating electrical machine;

FIG. **79** is a longitudinal sectional view of a rotor;

FIG. **80** is an enlarged view of a cross-sectional structure of a part of a magnet unit;

FIG. **81** is a view illustrating how easy axes of magnetization are oriented in a magnet;

FIG. **82** is a perspective view illustrating the structure of a stator;

FIG. **83** is an exploded view of a stator winding and a stator core;

FIG. **84** is a perspective view illustrating only the structure of a U-phase winding in the stator winding;

FIG. **85** is a longitudinal sectional view of the stator winding;

FIG. **86** is a view which illustrates electrical connections in each phase winding;

FIG. **87**(*a*) is a perspective view of a first type of coil module;

FIG. **87**(*b*) is a perspective view illustrating only a coil segment of the first type of coil module;

FIG. **87**(*c*) is a perspective view illustrating only a winding holder of the first type of coil module;

FIG. **87**(*d*) is a side view of the coil module;

FIG. **88**(*a*) is a transverse sectional view of the first type of coil module, which is taken along the line **88**A-**88**A in FIG. **87**(*d*);

FIG. **88**(*b*) is a transverse sectional view of the first type of coil module, which is taken along the line **88**B-**88**B in FIG. **87**(*d*);

FIG. **89**(*a*) is a perspective view of a second type of coil module;

FIG. **89**(*b*) is a side view of the second type of coil module;

FIG. **90**(*a*) is a transverse sectional view of the second type of coil module, which is taken along the line **90**A-**90**A in FIG. **89**(*b*);

FIG. **90**(*b*) is a transverse sectional view of the second type of coil module, which is taken along the line **90**B-**90**B in FIG. **89**(*b*);

FIG. **91** is a sectional view indicative of a longitudinal section of the stator;

FIG. **92** is a sectional view indicative of a transverse section of the stator, which is taken along the line **92-92** in FIG. **91**;

FIG. **93** is a sectional view indicative of the assembly of the stator core and one of first and second end rings and the first type of coil module that are separated from each other;

FIG. **94** is a longitudinal sectional view of an inner unit;

FIG. **95** is a longitudinal sectional view of the inner unit to which bearings are assembled;

FIG. **96** is a perspective view of a busbar module;

FIG. **97** is a longitudinal sectional view of a part of the bus bar module;

FIG. **98** is a view illustrating electrical connections between the respective-phase busbars and the respective-phase windings;

FIG. **99** is a longitudinal sectional view which illustrates an inner unit and a bus bar unit.

FIG. **100** is a longitudinal sectional view which illustrates an inner unit and a bus bar unit in the sixteenth modification.

FIG. **101** is a longitudinal sectional view which illustrates an inner unit and a bus bar unit in the seventeenth modification.

FIG. **102** is a longitudinal sectional view which illustrates an inner unit and a bus bar unit in the eighteenth modification.

FIG. **103** is a partial sectional view which illustrates a winding protrusion and a fitting hole.

EMBODIMENTS FOR CARRYING OUT THE INVENTION

The embodiments will be described below with reference to the drawings. Parts of the embodiments functionally or structurally corresponding to each other or associated with each other will be denoted by the same reference numbers or by reference numbers which are different in the hundreds place from each other. The corresponding or associated parts may refer to the explanation in the other embodiments.

The rotating electrical machine in the embodiments is configured to be used, for example, as a power source for vehicles. The rotating electrical machine may, however, be used widely for industrial, automotive, domestic, office automation, or game applications. In the following embodiments, the same or equivalent parts will be denoted by the same reference numbers in the drawings, and explanation thereof in detail will be omitted.

First Embodiment

The rotating electrical machine **10** in this embodiment is a synchronous polyphase ac motor having an outer rotor structure (i.e., an outer rotating structure). The outline of the rotating electrical machine **10** is illustrated in FIGS. **1** to **5**. FIG. **1** is a perspective longitudinal sectional view of the rotating electrical machine **10**. FIG. **2** is a longitudinal sectional view along the rotating shaft **11** of the rotating electrical machine **10**. FIG. **3** is a transverse sectional view (i.e., sectional view taken along the line III-III in FIG. **2**) of the rotating electrical machine **10** perpendicular to the rotating shaft **11**. FIG. **4** is a partially enlarged sectional view of FIG. **3**. FIG. **5** is an exploded view of the rotating electrical machine **10**. FIG. **3** omits hatching showing a section except the rotating shaft **11** for the sake of simplicity of the drawings. In the following discussion, a lengthwise direction of the rotating shaft **11** will also be referred to as an axial direction. A radial direction from the center of the rotating shaft **11** will be simply referred to as a radial direction. A direction along a circumference of the rotating shaft **11** about the center thereof will be simply referred to as a circumferential direction.

The rotating electrical machine **10** includes the bearing unit **20**, the housing **30**, the rotor **40**, the stator **50**, and the inverter unit **60**. These members are arranged coaxially with each other together with the rotating shaft **11** and assembled in a given sequence to complete the rotating electrical machine **10**. The rotating electrical machine **10** in this embodiment is equipped with the rotor **40** working as a magnetic field-producing unit or a field system and the stator **50** working as an armature and engineered as a revolving-field type rotating electrical machine.

The bearing unit **20** includes two bearings **21** and **22** arranged away from each other in the axial direction and the retainer **23** which retains the bearings **21** and **22**. The bearings **21** and **22** are implemented by, for example, radial ball bearings each of which includes the outer race **25**, the inner race **26**, and a plurality of balls **27** disposed between the outer race **25** and the inner race **26**. The retainer **23** is of a cylindrical shape. The bearings **21** and **22** are disposed radially inside the retainer **23**. The rotating shaft **11** and the rotor **40** are retained radially inside the bearings **21** and **22** to be rotatable. The bearings **21** and **22** are used as a set of bearings to rotatably retain the rotating shaft **11**.

Each of the bearings **21** and **22** holds the balls **27** using a retainer, not shown, to keep a pitch between the balls **27** constant. Each of the bearings **21** and **22** is equipped with seals on axially upper and lower ends of the retainer and also has non-conductive grease (e.g., non-conductive urease grease) installed inside the seals. The position of the inner race **26** is mechanically secured by a spacer to exert constant inner precompression on the inner race **26** in the form of a vertical convexity.

The housing **30** includes the cylindrical peripheral wall **31**. The peripheral wall **31** has a first end and a second end opposed to each other in an axial direction thereof. The peripheral wall **31** has the end surface **32** on the first end and the opening **33** in the second end. The opening **33** occupies the entire area of the second end. The end surface **32** has formed in the center thereof the circular hole **34**. The bearing unit **20** is inserted into the hole **34** and fixed using a fastener, such as a screw or a rivet. The hollow cylindrical rotor **40** and the hollow cylindrical stator **50** are disposed in an inner space defined by the peripheral wall **31** and the end surface **32** within the housing **30**. In this embodiment, the rotating electrical machine **10** is of an outer rotor type, so that the stator **50** is arranged radially inside the cylindrical rotor **40** within the housing **30**. The rotor **40** is retained in a cantilever form by a portion of the rotating shaft **11** located close to the end surface **32** in the axial direction.

The rotor **40** includes the hollow cylindrical magnetic holder **41** and the annular magnet unit **42** disposed radially inside the magnet holder **41**. The magnet holder **41** is of substantially a cup-shape and works as a magnet holding member. The magnet holder **41** includes the cylinder **43**, the attaching portion **44** which is of a cylindrical shape and smaller in diameter than the cylinder **43**, and the intermediate portion **45** connecting the cylinder **43** and the attaching portion **44** together. The cylinder **43** has the magnet unit **42** secured to an inner peripheral surface thereof.

The magnet holder **41** is made of cold rolled steel (SPCC), forging steel, or carbon fiber reinforced plastic (CFRP) which have a required degree of mechanical strength.

The rotating shaft **11** passes through the through-hole **44***a* of the attaching portion **44**. The attaching portion **44** is secured to a portion of the rotating shaft **11** disposed inside the through-hole **44***a*. In other words, the magnet holder **41** is secured to the rotating shaft **11** through the attaching portion **44**. The attaching portion **44** may preferably be joined to the rotating shaft **11** using concavities and convexities, such as a spline joint or a key joint, welding, or crimping, so that the rotor **40** rotates along with the rotating shaft **11**.

The bearings **21** and **22** of the bearing unit **20** are secured radially outside the attaching portion **44**. The bearing unit **20** is, as described above, fixed on the end surface **32** of the housing **30**, so that the rotating shaft **11** and the rotor **40** are retained by the housing **30** to be rotatable. The rotor **40** is, thus, rotatable within the housing **30**.

The rotor **40** is equipped with the attaching portion **44** arranged only at one of ends thereof opposed to each other in the axial direction of the rotor **40**. This cantilevers the rotor **40** on the rotating shaft **11**. The attaching portion **44** of the rotor **40** is rotatably retained at two points of supports using the bearings **21** and **22** of the bearing unit **20** which are located away from each other in the axial direction. In other words, the rotor **40** is held to be rotatable using the two bearings **21** and **22** which are separate at a distance away from each other in the axial direction on one of the axially opposed ends of the magnet holder **41**. This ensures the stability in rotation of the rotor **40** even though the rotor **40** is cantilevered on the rotating shaft **11**. The rotor **40** is retained by the bearings **21** and **22** at locations which are away from the center intermediate between the axially opposed ends of the rotor **40** in the axial direction thereof.

The bearing **22** of the bearing unit **20** which is located closer to the center of the rotor **40** (a lower one of the bearings **21** and **22** in the drawings) is different in dimension of a gap between each of the outer race **25** and the inner race and the balls **27** from the bearing **21** which is located farther away from the center of the rotor **40** (i.e., an upper one of the bearings **21** and **22**). For instance, the bearing **22** closer to the center of the rotor **40** is greater in the dimension of the gap from the bearing **21**. This minimizes adverse effects on the bearing unit **20** which arise from deflection of the rotor **40** or mechanical vibration of the rotor **40** Due to imbalance resulting from parts tolerance at a location close to the center of the rotor **40**. Specifically, the bearing **22** closer to the center of the rotor **40** is engineered to have dimensions of the gaps or plays increased using precompression, thereby absorbing the vibration generating in the cantilever structure. The precompression may be provided by either fixed position preload or constant pressure preload. In the case of the fixed position preload, the outer race **25** of each of the bearings **21** and **22** is joined to the retainer **23** using press-fitting or welding. The inner race **26** of each of the bearings **21** and **22** is joined to the rotating shaft **11** by press-fitting or welding. The precompression may be created by placing the outer race **25** of the bearing **21** away from the inner race **26** of the bearing **21** in the axial direction or alternatively placing the outer race **25** of the bearing **22** away from the inner race **26** of the bearing **22** in the axial direction.

In the case of the constant pressure preload, a preload spring, such as a wave washer **24**, is arranged between the bearing **22** and the bearing **21** to create the preload directed from a region between the bearing **22** and the bearing **21** toward the outer race **25** of the bearing **22** in the axial direction. In this case, the inner race **26** of each of the bearing **21** and the bearing **22** is joined to the rotating shaft **11** using press fitting or bonding. The outer race **25** of the bearing **21** or the bearing **22** is arranged away from the outer race **25** through a given clearance. This structure exerts pressure, as produced by the preload spring, on the outer race **25** of the bearing **22** to urge the outer race **25** away from the bearing **21**. The pressure is then transmitted through the rotating shaft **11** to urge the inner race **26** of the bearing **21** toward the bearing **22**, thereby bringing the outer race **25** of each of the bearings **21** and **22** away from the inner race **26** thereof in the axial direction to exert the preload on the bearings **21** and **22** in the same way as the fixed position preload.

The constant pressure preload does not necessarily need to exert the spring pressure, as illustrated in FIG. **2**, on the outer race **25** of the bearing **22**, but may alternatively be created by exerting the spring pressure on the outer race **25** of the bearing **21**. The exertion of the preload on the bearings **21** and **22** may alternatively be achieved by placing the inner race **26** of one of the bearings **21** and **22** away from the rotating shaft **11** through a given clearance therebetween and joining the outer race **25** of each of the bearings **21** and **22** to the retainer **23** using press-fitting or bonding.

Further, in the case where the pressure is created to bring the inner race **26** of the bearing **21** away from the bearing **22**, such pressure is preferably additionally exerted on the inner race **26** of the bearing **22** away from the bearing **21**. Conversely, in the case where the pressure is created to bring the inner race **26** of the bearing **21** close to the bearing **22**, such pressure is preferably additionally exerted on the inner race **26** of the bearing **22** to bring it close to the bearing **21**.

In a case where the rotating electrical machine **10** is used as a power source for a vehicle, there is a risk that mechanical vibration having a component oriented in a direction in which the preload is created may be exerted on the preload generating structure or that a direction in which the force of gravity acts on an object to which the preload is applied may be changed. In order to alleviate such a problem, the fixed position preload is preferably used in the case where the rotating electrical machine **10** is mounted in the vehicle.

The intermediate portion **45** includes the annular inner shoulder **49***a* and the annular outer shoulder **49***b*. The outer shoulder **49***b* is arranged outside the inner shoulder **49***a* in the radial direction of the intermediate portion **45**. The inner shoulder **49***a* and the outer shoulder **49***b* are separate from each other in the axial direction of the intermediate portion **45**. This layout results in a partial overlap between the cylinder **43** and the attaching portion **44** in the radial direction of the intermediate portion **45**. In other words, the cylinder **43** protrudes outside a base end portion (i.e., a lower portion, as viewed in the drawing) of the attaching portion **44** in the axial direction. The structure in this embodiment enables the rotor **40** to be retained by the rotating shaft **11** at a location closer to the center of gravity of the rotor **40** than a case where the intermediate portion **45** is shaped to be flat without any shoulder, thereby ensuring the stability in operation of the rotor **40**.

In the above described structure of the intermediate portion **45**, the rotor **40** has the annular bearing housing recess **46** which is formed in an inner portion of the intermediate portion **45** and radially surrounds the attaching portion **44**. The bearing housing recess **46** has a portion of the bearing unit **20** disposed therein. The rotor **40** also has the coil housing recess **47** which is formed in an outer portion of the intermediate portion **45** and radially surrounds the bearing housing recess **46**. The coil housing recess **47** has disposed therein the coil end **54** of the stator winding **51** of the stator **50**, which will be described later in detail. The housing recesses **46** and **47** are arranged adjacent each other in the axial direction. In other words, a portion of the bearing unit **20** is laid to overlap the coil end **54** of the stator winding **51** in the axial direction. This enables the rotating electrical machine **10** to have a length decreased in the axial direction.

The intermediate portion **45** extends or overhangs outward from the rotating shaft **11** in the radial direction. The intermediate portion **45** is equipped with a contact avoider which extends in the axial direction and avoids a physical contact with the coil end **54** of the stator winding **51** of the stator **50**. The intermediate portion **45** will also be referred to as an overhang.

The coil end **54** may be bent radially inwardly or outwardly to have a decreased axial dimension, thereby enabling the axial length of the stator **50** to be decreased. A direction in which the coil end **54** is bent is preferably determined depending upon installation thereof in rotor **40**. In the case where the stator **50** is installed radially inside the rotor **40**, a portion of the coil end **54** which is inserted into the rotor **40** is preferably bent radially inwardly. A coil end opposite the coil end **54** may be bent either inwardly or outwardly, but is preferably bent to an outward side where there is an enough space in terms of the production thereof.

The magnet unit **42** working as a magnetic portion is made up of a plurality of permanent magnets which are disposed radially inside the cylinder **43** to have different magnetic poles arranged alternately in a circumferential direction thereof. The magnet unit **42**, thus, has a plurality of magnetic poles arranged in the circumferential direction. The magnet unit **42** will also be described later in detail.

The stator **50** is arranged radially inside the rotor **40**. The stator **50** includes the stator winding **51** wound in a substantially cylindrical (annular) form and the stator core **52** used as a base member arranged radially inside the stator winding **51**. The stator winding **51** is arranged to face the annular magnet unit **42** through a given air gap therebetween. The stator winding **51** includes a plurality of phase windings each of which is made of a plurality of conductors which are arranged at a given pitch away from each other in the circumferential direction and joined together. In this embodiment, two three-phase windings: one including a U-phase winding, a V-phase winding, and a W-phase winding and the other including an X-phase winding, a Y-phase winding, and a Z-phase winding are used to complete the stator winding **51** as a six-phase winding.

The stator core **52** is formed by an annular stack of magnetic steel plates made of soft magnetic material and mounted radially inside the stator winding **51**. The magnetic steel plates are, for example, silicone nitride steel plates made by adding a small percent (e.g., 3%) of silicone nitride to iron. The stator winding **51** corresponds to an armature winding. The stator core **52** corresponds to an armature core.

The stator winding **51** overlaps the stator core **52** in the radial direction and includes the coil side portion **53** disposed radially outside the stator core **52** and the coil ends **54** and **55** overhanging at ends of the stator core **52** in the axial direction. The coil side portion **53** faces the stator core **52** and the magnet unit **42** of the rotor **40** in the radial direction. The stator **50** is arranged inside the rotor **40**. The coil end **54** that is one (i.e., an upper one, as viewed in the drawings) of the axially opposed coil ends **54** and **55** and arranged close to the bearing unit **20** is disposed in the coil housing recess **47** defined by the magnet holder **41** of the rotor **40**. The stator **50** will also be described later in detail.

The inverter unit **60** includes the unit base **61** secured to the housing **30** using fasteners, such as bolts, and a plurality of electrical components **62** mounted on the unit base **61**. The unit base **61** is made from, for example, carbon fiber reinforced plastic (CFRP). The unit base **61** includes the end plate **63** secured to an edge of the opening **33** of the housing **30** and the casing **64** which is formed integrally with the end plate **63** and extends in the axial direction. The end plate **63** has the circular opening **65** formed in the center thereof. The casing **64** extends upward from a peripheral edge of the opening **65**.

The stator **50** is arranged on an outer peripheral surface of the casing **64**. Specifically, an outer diameter of the casing **64** is selected to be identical with or slightly smaller than an inner diameter of the stator core **52**. The stator core **52** is attached to the outer side of the casing **64** to complete a unit made up of the stator **50** and the unit base **61**. The unit base **61** is secured to the housing **30**, so that the stator **50** is unified with the housing **50** in a condition where the stator core **52** is installed on the casing **64**.

The stator core **52** may be bonded, shrink-fit, or press-fit on the unit base **61**, thereby eliminating positional shift of the stator core **52** relative to the unit base **61** both in the circumferential direction and in the axial direction.

The casing **64** has a radially inner storage space in which the electrical components **62** are disposed. The electrical components **62** are arranged to surround the rotating shaft **11** within the storage space. The casing **64** functions as a storage space forming portion. The electrical components **62** include the semiconductor modules **66**, the control board **67**, and the capacitor module **68** which constitute an inverter circuit.

The unit base **61** serves as a stator holder (i.e., an armature holder) which is arranged radially inside the stator **50** and retains the stator **50**. The housing **30** and the unit base **61** define a motor housing for the rotating electrical machine **10**. In the motor housing, the retainer **23** is secured to a first end of the housing **30** which is opposed to a second end of the housing **30** through the rotor **40** in the axial direction. The second end of the housing **30** and the unit base **61** are joined together. For instance, in an electric-powered vehicle, such as an electric automobile, the motor housing is attached to a side of the vehicle to install the rotating electrical machine **10** in the vehicle.

The inverter unit **60** will be also be described using FIG. **6** that is an exploded view in addition to FIGS. **1** to **5**.

The casing **64** of the unit base **61** includes the cylinder **71** and the end surface **72** that is one of ends of the cylinder **71** which are opposed to each other in the axial direction of the cylinder **71** (i.e., the end of the casing **64** close to the bearing unit **20**). The end of the cylinder **71** opposed to the end surface **72** in the axial direction is shaped to fully open to the opening **65** of the end plate **63**. The end surface **72** has formed in the center thereof the circular hole **73** through which the rotating shaft **11** is insertable. The hole **73** has fitted therein the sealing member **171** which hermetically seals an air gap between the hole **73** and the outer periphery of the rotating shaft **11**. The sealing member **171** is preferably implemented by, for example, a resinous slidable seal.

The cylinder **71** of the casing **64** serves as a partition which isolates the rotor **40** and the stator **50** arranged radially outside the cylinder **71** from the electrical components **62** arranged radially inside the cylinder **71**. The rotor **40**, the stator **50**, and the electrical components **62** are arranged radially inside and outside the cylinder **71**.

The electrical components **62** are electrical devices making up the inverter circuit equipped with a motor function and a generator function. The motor function is to deliver electrical current to the phase windings of the stator winding **51** in a given sequence to turn the rotor **40**. The generator function is to receive a three-phase ac current flowing through the stator winding **51** in response to the rotation of the rotating shaft **11** and generate and output electrical power. The electrical components **62** may be engineered to perform either one of the motor function and the generator function. In a case where the rotating electrical machine **10** is used as a power source for a vehicle, the generator function provides a regenerative function to output a regenerated electrical power.

Specifically, the electrical components **62**, as demonstrated in FIG. **4**, include the hollow cylindrical capacitor module **68** arranged around the rotating shaft **11** and the semiconductor modules **66** mounted on the capacitor module **68**. The capacitor module **68** has a plurality of smoothing capacitors **68**_a_ connected in parallel to each other. Specifically, each of the capacitors **68**_a_ is implemented by a stacked-film capacitor which is made of a plurality of film capacitors stacked in a trapezoidal shape in cross section. The capacitor module **68** is made of the twelve capacitors **68**_a_ arranged in an annular shape.

The capacitors **68**_a_ may be produced by preparing a long film which has a given width and is made of a stack of films and cutting the long film into isosceles trapezoids each of which has a height identical with the width of the long film and whose short bases and long bases are alternately arranged. Electrodes are attached to the thus produced capacitor devices to complete the capacitors **68**_a_.

The semiconductor module **66** includes, for example, a semiconductor switch, such as a MOSFET or an IGBT and is of substantially a planar shape. In this embodiment, the rotating electrical machine **10** is, as described above, equipped with two sets of three-phase windings and has the inverter circuits, one for each set of the three-phase windings. The electrical components **62**, therefore, include a total of twelve semiconductor modules **66** which are arranged in an annular form to make up the semiconductor module group **66**A.

The semiconductor modules **66** are interposed between the cylinder **71** of the casing **64** and the capacitor module **68**. The semiconductor module group **66**A has an outer peripheral surface placed in contact with an inner peripheral surface of the cylinder **71**. The semiconductor module group **66**A also has an inner peripheral surface placed in contact with an outer peripheral surface of the capacitor module **68**. This causes heat, as generated in the semiconductor modules **66**, to be transferred to the end plate **63** through the casing **64**, so that it is dissipated from the end plate **63**.

The semiconductor module group **66**A preferably has the spacers **69** disposed radially outside the outer peripheral surface thereof, i.e., between the semiconductor modules **66** and the cylinder **71**. A combination of the capacitor modules **68** is so arranged as to have a regular dodecagonal section extending perpendicular to the axial direction thereof, while the inner periphery of the cylinder **71** has a circular transverse section. The spacers **69** are, therefore, each shaped to have a flat inner peripheral surface and a curved outer peripheral surface. The spacers **69** may alternatively be formed integrally with each other in an annular shape and disposed radially outside the semiconductor module group **66**A. The spacers **69** are highly thermally conductive and made of, for example, metal, such as aluminum or heat dissipating gel sheet. The inner periphery of the cylinder **71** may alternatively be shaped to have a dodecagonal transverse section like the capacitor modules **68**. In this case, the spacers **69** are each preferably shaped to have a flat inner peripheral surface and a flat outer peripheral surface.

In this embodiment, the cylinder **71** of the casing **64** has formed therein the coolant path **74** through which coolant flows. The heat generated in the semiconductor modules **66** is also released to the coolant flowing in the coolant path **74**. In other words, the casing **64** is equipped with a cooling mechanism. The coolant path **74** is, as clearly illustrated in FIGS. **3** and **4**, formed in an annular shape and surrounds the electrical components **62** (i.e., the semiconductor modules **66** and the capacitor module **68**). The semiconductor modules **66** are arranged along the inner peripheral surface of the cylinder **71**. The coolant path **74** is laid to overlap the semiconductor modules **66** in the radial direction.

The stator **50** is arranged outside the cylinder **71**. The electrical components **62** are arranged inside the cylinder **71**. This layout causes the heat to be transferred from the stator **50** to the outer side of the cylinder **71** and also transferred from the electrical components **62** (e.g., the semiconductor modules **66**) to the inner side of the cylinder **71**. It is possible to simultaneously cool the stator **50** and the semiconductor modules **66**, thereby facilitating dissipation of thermal energy generated by heat-generating members of the rotating electrical machine **10**.

Further, at least one of the semiconductor modules **66** which constitute part or all of the inverter circuits serving to energize the stator winding **51** to drive the rotating electrical machine is arranged in a region surrounded by the stator core **52** disposed radially outside the cylinder **71** of the casing **64**. Preferably, one of the semiconductor modules **66** may be arranged fully inside the region surrounded by the stator core **52**. More preferably, all the semiconductor modules **66** may be arranged fully in the region surrounded by the stator core **52**.

At least a portion of the semiconductor modules **66** is arranged in a region surrounded by the coolant path **74**. Preferably, all the semiconductor modules **66** may be arranged in a region surrounded by the yoke **141**.

The electrical components **62** include the insulating sheet **75** disposed on one of axially opposed end surfaces of the capacitor module **68** and the wiring module **76** disposed on the other end surface of the capacitor module **68**. The capacitor module **68** has two axially-opposed end surfaces: a first end surface and a second end surface. The first end surface of the capacitor module **68** closer to the bearing unit **20** faces the end surface **72** of the casing **64** and is laid on the end surface **72** through the insulating sheet **75**. The second end surface of the capacitor module **68** closer to the opening **65** has the wiring module **76** mounted thereon.

The wiring module **76** includes the resin-made circular plate-shaped body **76**_a_ and a plurality of bus bars **76**_b_ and **76**_c_ embedded in the body **76**_a_. The bus bars **76**_b_ and **76**_c_ electrically connect the semiconductor modules **66** and the capacitor module **68** together. Specifically, the semiconductor modules **66** are equipped with the connecting pins **66**_a_ extending from axial ends thereof. The connecting pins **66**_a_ connect with the bus bars **76**_b_ radially outside the body **76**_a_. The bus bars **76**_c_ extend away from the capacitor module **68** radially outside the body **76**_a_ and have top ends connecting with the wiring members **79** (see FIG. **2**).

The capacitor module **68**, as described above, has the insulating sheet **75** mounted on the first end surface thereof. The capacitor module **68** also has the wiring module **76** mounted on the second end surface thereof. The capacitor module **68**, therefore, has two heat dissipating paths which extend from the first and second end surfaces of the capacitor module **68** to the end surface **72** and the cylinder **71**. Specifically, a heat dissipating path is defined which extends from the first end surface to the end surface **72**. Another heat dissipating path is defined which extends from the second end surface to the cylinder **71**. This enables the heat to be released from the end surfaces of the capacitor module **68** other than the outer peripheral surface on which the semiconductor modules **66** are arranged. In other words, it is possible to dissipate the heat not only in the radial direction, but also in the axial direction.

The capacitor module **68** is of a hollow cylindrical shape and has the rotating shaft **11** arranged therewithin at a given interval away from the inner periphery of the capacitor module **68**, so that heat generated by the capacitor module **68** will be dissipated from the hollow cylindrical space. The rotation of the rotating shaft **11** usually produces a flow of air, thereby enhancing cooling effects.

The wiring module **76** has the disc-shaped control board **67** attached thereto. The control board **67** includes a printed circuit board (PCB) on which given wiring patterns are formed and also has ICs and the control device **77** mounted thereon. The control device **77** serves as a controller and is made of a microcomputer. The control board **67** is secured to the wiring module **76** using fasteners, such as screws. The control board **67** has formed in the center thereof the hole **67***a* through which the rotating shaft **11** passes.

The wiring module **76** has a first surface and a second surface opposed to each other in the axial direction, that is, a thickness-wise direction of the wiring module **76**. The first surface faces the capacitor module **68**. The wiring module **76** has the control board **67** mounted on the second surface thereof. The bus bars **76***c* of the wiring module **76** extend from one of surfaces of the control board **67** to the other. The control board **67** may have cut-outs for avoiding physical interference with the bus bars **76***c*. For instance, the control board **67** may have the cut-outs formed in portions of the circular outer edge thereof.

The electrical components **62** are, as described already, arranged inside the space surrounded by the casing **64**. The housing **30**, the rotor **40**, and the stator **50** are disposed outside the space in the form of layers. This structure serves to shield against electromagnetic noise generated in the inverter circuits. Specifically, the inverter circuit works to control switching operations of the semiconductor modules **66** in a PWM control mode using a given carrier frequency. The switching operations usually generate electromagnetic noise against which the housing **30**, the rotor **40**, and the stator **50** which are arranged outside the electrical components **62** shield.

Further, at least a portion of the semiconductor modules **66** is arranged inside the region surrounded by the stator core **52** located radially outside the cylinder **71** of the casing **64**, thereby minimizing adverse effects of magnetic flux generated by the semiconductor modules **66** on the stator winding **51** as compared with a case where the semiconductor modules **66** and the stator winding **51** are arranged without the stator core **52** interposed therebetween. The magnetic flux created by the stator winding **51** also hardly affects the semiconductor modules **66**. It is more effective that the whole of the semiconductor modules **66** are located in the region surrounded by the stator core **52** disposed radially outside the cylinder **71** of the casing **64**. When at least a portion of the semiconductor modules **66** is surrounded by the coolant path **74**, it offers a beneficial advantage that the heat produced by the stator winding **51** or the magnet unit **42** is prevented from reaching the semiconductor modules **66**.

The cylinder **71** has the through-holes **78** which are formed near the end plate **63** and through which the wiring members **79** (see FIG. **2**) pass to electrically connect the stator **50** disposed outside the cylinder **71** and the electrical components **62** arranged inside the cylinder **71**. The wiring members **79**, as illustrated in FIG. **2**, connect with ends of the stator winding **51** and the bus bars **76***c* of the wiring module **76** using crimping or welding techniques. The wiring members **79** are implemented by, for example, bus bars whose joining surfaces are preferably flattened. A single through-hole **78** or a plurality of through-holes **78** are preferably provided. This embodiment has two through-holes **78**. The use of the two through-holes **78** facilitates the ease with which terminals extending from the two sets of the three-phase windings are connected by the wiring members **79**, and is suitable for achieving multi-phase wire connections.

The rotor **40** and the stator **50** are, as described already in FIG. **4**, arranged within the housing **30** in this order in a radially inward direction. The inverter unit **60** is arranged radially inside the stator **50**. If a radius of the inner periphery of the housing **30** is defined as d, the rotor **40** and the stator **50** are located radially outside a distance of d×0.705 away from the center of rotation of the rotor **40**. If a region located radially inside the inner periphery of the stator **50** (i.e., the inner circumferential surface of the stator core **52**) is defined as a first region **X1**, and a region radially extending from the inner periphery of the stator **50** to the housing **30** is defined as a second region **X2**, a cross-sectional area of the first region **X1** is set greater than that of the second region **X2**. In a region where the magnet unit **42** of the rotor **40** overlaps the stator winding **51**, the volume of the first region **X1** is larger than that of the second region **X2**.

The rotor **40** and the stator **50** are fabricated as a magnetic circuit component assembly. In the housing **30**, the first region **X1** which is located radially inside the inner peripheral surface of the magnetic circuit component assembly is larger in volume than the region **X2** which lies between the inner peripheral surface of the magnetic circuit component assembly and the housing **30** in the radial direction.

Next, the structures of the rotor **40** and the stator **50** will be described below in more detail.

Typical rotating electrical machines are known which are equipped with a stator with an annular stator core which is made of a stack of steel plates and has a stator winding wound in a plurality of slots arranged in a circumferential direction of the stator core. Specifically, the stator core has teeth extending in a radial direction thereof at a given interval away from a yoke. Each slot is formed between the two radially adjacent teeth. In each slot, a plurality of conductors are arranged in the radial direction in the form of layers to form the stator winding.

However, the above described stator structure has a risk that when the stator winding is energized, an increase in magnetomotive force in the stator winding may result in magnetic saturation in the teeth of the stator core, thereby restricting torque density in the rotating electrical machine. In other words, rotational flux, as created by the energization of the stator winding of the stator core, is thought of as concentrating on the teeth, which has a risk of causing magnetic saturation.

Generally, IPM (Interior Permanent Magnet) rotors are known which have a structure in which permanent magnets are arranged on a d-axis of a d-q axis coordinate system, and a rotor core is placed on a q-axis of the d-q axis coordinate system. Excitation of a stator winding near the d-axis will cause an excited magnetic flux to flow from a stator to a rotor according to Fleming's rules. This causes magnetic saturation to occur widely in the rotor core on the q-axis.

FIG. **7** is a torque diagrammatic view which demonstrates a relationship between an ampere-turn (AT) representing a magnetomotive force created by the stator winding and a torque density (Nm/L). A broken line indicates characteristics of a typical IPM rotor-rotating electrical machine. FIG. **7** shows that in the typical rotating electrical machine, an increase in magnetomotive force in the stator will cause magnetic saturation to occur at two places: the tooth between the slots and the q-axis rotor (i.e., the rotor core on the q-axis), thereby restricting an increase in torque. In this way, a design value of the ampere-turn is restricted at **A1** in the typical rotating electrical machine.

In order to alleviate the above problem in this embodiment, the rotating electrical machine **10** is designed to have an additional structure, as will be described below, in order to eliminate the restriction arising from the magnetic saturation. Specifically, as a first measure, the stator **50** is designed to have a slot-less structure for eliminating the magnetic saturation occurring in the teeth of the stator core of the stator and also to use an SPM (Surface Permanent Magnet) rotor for eliminating the magnetic saturation occurring in a q-axis core of the IPM rotor. The first measure serves to eliminate the above described two places where the magnetic saturation occurs, but however, may result in a decrease in torque in a low-current region (see an alternate long and short dash line in FIG. **7**). In order to alleviate this problem, as a second measure, a polar anisotropic structure is employed to increase the length of a magnetic path of magnets in the magnet unit **42** of the rotor **40** to enhance a magnetic force in order to increase a magnetic flux in the SPM rotor to minimize the torque decrease.

Additionally, as a third measure, a flattened conductor structure is employed to decrease a thickness of conductors of the coil side portion **53** of the stator winding **51** in the radial direction of the stator **50** for compensating for the torque decrease. The above magnetic force-enhanced polar anisotropic structure is thought of as resulting in a flow of large eddy current in the stator winding **51** facing the magnet unit **42**. The third measure is, however, to employ the flattened conductor structure in which the conductors have a decreased thickness in the radial direction, thereby minimizing the generation of the eddy current in the stator winding **51** in the radial direction. In this way, the above first to third structures are, as indicated by a solid line in FIG. **7**, expected to greatly improve the torque characteristics using high-magnetic force magnets and also alleviate a risk of generation of a large eddy current resulting from the use of the high-magnetic force magnets.

Additionally, as a fourth measure, a magnet unit is employed which has a polar anisotropic structure to create a magnetic density distribution approximating a sine wave. This increases a sine wave matching percentage using pulse control, as will be described later, to enhance the torque and also results in a moderate change in magnetic flux, thereby minimizing an eddy-current loss (i.e., a copper loss caused by eddy current) as compared with radial magnets.

The sine wave matching percentage will be described below. The sine wave matching percentage may be derived by comparing a waveform, a cycle, and a peak value of a surface magnetic flux density distribution measured by actually moving a magnetic flux probe on a surface of a magnet with those of a sine wave. The since wave matching percentage is given by a percentage of an amplitude of a primary waveform that is a waveform of a fundamental wave in a rotating electrical machine to that of the actually measured waveform, that is, an amplitude of the fundamental wave to which a harmonic component is added. An increase in the sine wave matching percentage will cause the waveform in the surface magnetic flux density distribution to approach the waveform of the sine wave. When an electrical current of a primary sine wave is delivered by an inverter to a rotating electrical machine equipped with magnets having an improved sine wave matching percentage, it will cause a large degree of torque to be produced, combined with the fact that the waveform in the surface magnetic flux density distribution of the magnet is close to the waveform of a sine wave. The surface magnetic flux density distribution may alternatively be derived using electromagnetic analysis according to Maxwell's equations.

As a fifth measure, the stator winding **51** is designed to have a conductor strand structure made of a bundle of wires. In the conductor strand structure of the stator winding **51**, the wires are connected parallel to each other, thus enabling a high current or large amount of current to flow in the stator winding **51** and also minimizing an eddy current occurring in the conductors widened in the circumferential direction of the stator **50** more effectively than the third measure in which the conductors are flattened in the radial direction because each of the wires has a decreased transverse sectional area. The use of the bundle of the wires will cancel an eddy current arising from magnetic flux occurring according to Ampere's circuital law in response to the magnetomotive force produced by the conductors.

The use of the fourth and fifth measures minimizes the eddy-current loss resulting from the high magnetic force produced by the high-magnetic force magnets provided by the second measure and also enhance the torque.

The slot-less structure of the stator **50**, the flattened conductor structure of the stator winding **51**, and the polar anisotropic structure of the magnet unit **42** will be described below. The slot-less structure of the stator **50** and the flattened conductor structure of the stator winding **51** will first be discussed. FIG. **8** is a transverse sectional view illustrating the rotor **40** and the stator **50**. FIG. **9** is a partially enlarged view illustrating the rotor **40** and the stator **50** in FIG. **8**. FIG. **10** is a transverse sectional view of the stator **50** taken along the line X-X in FIG. **11**. FIG. **11** is a longitudinal sectional view of the stator **50**. FIG. **12** is a perspective view of the stator winding **51**. FIGS. **8** and **9** indicate directions of magnetization of magnets of the magnet unit **42** using arrows.

The stator core **52** is, as clearly illustrated in FIGS. **8** to **11**, of a cylindrical shape and made of a plurality of magnetic steel plates stacked in the axial direction of the stator core **52** to have a given thickness in a radial direction of the stator core **52**. The stator winding **51** is mounted on the outer periphery of the stator core **52** which faces the rotor **40**. The outer peripheral surface of the stator core **52** facing the rotor **40** serves as a conductor mounting portion (i.e., a conductor area). The outer peripheral surface of the stator core **52** is shaped as a curved surface without any irregularities. A plurality of conductor groups **81** are arranged on the outer peripheral surface of the stator core **52** at given intervals away from each other in the circumferential direction of the stator core **52**. The stator core **52** functions as a back yoke that is a portion of a magnetic circuit working to rotate the rotor **40**. The stator **50** is designed to have a structure in which a tooth (i.e., a core) made of a soft magnetic material is not disposed between a respective two of the conductor groups **81** arranged adjacent each other in the circumferential direction (i.e., the slot-less structure). In this embodiment, a resin material of the sealing member **57** is disposed in the space or gap **56** between a respective adjacent two of the conductor groups **81**. In other words, the stator **50** has an inter-conductor member which is disposed between the conductor groups **81** arranged adjacent each other in the circumferential direction of the stator **50** and made of a non-magnetic material. The inter-conductor members serve as the sealing members **57**. Before the sealing members **57** are placed to seal the gaps **56**, the conductor groups **81** are arranged in the circumferential direction radially outside the stator core **52** at a given interval away from each other through the gaps **56** that are conductor-to-conductor regions. This makes up the slot-less structure of the stator **50**. In other words, each of the conductor groups **81** is, as described later in detail, made of two conductors **82**. An interval between a respective two of the conductor groups **81** arranged adjacent each other in the circumferential direction of the stator **50** is occupied only by a non-magnetic material. The non-magnetic material, as referred to herein, includes a non-magnetic gas, such as air, or a non-magnetic liquid. In the following discussion, the sealing members **57** will also be referred to as inter-conductor members.

The structure, as referred to herein, in which the teeth are respectively disposed between the conductor groups **81** arrayed in the circumferential direction means that each of the teeth has a given thickness in the radial direction and a given width in the circumferential direction of the stator **50**, so that a portion of the magnetic circuit, that is, a magnet magnetic path lies between the adjacent conductor groups **81**. In contrast, the structure in which no tooth lies between the adjacent conductor groups **81** means that there is no magnetic circuit between the adjacent conductor groups **81**.

The stator winding (i.e., the armature winding) **51**, as illustrated in FIG. **10**, has a given thickness T**2** (which will also be referred to below as a first dimension) and a width W**2** (which will also be referred to below as a second dimension). The thickness T**2** is given by a minimum distance between an outer side surface and an inner side surface of the stator winding **51** which are opposed to each other in the radial direction of the stator **50**. The width W**2** is given by a dimension of a portion of the stator winding **51** which functions as one of multiple phases (i.e., the U-phase, the V-phase, the W-phase, the X-phase, the Y-phase, and the Z-phase in this embodiment) of the stator winding **51** in the circumferential direction. Specifically, in a case where the two conductor groups **81** arranged adjacent each other in the circumferential direction in FIG. **10** serve as one of the three phases, for example, the U-phase winding, a distance between circumferentially outermost ends of the two circumferentially adjacent conductor groups **81** is the width W**2**. The thickness T**2** is smaller than the width W**2**.

The thickness T**2** is preferably set smaller than the sum of widths of the two conductor groups **81** within the width W**2**. If the stator winding **51** (more specifically, the conductor **82**) is designed to have a true circular transverse section, an oval transverse section, or a polygonal transverse section, the cross section of the conductor **82** taken in the radial direction of the stator **50** may be shaped to have a maximum dimension W**12** in the radial direction of the stator **50** and a maximum dimension W**11** in the circumferential direction of the stator **50**.

The stator winding **51** is, as can be seen in FIGS. **10** and **11**, sealed by the sealing members **57** which are formed by a synthetic resin mold. Specifically, the stator winding **51** and the stator core **52** are put in a mould together when the sealing members **57** are moulded by the resin. The resin may be considered as a non-magnetic material or an equivalent thereof whose Bs (saturation magnetic flux density) is zero.

As a transverse section is viewed in FIG. **10**, the sealing members **57** are provided by placing synthetic resin in the gaps **56** between the conductor groups **81**. The sealing members **57** serve as insulators arranged between the conductor groups **81**. In other words, each of the sealing members **57** functions as an insulator in one of the gaps **56**. The sealing members **57** occupy a region which is located radially outside the stator core **52**, and includes all the conductor groups **81**, in other words, which is defined to have a dimension larger than that of each of the conductor groups **81** in the radial direction.

As a longitudinal section is viewed in FIG. **11**, the sealing members **57** lie to occupy a region including the turns **84** of the stator winding **51**. Radially inside the stator winding **51**, the sealing members **57** lie in a region including at least a portion of the axially opposed ends of the stator core **52**. In this case, the stator winding **51** is fully sealed by the resin except for the ends of each phase winding, i.e., terminals joined to the inverter circuits.

The structure in which the sealing members **57** are disposed in the region including the ends of the stator core **52** enables the sealing members **57** to compress the stack of the steel plates of the stator core **52** inwardly in the axial direction. In other words, the sealing members **57** work to firmly retain the stack of the steel plates of the stator core **52**. In this embodiment, the inner peripheral surface of the stator core **52** is not sealed using resin, but however, the whole of the stator core **52** including the inner peripheral surface may be sealed using resin.

In a case where the rotating electrical machine **10** is used as a power source for a vehicle, the sealing members **57** are preferably made of a high heat-resistance fluororesin, epoxy resin, PPS resin, PEEK resin, LCP resin, silicone resin, PAI resin, or PI resin. In terms of a linear coefficient expansion to minimize breakage of the sealing members **57** due to an expansion difference, the sealing members **57** are preferably made of the same material as that of an outer film of the conductors of the stator winding **51**. The silicone resin whose linear coefficient expansion is twice or more those of other resins is preferably excluded from the material of the sealing members **57**. In a case of electrical products, such as electric vehicles equipped with no combustion engine, PPO resin, phenol resin, or FRP resin which resists 180° C. may be used, except in fields where an ambient temperature of the rotating electrical machine is expected to be not higher than 100° C.

The degree of torque outputted by the rotating electrical machine **10** is usually proportional to the degree of magnetic flux. In a case where a stator core is equipped with teeth, a maximum amount of magnetic flux in the stator core is restricted depending upon the saturation magnetic flux density in the teeth, while in a case where the stator core is not equipped with teeth, the maximum amount of magnetic flux in the stator core is not restricted. Such a structure is, therefore, useful for increasing an amount of electrical current delivered to the stator winding **51** to increase the degree of torque produced by the rotating electrical machine **10**.

This embodiment employs the slot-less structure in which the stator **50** is not equipped with teeth, thereby resulting in a decrease in inductance of the stator **50**. Specifically, a stator of a typical rotating electrical machine in which conductors are disposed in slots isolated by teeth from each other has an inductance of approximately 1 mH, while the stator **50** in this embodiment has a decreased inductance of 5 to 60 μH. The rotating electrical machine **10** in this embodiment is of an outer rotor type, but has a decreased inductance of the stator **50** to decrease a mechanical time constant Tm. In other words, the rotating electrical machine **10** is capable of outputting a high degree of torque and designed to have a decreased value of the mechanical time constant Tm. If inertia is defined as J, inductance is defined as L, torque constant is defined as Kt, and back electromotive force constant is defined as Ke, the mechanical time constant Tm is calculated according to the equation of $Tm=(J\times L)/(Kt\times Ke)$. This shows that a decrease in inductance L will result in a decrease in mechanical time constant Tm.

Each of the conductor groups **81** arranged radially outside the stator core **52** is made of a plurality of conductors **82** whose transverse section is of a flattened rectangular shape and which are disposed on one another in the radial direction of the stator core **52**. Each of the conductors **82** is oriented to have a transverse section meeting a relation of radial dimension<circumferential dimension. This causes each of the conductor groups **81** to be thin in the radial direction. A conductive region of the conductor group **81** also extends inside a region occupied by teeth of a typical stator. This creates a flattened conductive region structure in which a sectional area of each of the conductors **82** is increased in the circumferential direction, thereby alleviating a risk that the amount of thermal energy may be increased by a decrease in sectional area of a conductor arising from flattening of the conductor. A structure in which a plurality of conductors are arranged in the circumferential direction and connected in parallel to each other is usually subjected to a decrease in sectional area of the conductors by a thickness of a coated layer of the conductors, but however, has beneficial advantages obtained for the same reasons as described above. In the following discussion, each of the conductor groups **81** or each of the conductors **82** will also be referred to as a conductive member.

The stator **50** in this embodiment is, as described already, designed to have no slots, thereby enabling the stator winding **51** to be designed to have a conductive region of an entire circumferential portion of the stator **50** which is larger in size than a non-conductive region unoccupied by the stator winding **51** in the stator **50**. In typical rotating electrical machines for vehicles, a ratio of the conductive region/the non-conductive region is usually one or less. In contrast, this embodiment has the conductor groups **81** arranged to have the conductive region substantially identical in size with or larger in size than the non-conductive region. If the conductor region, as illustrated in FIG. **10**, occupied by the conductor **82** (i.e., the straight section **83** which will be described later in detail) in the circumferential direction is defined as WA, and a conductor-to-conductor region that is an interval between a respective adjacent two of the conductors **82** is defined as WB, the conductor region WA is larger in size than the conductor-to-conductor region WB in the circumferential direction.

The conductor group **81** of the stator winding **51** has a thickness in the radial direction thereof which is smaller than a circumferential width of a portion of the stator winding **51** which lies in a region of one magnetic pole and serves as one of the phases of the stator winding **51**. In the structure in which each of the conductor groups **81** is made up of the two conductors **82** stacked in the form of two layers lying on each other in the radial direction, and the two conductor groups **81** are arranged in the circumferential direction within a region of one magnetic pole for each phase, a relation of $Tc \times 2 < Wc \times 2$ is met where Tc is the thickness of each of the conductors **82** in the radial direction, and Wc is the width of each of the conductors **82** in the circumferential direction. In another structure in which each of the conductor groups **81** is made up of the two conductors **82**, and each of the conductor groups **81** lies within the region of one magnetic pole for each phase, a relation of $Tc \times 2 < Wc$ is preferably met. In other words, in the stator winding **51** which is designed to have conductor portions (i.e., the conductor groups **81**) arranged at a given interval away from each other in the circumferential direction, the thickness of each conductor portion (i.e., the conductor group **81**) in the radial direction is set smaller than the width of a portion of the stator winding **51** lying in the region of one magnetic pole for each phase in the circumferential direction.

In other words, each of the conductors **82** is preferably shaped to have the thickness Tc in the radial direction which is smaller than the width Wc in the circumferential direction. The thickness 2Tc of each of the conductor groups **81** each made of a stack of the two conductors **82** in the radial direction is preferably smaller than the width Wc of each of the conductor groups **81** in the circumferential direction.

The degree of torque produced by the rotating electrical machine **10** is substantially inversely proportional to the thickness of the stator core **52** in the radial direction. The conductor groups **81** arranged radially outside the stator core **52** are, as described above, designed to have the thickness decreased in the radial direction. This design is useful in increasing the degree of torque outputted by the rotating electrical machine **10**. This is because a distance between the magnet unit **42** of the rotor **40** and the stator core **52** (i.e., a distance in which there is no iron) may be decreased to decrease the magnetic resistance. This enables interlinkage magnetic flux in the stator core **52** produced by the permanent magnets to be increased to enhance the torque.

The decrease in thickness of the conductor groups **81** facilitates the ease with which a magnetic flux leaking from the conductor groups **81** is collected in the stator core **52**, thereby preventing the magnetic flux from leaking outside the stator core **52** without being used for enhancing the torque. This avoids a drop in magnetic force arising from the leakage of the magnetic flux and increases the interlinkage magnetic flux in the stator core **52** produced by the permanent magnets, thereby enhancing the torque.

Each of the conductors **82** is made of a coated conductor formed by covering the surface of the conductor body **82***a* with the coating **82***b*. The conductors **82** stacked on one another in the radial direction are, therefore, insulated from each other. Similarly, the conductors **82** are insulated from the stator core **52**. The insulating coating **82***b* may be a coating of each wire **86**, as will be described later in detail, in a case where each wire **86** is made of wire with a self-bonded coating or may be made by an additional insulator disposed on a coating of each wire **86**. Each phase winding made of the conductors **82** is insulated by the coating **82***b* except an exposed portion thereof for joining purposes. The exposed portion includes, for example, an input or an output terminal or a neutral point in a case of a star connection. The conductor groups **81** arranged adjacent each other in the radial direction are firmly adhered to each other using resin or self-bonding coated wire, thereby minimizing a risk of insulation breakdown, mechanical vibration, or noise caused by rubbing of the conductors **82**.

In this embodiment, the conductor body **82***a* is made of a collection of a plurality of wires **86**. Specifically, the conductor body **82***a* is, as can be seen in FIG. **13**, made of a strand of the twisted wires **86**. Each of the wires **86** is, as can be seen in FIG. **14**, made of a bundle of a plurality of thin conductive fibers **87**. For instance, each of the wires **86** is made of a complex of CNT (carbon nanotube) fibers. The CNT fibers include boron-containing microfibers in which at least a portion of carbon is substituted with boron. Instead of the CNT fibers that are carbon-based microfibers, vapor grown carbon fiber (VGCF) may be used, but however, CNT fiber is preferable. The surface of the wire **86** is covered with a layer of insulating polymer, such as enamel. The surface of the wire **86** is preferably covered with an enamel coating, such as polyimide coating or amide-imide coating.

The conductors **82** constitute n-phase windings of the stator winding **51**. The wires **86** of each of the conductors **82** (i.e., the conductor body **82***a*) are placed in contact with each other. Each of the conductors **82** has one of more portions which are formed by twisting the wires **86** and define one or more portions of a corresponding one of the phase-windings. A resistance value between the twisted wires **86** is larger than that of each of the wires **86**. In other words, the respective adjacent two wires **86** have a first electrical resistivity in a direction in which the wires **86** are arranged adjacent each other. Each of the wires **86** has a second electrical resistivity in a lengthwise direction of the wire **86**. The first electrical resistivity is larger than the second electrical resistivity. Each of the conductors **82** may be made of an assembly of wires, i.e., the twisted wires **86** covered with insulating members whose first electrical resistivity is very high. The conductor body **82***a* of each of the conductors **82** is made of a strand of the twisted wires **86**.

The conductor body **82***a* is, as described above, made of the twisted wires **86**, thereby reducing an eddy current created in each of the wires **86**, which reduces an eddy current in the conductor body **82***a*. Each of the wires **86** is twisted, thereby causing each of the wires **86** to have portions where directions of applied magnetic field are opposite each other, which cancels a back electromotive force. This results in a reduction in the eddy current. Particularly, each of the wires **86** is made of the conductive fibers **87**, thereby enabling the conductive fibers **87** to be thin and also enabling the number of times the conductive fibers **87** are twisted to be increased, which enhances the reduction in eddy current.

How to insulate the wires **86** from each other is not limited to the above described use of the polymer insulating layer, but the contact resistance may be used to resist a flow of current between the wires **86**. In other words, the above beneficial advantage is obtained by a difference in potential arising from a difference between the resistance between the twisted wires **86** and the resistance of each of the wires **86** as long as the resistance between the wires **86** is larger than that of each of the wires **86**. For instance, the contact resistance may be increased by using production equipment for the wires **86** and production equipment for the stator **50** (i.e., an armature) of the rotating electrical machine **10** as discrete devices to cause the wires **86** to be oxidized during a transport time or a work interval.

Each of the conductors **82** is, as described above, of a low-profile or flattened rectangular shape in cross section. The multiple conductors **82** are arranged in the radial direction. Each of the conductors **82** is made of a strand of the wires **86** each of which is formed by a self-bonding coating wire equipped with, for example, a fusing or bonding layer or an insulating layer and which are twisted with the bonding layers fused together. Each of the conductors **82** may alternatively be made by forming twisted wires with no bonding layer or twisted self-bonding coating wires into a desired shape using synthetic resin. The insulating coating **82***b* of each of the conductors **82** may have a thickness of 80 μm to 100 μm which is larger than that of a coating of typical wire (i.e., 5 μm to 40 μm). In this case, a required degree of insulation between the conductors **82** is achieved even if no insulating sheet is interposed between the conductors **82**.

It is also advisable that the insulating coating **82***b* be higher in degree of insulation than the insulating layer of the wire **86** to achieve insulation between the phase windings. For instance, the polymer insulating layer of the wire **86** has a thickness of, for example, 5 μm. In this case, the thickness of the insulating coating **82***b* of the conductor **82** is preferably selected to be 80 μm to 100 μm to achieve the insulation between the phase windings.

Each of the conductors **82** may alternatively be made of a bundle of the untwisted wires **86**. In brief, each of the conductors **82** may be made of a bundle of the wires **86** whose entire lengths are twisted, whose portions are twisted, or whose entire lengths are untwisted. Each of the conductors **82** constituting the conductor portion is, as described above, made of a bundle of the wires **86**. The resistance between the wires **86** is larger than that of each of the wires **86**.

The conductors **82** are each bent and arranged in a given pattern in the circumferential direction of the stator winding **51**, thereby forming the phase-windings of the stator winding **51**. The stator winding **51**, as illustrated in FIG. **12**, includes the coil side portion **53** and the coil ends **54** and **55**. The conductors **82** have the straight sections **83** which extend straight in the axial direction of the stator winding **51** and form the coil side portion **53**. The conductors **82** have the turns **84** which are arranged outside the coil side portion **53** in the axial direction and form the coil ends **54** and **55**. Each of the conductor **82** is made of a wave-shaped string of conductor formed by alternately arranging the straight sections **83** and the turns **84**. The straight sections **83** are arranged to face the magnet unit **42** in the radial direction. The straight sections **83** are arranged at a given interval away from each other and joined together using the turns **84** located outside the magnet unit **42** in the axial direction. The straight sections **83** correspond to a magnet facing portion.

In this embodiment, the stator winding **51** is shaped in the form of an annular distributed winding. In the coil side portion **53**, the straight sections **83** are arranged at an interval away from each other which corresponds to each pole pair of the magnet unit **42** for each phase. In each of the coil ends **54** and **55**, the straight sections **83** for each phase are joined together by the turn **84** which is of a V-shape. The straight sections **83** which are paired for each pole pair are opposite to each other in a direction of flow of electrical current. A respective two of the straight sections **83** which are joined together by each of the turns **84** are different between the coil end **54** and the coil end **55**. The joints of the straight sections **83** by the turns **84** are arranged in the circumferential direction on each of the coil ends **54** and **55** to complete the stator winding in a hollow cylindrical shape.

More specifically, the stator winding **51** is made up of two pairs of the conductors **82** for each phase. The stator winding **51** is equipped with a first three-phase winding set including the U-phase winding, the V-phase winding, and the W-phase winding and a second three-phase phase winding set including the X-phase winding, the Y-phase winding, and the Z-phase winding. The first three-phase phase winding set and the second three-phase winding set are arranged adjacent each other in the radial direction in the form of two layers. If the number of phases of the stator winding **51** is defined as S (i.e., 6 in this embodiment), the number of the conductors **82** for each phase is defined as m, $2\times S\times m=2Sm$ conductors **82** are used for each pole pair in the stator winding **51**. The rotating electrical machine in this embodiment is designed so that the number of phases S is 6, the number m is 4, and 8 pole pairs are used. $6\times 4\times 8=192$ conductors **82** are arranged in the circumferential direction of the stator core **52**.

The stator winding **51** in FIG. **12** is designed to have the coil side portion **53** which has the straight sections **82** arranged in the form of two overlapping layers disposed adjacent each other in the radial direction. Each of the coil ends **54** and **55** has a respective two of the turns **84** which extend from the radially overlapping straight sections **82** in opposite circumferential directions. In other words, the conductors **82** arranged adjacent each other in the radial direction are opposite to each other in direction in which the turns **84** extend except for ends of the stator winding **51**.

A winding structure of the conductors **82** of the stator winding **51** will be described below in detail. In this embodiment, the conductors **82** formed in the shape of a wave winding are arranged in the form of a plurality of layers (e.g., two layers) disposed adjacent or overlapping each other in the radial direction. FIGS. **15**(*a*) and **15**(*b*) illustrate the layout of the conductors **82** which form the n^{th} layer. FIG. **15**(*a*) shows the configurations of the conductor **82**, as the side of the stator winding **51** is viewed. FIG. **15**(*b*) shows the configurations of the conductors **82** as viewed in the axial direction of the stator winding **51**. In FIGS. **15**(*a*) and **15**(*b*), locations of the conductor groups **81** are indicated by symbols D**1**, D**2**, D**3** . . . , and D**9**. For the sake of simplicity of disclosure, FIGS. **15**(*a*) and **15**(*b*) show only three conductors **82** which will be referred to herein as the first conductor **82**_A, the second conductor **82**_B, and the third conductor **82**_C.

The conductors **82**_A to **82**_C have the straight sections **83** arranged at a location of the n^{th} layer, in other words, at the same position in the circumferential direction. Every two of the straight sections **82** which are arranged at **6** pitches (corresponding to 3×m pairs) away from each other are joined together by one of the turns **84**. In other words, in the conductors **82**_A to **82**_C, an outermost two of the seven straight sections **83** arranged in the circumferential direction of the stator winding **51** on the same circle defined about the center of the rotor **40** are joined together using one of the turns **84**. For instance, in the first conductor **82**_A, the straight sections **83** placed at the locations D**1** and D**7** are joined together by the inverse V-shaped turn **84**. The conductors **82**_B and **82**_C are arranged at an interval equivalent to an interval between a respective adjacent two of the straight sections **83** away from each other in the circumferential direction at the location of the n^{th} layer. In this layout, the conductors **82**_A to **82**_C are placed at a location of the same layer, thereby resulting in a risk that the turns **84** thereof may physically interfere with each other. In order to alleviate such a risk, each of the turns **84** of the conductors **82**_A to **82**_C in this embodiment is shaped to have an interference avoiding portion formed by offsetting a portion of the turn **84** in the radial direction.

Specifically, the turn **84** of each of the conductors **82**_A to **82**_C includes the slant portion **84***a*, the head portion **84***b*, the slant portion **84***c*, and the return portion **84***d*. The slant portion **84***a* extends in the circumferential direction of the same circle (which will also be referred to as a first circle). The head portion **84** extends from the slant portion **84***a* radially inside the first circle (i.e., upward in FIG. **15**(*b*)) to reach another circle (which will also be referred to as a second circle). The slant portion **84***c* extends in the circumferential direction of the second circle. The return portion **84***d* returns from the second circle back to the first circle. The head portion **84***b*, the slant portion **84***c*, and the return portion **84***d* define the interference avoiding portion. The slant portion **84***c* may be arranged radially outside the slant portion **84***a*.

In other words, each of the conductors **82**_A to **82**_C has the turn **84** shaped to have the slant portion **84***a* and the slant portion **84***c* which are arranged on opposite sides of the head portion **84***b* at the center in the circumferential direction. The locations of the slant portions **84***a* and **84***b* are different from each other in the radial direction (i.e., a direction perpendicular to the drawing of FIG. **15**(*a*) or a vertical direction in FIG. **15**(*b*)). For instance, the turn **84** of the first conductor **82**_A is shaped to extend from the location D**1** on the n^{th} layer in the circumferential direction, be bent at the head portion **84***b* that is the center of the circumferential length of the turn **84** in the radial direction (e.g., radially inwardly), be bent again in the circumferential direction, extend again in the circumferential direction, and then be bent at the return portion **84***d* in the radial direction (e.g., radially outwardly) to reach the location D**7** on the n^{th} layer.

With the above arrangements, the slant portions **84***a* of the conductors **82**_A to **82**_C are arranged vertically or downward in the order of the first conductor **82**_A, the second conductor **82**_B, and the third conductor **82**_C. The head portions **84***b* change the order of the locations of the conductors **82**_A to **82**_C in the vertical direction, so that the slant portions **84***c* are arranged vertically or downward in the order of the third conductor **82**_**3**, the second conductor **82**_B, and the first conductor **82**_A. This layout achieves an arrangement of the conductors **82**_A to **82**_C in the circumferential direction without any physical interference with each other.

In the structure wherein the conductors **82** are laid to overlap each other in the radial direction to form the conductor group **81**, the turns **84** leading to a radially innermost one and a radially outermost one of the straight sections **83** forming the two or more layers are preferably located radially outside the straight sections **83**. In a case where the conductors **83** forming the two or more layers are bent in the same radial direction near boundaries between ends of the turns **84** and the straight sections **83**, the conductors **83** are preferably shaped not to deteriorate the insulation therebetween due to physical interference of the conductors **83** with each other.

In the example of FIGS. **15**(*a*) and **15**(*b*), the conductors **82** laid on each other in the radial direction are bent radially at the return portions **84***d* of the turns **84** at the location D**7** to D**9**. It is advisable that the conductor **82** of the n^{th} layer and the conductor **82** of the $n+1^{th}$ layer be bent, as illustrated in FIG. **16**, at radii of curvature different from each other. Specifically, the radius of curvature R**1** of the conductor **82** of the n^{th} layer is preferably selected to be smaller than the radius of curvature R**2** of the conductor **82** of the $n+1^{th}$ layer.

Additionally, radial displacements of the conductor **82** of the n^{th} layer and the conductor **82** of the $n+1^{th}$ layer are preferably selected to be different from each other. If the amount of radial displacement of the conductor **82** of the n^{th} layer is defined as S**1**, and the amount of radial displacement of the conductor **82** of the $n+1^{th}$ layer located radially outside the nth layer defined as S**2**, the amount of radial displacement S**1** is preferably selected to be greater than the amount of radial displacement S**2**.

The above layout of the conductors **82** eliminates the risk of interference with each other, thereby ensuring a required degree of insulation between the conductors **82** even when the conductors **82** laid on each other in the radial direction are bent in the same direction.

The structure of the magnet unit **42** of the rotor **40** will be described below. In this embodiment, the magnet unit **42** is made of permanent magnets in which a remanent flux density Br=1.0 T, and an intrinsic coercive force Hcj=400 kA/m. The permanent magnets used in this embodiment are implemented by sintered magnets formed by sintering grains of magnetic material and compacting them into a given shape and have the following specifications. The intrinsic coercive force Hcj on a J-H curve is 400 kA/m or more. The remanent flux density Br on the J-H curve is 1.0 T or more. Magnets designed so that when 5,000 to 10,000 AT is applied thereto by phase-to-phase excitation, a magnetic distance between paired poles, i.e., between a N-pole and an S-pole, in other words, of a path in which a magnetic flux flows between the N-pole and the S-pole, a portion lying in the magnet has a length of 25 mm may be used to meet a relation of Hcj=10000 A without becoming demagnetized.

In other words, the magnet unit **42** is engineered so that a saturation magnetic flux density Js is 1.2 T or more, a grain size is 10 μm or less, and a relation of Js×a≥1.0 T is met where a is an orientation ratio.

The magnet unit **42** will be additionally described below. The magnet unit **42** (i.e., magnets) has a feature that Js meets a relation of 2.15 T≥Js≥1.2 T. In other words, magnets used in the magnet unit **42** may be FeNi magnets having NdFe11TiN, Nd2Fe14B, Sm2Fe17N3, or L10 crystals. Note that samarium-cobalt magnets, such as SmCo5, FePt, Dy2Fe14B, or CoPt magnets can not be used. When magnets in which high Js characteristics of neodymium are slightly lost, but a high degree of coercive force of Dy is ensured using the heavy rare earth dysprosium, like in isomorphous compounds, such as Dy2Fe14B and Nd2Fe14B, sometimes meets a relation of 2.15 T≥Js≥1.2 T, they may be used in the magnet unit **42**. Such a type of magnet will also be referred to herein as [Nd1−xDyx]2Fe14B]. Further, a magnet contacting different types of compositions, in other words, a magnet made from two or more types of materials, such as FeNi and Sm2Fe17N3, may be used to meet a relation of 2.15 T≥Js≥1.2 T. A mixed magnet made by adding a small amount of, for example, Dy2Fe14B in which Js<1 T to an Nd2Fe14B magnet in which Js=1.6 T, meaning that Js is sufficient to enhance the coercive force, may also be used to meet a relation of 2.15 T≥Js≥1.2 T.

In use of the rotating electrical machine at a temperature outside a temperature range of human activities which is higher than, for example, 60° C. exceeding temperatures of deserts, for example, within a passenger compartment of a vehicle where the temperature may rise to 80° C. in summer, the magnet preferably contains FeNi or Sm2Fe17N3 components which are less dependent on temperature. This is because motor characteristics are greatly changed by temperature-dependent factors thereof in motor operations within a range of approximately −40° which is within a range experienced by societies in Northern Europe to 60° C. or more experienced in desert regions or at 180 to 240° C. that is a heat resistance temperature of the enamel coating, which leads to a difficulty in achieving a required control operation using the same motor driver. The use of FeNi containing the above described L10 crystals or Sm2Fe17N3 magnets will result in a decrease in load on the motor driver because characteristics thereof have temperature-dependent factors lower than half that of Nd2Fe14B magnets.

Additionally, the magnet unit **42** is engineered to use the above described magnet mixing so that a particle size of fine powder before being magnetically oriented is lower than or equal to 10 μm and higher than or equal to a size of single-domain particles. The coercive force of a magnet is usually increased by decreasing the size of powered particles thereof to a few hundred nm. In recent years, smallest possible particles have been used. If the particles of the magnet are too small, the BHmax (i.e., the maximum energy product) of the magnet will be decreased due to oxidization thereof. It is, thus, preferable that the particle size of the magnet is higher than or equal to the size of the single-domain particles. The particle size being only up to the size of the single-domain particles is known to increase the coercive force of the magnet. The particle size, as referred to herein, refers to the diameter or size of fine powdered particles in a magnetic orientation operation in production processes of magnets.

Each of the first magnet **91** and the second magnet **92** of the magnet unit **42** are made of sintered magnets formed by firing or heating magnetic powder at high temperatures and compacting it. The sintering is achieved so as to meet conditions where the saturation magnetization Js of the magnet unit **42** is 1.2 T (Tesla) or more, the particle size of the first magnet **91** and the second magnet **92** is 10 μm or less, and Js×a is higher than or equal to 1.0 T (Tesla) where a is an orientation ratio. Each of the first magnet **91** and the second magnet **92** are also sintered to meet the following conditions. By performing the magnetic orientation in the magnetic orientation operation in the production processes of the first magnet **91** and the second magnet **92**, they have an orientation ratio different to the definition of orientation of magnetic force in a magnetization operation for isotropic magnets. The magnet unit **42** in this embodiment is designed to have the saturation magnetization Js more than or equal to 1.2 T and the orientation ratio a of the first magnet **91** and the second magnet **92** which is high to meet a relation of Jr≥Js×a≥1.0 T. The orientation ratio a, as referred to herein, is defined in the following way. If each of the first magnet **91** and the second magnet **92** has six easy axes of magnetization, five of the easy axes of magnetization are oriented in the same direction A**10**, and a remaining one of the easy axes of magnetization is oriented in the direction B**10** angled at 90 degrees to the direction A**10**, then a relation of a=5/6 is met. Alternatively, if each of the first magnet **91** and the second magnet **92** has six easy axes of magnetization, five of the easy axes of magnetization are oriented in the same direction A**10**, and a remaining one of the easy axes of magnetization is oriented in the direction B**10** angled at 45 degrees to the direction A**10**, then a relation of a=(5+0.707)/6 is met since a component oriented in the direction A**10** is expressed by cos 45°=0.707. The first magnet **91** and the second magnet **92** in this embodiment are, as described above, each made using sintering techniques, but however, they may be produced in another way as long as the above conditions are satisfied. For instance, a method of forming an MQ3 magnet may be used.

In this embodiment, permanent magnets are used which are magnetically oriented to control the easy axis of magnetization thereof, thereby enabling a magnetic circuit length within the magnets to be longer than that within typical linearly oriented magnets which produces a magnetic flux density of 1.0 T or more. In other words, the magnetic circuit length for one pole pair in the magnets in this embodiment may be achieved using magnets with a small volume. Additionally, a range of reversible flux loss in the magnets is not lost when subjected to severe high temperatures, as compared with use of typical linearly oriented magnets. The inventors of this application have found that characteristics similar to those of anisotropic magnets are obtained even using prior art magnets.

The easy axis of magnetization represents a crystal orientation in which a crystal is easy to magnetize in a magnet. The orientation of the easy axis of magnetization in the magnet, as referred to herein, is a direction in which an orientation ratio is 50% or more where the orientation ratio indicates the degree to which easy axes of magnetization of crystals are aligned with each other or a direction of an average of magnetic orientations in the magnet.

The magnet unit **42** is, as clearly illustrated in FIGS. **8** and **9**, of an annular shape and arranged inside the magnet holder **41** (specifically, radially inside the cylinder **43**). The magnet unit **42** is equipped with the first magnets **91** and the second magnets **92** which are each made of a polar anisotropic magnet. Each of the first magnets **91** and each of the second magnets **92** are different in magnetic polarity from each other. The first magnets **91** and the second magnets **92** are arranged alternately in the circumferential direction of the magnet unit **42**. Each of the first magnets **91** is engineered to have a portion creating an N-pole near the stator winding **51**. Each of the second magnets **92** is engineered to have a portion creating an S-pole near the stator winding **51**. The first magnets **91** and the second magnets **92** are each made of, for example, a permanent rare earth magnet, such as a neodymium magnet.

Each of the magnets **91** and **92** is engineered to have a direction of magnetization (which will also be referred to below as a magnetization direction) which extends in an annular shape in between a d-axis (i.e., a direct-axis) and a q-axis (i.e., a quadrature-axis) in a known d-q coordinate system where the d-axis represents the center of a magnetic pole, and the q-axis represents a magnetic boundary between the N-pole and the S-pole, in other words, where a density of magnetic flux is zero Tesla. In each of the magnets **91** and **92**, the magnetization direction is oriented in the radial direction of the annular magnet unit **42** Close to the d-axis and also oriented in the circumferential direction of the annular magnet unit **42** Closer to the q-axis. This layout will also be described below in detail. Each of the magnets **91** and **92**, as can be seen in FIG. **9**, includes a first portion **250** and two second portions **260** arranged on opposite sides of the first portion **250** in the circumferential direction of the magnet unit **42**. The first portion **250** is located closer to the d-axis than the second portions **260** are. The second portions **260** are arranged closer to the q-axis than the first portion **250** is. The direction in which the easy axis of magnetization **300** extends in the first portion **250** is oriented more parallel to the d-axis than the direction in which the easy axis of magnetization **310** extends in the second portions **260**. To say it in a different way, the easy axis of magnetization has a first portion lying in the first portion **250** of each of the magnets **91** and **92** and second portions lying in the second portions **260** of each of the magnets **91** and **92**. The first portion of the easy axis of magnetization extends more parallel to the d-axis than the second portions of the easy axis of magnetization do. In other words, the magnet unit **42** is engineered so that an angle θ**11** which the easy axis of magnetization **300** in the first portion **250** makes with the d-axis is selected to be smaller than an angle θ**12** which the easy axis of magnetization **310** in the second portion **260** makes with the q-axis.

More specifically, if a direction from the stator **50** (i.e., an armature) toward the magnet unit **42** on the d-axis is defined to be positive, the angle θ**11** represents an angle which the easy axis of magnetization **300** makes with the d-axis. Similarly, if a direction from the stator **50** (i.e., an armature) toward the magnet unit **42** on the q-axis is defined to be positive, the angle θ**12** represents an angle which the easy axis of magnetization **310** makes with the q-axis. In this embodiment, each of the angle θ**11** and the angle θ**12** is set to be 90° or less. Each of the easy axes of magnetization **300** and **310**, as referred to herein, is defined in the following way. If in each of the magnets **91** and **92**, a first one of the easy axes of magnetization is oriented in a direction A**11**, and a second one of the easy axes of magnetization is oriented in a direction B**11**, an absolute value of cosine of an angle θ which the direction A**11** and the direction B**11** make with each other (i.e., $|\cos \theta|$) is defined as the easy axis of magnetization **300** or the easy axis of magnetization **310**.

The magnets **91** are different in easy axis of magnetization from the magnets **92** in regions close to the d-axis and the q-axis. Specifically, in the region close to the d-axis, the direction of the easy axis of magnetization is oriented approximately parallel to the d-axis, while in the region close to the q-axis, the direction of the easy axis of magnetization is oriented approximately perpendicular to the q-axis. Annular magnetic paths are created according to the directions of easy axes of magnetization. In each of the magnets **91** and **92**, the easy axis of magnetization in the region close to the d-axis may be oriented parallel to the d-axis, while the easy axis of magnetization in the region close to the q-axis may be oriented perpendicular to the q-axis.

Each of the magnets **91** and **92** is shaped to have a first peripheral surface facing the stator **50** (i.e., a lower surface viewed in FIG. **9** which will also be referred to as a stator-side outer surface) and a second peripheral surface facing the q-axis in the circumferential direction. The first and second peripheral surfaces function as magnetic flux acting surfaces into and from which magnetic flux flows. The magnetic paths are each created to extend between the magnetic flux acting surfaces (i.e., between the stator-side outer surface and the second peripheral surface facing the q-axis).

In the magnet unit **42**, a magnetic flux flows in an annular shape between a respective adjacent two of the N-poles and the S-poles of the magnets **91** and **92**, so that each of the magnetic paths has an increased length, as compared with, for example, radial anisotropic magnets. A distribution of the magnetic flux density will, therefore, exhibit a shape similar to a sine wave illustrated in FIG. **17**. This facilitates concentration of magnetic flux around the center of the magnetic pole unlike a distribution of magnetic flux density of a radial anisotropic magnet demonstrated in FIG. **18** as a comparative example, thereby enabling the degree of torque produced by the rotating electrical machine **10** to be increased. It has also been found that the magnet unit **42** in this embodiment has the distribution of the magnetic flux density distinct from that of a typical Halbach array magnet. In FIGS. **17** and **18**, a horizontal axis indicates the electrical angle, while a vertical axis indicates the magnetic flux density. 90° on the horizontal axis represents the d-axis (i.e., the center of the magnetic pole). 0° and 180° on the horizontal axis represent the q-axis.

Accordingly, the above described structure of each of the magnets **91** and **92** functions to enhance the magnet magnetic flux thereof on the d-axis and reduce a change in magnetic flux near the q-axis. This enables the magnets **91** and **92** to be produced which have a smooth change in surface magnetic flux from the q-axis to the d-axis on each magnetic pole.

The sine wave matching percentage in the distribution of the magnetic flux density is preferably set to, for example, 40% or more. This improves the amount of magnetic flux around the center of a waveform of the distribution of the magnetic flux density as compared with a radially oriented magnet or a parallel oriented magnet in which the sine wave matching percentage is approximately 30%. By setting the sine wave matching percentage to be 60% or more, the amount of magnetic flux around the center of the waveform is improved, as compared with a concentrated magnetic flux array, such as the Halbach array.

In the radial anisotropic magnet demonstrated in FIG. **18**, the magnetic flux density changes sharply near the q-axis. The more sharp the change in magnetic flux density, the more an eddy current generated in the stator winding **51** will increase. The magnetic flux close to the stator winding **51** also sharply changes. In contrast, the distribution of the magnetic flux density in this embodiment has a waveform approximating a sine wave. A change in magnetic flux density near the q-axis is, therefore, smaller than that in the radial anisotropic magnet near the q-axis. This minimizes the generation of the eddy current.

The magnet unit **42** Creates a magnetic flux oriented perpendicular to the magnetic flux acting surface **280** close to the stator **50** near the d-axis (i.e., the center of the magnetic pole) in each of the magnets **91** and **92**. Such a magnetic flux extends in an arc-shape farther away from the d-axis as departing from the magnetic flux acting surface **280** close to the stator **50**. The more perpendicular to the magnetic flux acting surface the magnetic flux extends, the stronger the magnetic flux is. The rotating electrical machine **10** in this embodiment is, as described above, designed to shape each of the conductor groups **81** to have a decreased thickness in the radial direction, so that the radial center of each of the conductor groups **81** is located close to the magnetic flux acting surface of the magnet unit **42**, thereby causing the strong magnetic flux to be applied to the stator **50** from the rotor **40**.

The stator **50** has the cylindrical stator core **52** arranged radially inside the stator winding **51**, that is, on the opposite side of the stator winding **51** to the rotor **40**. This causes the magnetic flux extending from the magnetic flux acting surface of each of the magnets **91** and **92** to be attracted by the stator core **52**, so that it circulates through the magnetic path partially including the stator core **52**. This enables the orientation of the magnetic flux and the magnetic path to be optimized.

Steps to assemble the bearing unit **20**, the housing **30**, the rotor **40**, the stator **50**, and the inverter unit **60** illustrated in FIG. **5** will be described below as a production method of the rotating electrical machine **10**. The inverter unit **60** is, as illustrated in FIG. **6**, equipped with the unit base **61** and the electrical components **62**. Operation processes including installation processes for the unit base **61** and the electrical components **62** will be explained. In the following discussion, an assembly of the stator **50** and the inverter unit **60** will be referred to as a first unit. An assembly of the bearing unit **20**, the housing **30**, and the rotor **40** will be referred to as a second unit.

The production processes include:

- a first step of installing the electrical components **62** radially inside the unit base **61**;
- a second step of installing the unit base **61** radially inside the stator **50** to make the first unit;
- a third step of inserting the attaching portion **44** of the rotor **40** into the bearing unit **20** installed in the housing **30** to make the second unit;
- a fourth step of installing the first unit radially inside the second unit; and
- a fifth step of fastening the housing **30** and the unit base **61** together. The order in which the above steps are performed is the first step→the second step→the third step→the fourth step→the fifth step.

In the above production method, the bearing unit **20**, the housing **30**, the rotor **40**, the stator **50**, and the inverter unit **60** are assembled as a plurality of sub-assemblies, and the sub-assemblies are assembled, thereby facilitating handling thereof and achieving completion of inspection of each sub-assembly. This enables an efficient assembly line to be established and thus facilitates multi-product production planning.

In the first step, a high thermal conductivity material is applied or adhered to at least one of the radial inside of the unit base **61** and the radial outside of the electrical components **62**. Subsequently, the electrical components may be mounted on the unit base **61**. This achieves efficient transfer of heat, as generated by the semiconductor modules **66**, to the unit base **61**.

In the third step, an insertion operation for the rotor **40** may be achieved with the housing **30** and the rotor **40** arranged coaxially with each other. Specifically, the housing **30** and the rotor **40** are assembled while sliding one of the housing **30** and the rotor **40** along a jig which positions the outer peripheral surface of the rotor **40** (i.e., the outer peripheral surface of the magnetic holder **41**) or the inner peripheral surface of the rotor **40** (i.e., the inner peripheral surface of the magnet unit **42**) with respect to, for example, the inner peripheral surface of the housing **30**. This achieves the assembly of heavy-weight parts without exertion of unbalanced load to the bearing unit **20**. This results in improvement of reliability in operation of the bearing unit **20**.

In the fourth step, the first unit and the second unit may be installed while being placed coaxially with each other. Specifically, the first unit and the second unit are installed while sliding one of the first unit and the second unit along a jig which positions the inner peripheral surface of the unit base **61** with respect to, for example, the inner peripheral surfaces of the rotor **40** and the attaching portion **44**. This achieves the installation of the first and second units without any physical interference therebetween within a small clearance between the rotor **40** and the stator **50**, thereby eliminating risks of defects caused by the installation, such as physical damage to the stator winding **51** or damage to the permanent magnets.

The above steps may alternatively be scheduled as the second step→the third step→the fourth step→the fifth step→the first step. In this order, the delicate electrical components **62** are finally installed, thereby minimizing stress on the electrical components in the installation processes.

The structure of a control system for controlling an operation of the rotating electrical machine **10** will be described below. FIG. **19** is an electrical circuit diagram of the control system for the rotating electrical machine **10**. FIG. **20** is a functional block diagram which illustrates control steps performed by the controller **110**.

FIG. **19** illustrates two sets of three-phase windings **51***a* and **51***b*. The three-phase winding **51***a* includes a U-phase winding, a V-phase winding, and a W-phase winding. The three-phase winding **51***b* includes an X-phase winding, a Y-phase winding, and a Z-phase winding. The first inverter **101** and the second inverter **102** are provided as electrical power converters for the three-phase windings **51***a* and **51***b*, respectively. The inverters **101** and **102** are made of bridge circuits with as many upper and lower arms as there are the phase-windings. The current delivered to the phase windings of the stator winding **51** is regulated by turning on or off switches (i.e., semiconductor switches) mounted on the upper and lower arms.

The dc power supply **103** and the smoothing capacitor **104** are connected parallel to the inverters **101** and **102**. The dc power supply **103** is made of, for example, a plurality of series-connected cells. The switches of the inverters **101** and **102** correspond to the semiconductor modules **66** in FIG. **1**. The capacitor **104** corresponds to the capacitor module **68** in FIG. **1**.

The controller **110** is equipped with a microcomputer made of a CPU and memories and works to perform control energization by turning on or off the switches of the inverters **101** and **102** using several types of measured information measured in the rotating electrical machine **10** or requests for a motor mode or a generator mode of the rotating electrical machine **10**. The controller **110** corresponds to the control device **77** shown in FIG. **6**. The measured information about the rotating electrical machine **10** includes, for example, an angular position (i.e., an electrical angle) of the rotor **40** measured by an angular position sensor, such as a resolver, a power supply voltage (i.e., voltage inputted into the inverters) measured by a voltage sensor, and electrical current delivered to each of the phase-windings, as measured by a current sensor. The controller **110** produces and outputs an operation signal to operate each of the switches of the inverters **101** and **102**. A request for electrical power generation is a request for driving the rotating electrical machine **10** in a regenerative mode, for example, in a case where the rotating electrical machine **10** is used as a power source for a vehicle.

The first inverter **101** is equipped with a series-connected part made up of an upper arm switch Sp and a lower arm switch Sn for each of the three-phase windings: the U-phase winding, the V-phase winding, and the W-phase winding. The upper arm switches Sp are connected at high-potential terminals thereof to a positive terminal of the dc power supply **103**. The lower arm switches Sn are connected at low-potential terminals thereof to a negative terminal (i.e., ground) of the dc power supply **103**. Intermediate joints of the upper arm switches Sp and the lower arm switches Sn are connected to ends of the U-phase winding, the V-phase winding, and the W-phase winding. The U-phase winding, the V-phase winding, and the W-phase winding are connected in the form of a star connection (i.e., Y-connection). The other ends of the U-phase winding, the V-phase winding, and the W-phase winding are connected with each other at a neutral point.

The second inverter **102** is, like the first inverter **101**, equipped with a series-connected part made up of an upper arm switch Sp and a lower arm switch Sn for each of the three-phase windings: the X-phase winding, the Y-phase winding, and the Z-phase winding. The upper arm switches Sp are connected at high-potential terminals thereof to the positive terminal of the dc power supply **103**. The lower arm switches Sn are connected at low-potential terminals thereof to the negative terminal (i.e., ground) of the dc power supply **103**. Intermediate joints of the upper arm switches Sp and the lower arm switches Sn are connected to ends of the X-phase winding, the Y-phase winding, and the Z-phase winding. The X-phase winding, the Y-phase winding, and the Z-phase winding are connected in the form of a star connection (i.e., Y-connection). The other ends of the X-phase winding, the Y-phase winding, and the Z-phase winding are connected with each other at a neutral point.

FIG. **20** illustrates a current feedback control operation to control electrical currents delivered to the U-phase winding, the V-phase winding, and the W-phase winding and a current feedback control operation to control electrical currents delivered to the X-phase winding, the Y-phase winding, and the Z-phase winding. The control operation for the U-phase winding, the V-phase winding, and the W-phase winding will first be discussed.

In FIG. **20**, the current command determiner **111** uses a torque-dq map to determine current command values for the d-axis and the q-axis using a torque command value in the motor mode of the rotating electrical machine **10** (which will also be referred to as a motor-mode torque command value), a torque command value in the generator mode of the rotating electrical machine **10** (which will be referred to as a generator-mode torque command value), and an electrical angular velocity ω derived by differentiating an electrical angle θ with respect to time. The current command determiner **111** is shared between the U-, V-, and W-phase windings and the X-, Y-, and W-phase windings. The generator-mode torque command value is a regenerative torque command value in a case where the rotating electrical machine **10** is used as a power source of a vehicle.

The d-q converter **112** works to convert currents (i.e., three phase currents), as measured by current sensors mounted for the respective phase windings, into a d-axis current and a q-axis current that are components in a two-dimensional rotating Cartesian coordinate system in which a d-axis is defined as a direction of an axis of a magnetic field or field direction.

The d-axis current feedback control device **113** determines a command voltage for the d-axis as a manipulated variable for bringing the d-axis current into agreement with the current command value for the d-axis in a feedback mode. The q-axis current feedback control device **114** determines a command voltage for the q-axis as a manipulated variable for bringing the q-axis current into agreement with the current command value for the q-axis in a feedback mode. The feedback control devices **113** and **114** calculates the command voltage as a function of a deviation of each of the d-axis current and the q-axis current from a corresponding one of the current command values using PI feedback techniques.

The three-phase converter **115** works to convert the command values for the d-axis and the q-axis into command values for the U-phase, V-phase, and W-phase windings. Each of the devices **111** to **115** is engineered as a feedback controller to perform a feedback control operation for a fundamental current in the d-q transformation theory. The command voltages for the U-phase, V-phase, and W-phase windings are feedback control values.

The operation signal generator **116** uses the known triangle wave carrier comparison to produce operation signals for the first inverter **101** as a function of the three-phase command voltages. Specifically, the operation signal generator **116** works to produce switch operation signals (i.e., duty signals) for the upper and lower arms for the three-phase windings (i.e., the U-, V-, and W-phase windings) under PWM control based on comparison of levels of signals derived by normalizing the three-phase command voltages using the power supply voltage with a level of a carrier signal, such as a triangle wave signal.

The same structure as described above is provided for the X-, Y-, and Z-phase windings. The d-q converter **122** works to convert currents (i.e., three phase currents), as measured by current sensors mounted for the respective phase windings, into a d-axis current and a q-axis current that are components in the two-dimensional rotating Cartesian coordinate system in which the d-axis is defined as the direction of the axis of the magnetic field.

The d-axis current feedback control device **123** determines a command voltage for the d-axis. The q-axis current feedback control device **124** determines a command voltage for the q-axis. The three-phase converter **125** works to convert the command values for the d-axis and the q-axis into command values for the X-phase, Y-phase, and Z-phase windings. The operation signal generator **126** produces operation signals for the second inverter **102** as a function of the three-phase command voltages. Specifically, the operation signal generator **126** works to switch operation signals (i.e., duty signals) for the upper and lower arms for the three-phase windings (i.e., the X-, Y-, and Z-phase windings) based on comparison of levels of signals derived by normalizing the three-phase command voltages using the power supply voltage with a level of a carrier signal, such as a triangle wave signal.

The driver **117** works to turn on or off the switches Sp and Sn in the inverters **101** and **102** in response to the switch operation signals produced by the operation signal generators **116** and **126**.

Subsequently, a torque feedback control operation will be described below. This operation is to increase an output of the rotating electrical machine **10** and reduce torque loss in the rotating electrical machine **10**, for example, in a high-speed and high-output range wherein output voltages from the inverters **101** and **102** rise. The controller **110** selects one of the torque feedback control operation and the current feedback control operation and perform the selected one as a function of an operating condition of the rotating electrical machine **10**.

FIG. **21** shows the torque feedback control operation for the U-, V-, and W-phase windings and the torque feedback control operation for the X-, Y-, and Z-phase windings. In FIG. **21**, the same reference numbers as employed in FIG. **20** refer to the same parts, and explanation thereof in detail will be omitted here. The control operation for the U-, V-, and W-phase windings will be described first.

The voltage amplitude calculator **127** works to calculate a voltage amplitude command that is a command value of a degree of a voltage vector as a function of the motor-mode torque command value or the generator-mode torque command value for the rotating electrical machine **10** and the electrical angular velocity ω derived by differentiating the electrical angle θ with respect to time.

The torque calculator **128***a* works to estimate a torque value in the U-phase, V-phase, or the W-phase as a function of the d-axis current and the q-axis current converted by the d-q converter **112**. The torque calculator **128***a* may be designed to calculate the voltage amplitude command using a map listing relations among the d-axis current, the q-axis current, and the voltage amplitude command.

The torque feedback controller **129***a* calculates a voltage phase command that is a command value for a phase of the voltage vector as a manipulated variable for bringing the estimated torque value into agreement with the motor-mode torque command value or the generator-mode torque command value in the feedback mode. Specifically, the torque feedback controller **129***a* calculates the voltage phase command as a function of a deviation of the estimated torque value from the motor-mode torque command value or the generator-mode torque command value using PI feedback techniques.

The operation signal generator **130***a* works to produce the operation signal for the first inverter **101** using the voltage amplitude command, the voltage phase command, and the electrical angle θ. Specifically, the operation signal generator **130***a* calculates the command values for the three-phase windings based on the voltage amplitude command, the voltage phase command, and the electrical angle θ and then generates switching operation signals for the upper and lower arms for the three-phase windings by means of PWM control based on comparison of levels of signals derived by normalizing the three-phase command voltages using the power supply voltage with a level of a carrier signal, such as a triangle wave signal.

The operation signal generator **130***a* may alternatively be designed to produce the switching operation signals using pulse pattern information that is map information about relations among the voltage amplitude command, the voltage phase command, the electrical angle θ, and the switching operation signal, the voltage amplitude command, the voltage phase command, and the electrical angle θ.

The same structure as described above is provided for the X-, Y-, and Z-phase windings. The torque calculator **128***b* works to estimate a torque value in the X-phase, Y-phase, or the Z-phase as a function of the d-axis current and the q-axis current converted by the d-q converter **122**.

The torque feedback controller **129***b* calculates a voltage phase command as a manipulated variable for bringing the estimated torque value into agreement with the motor-mode torque command value or the generator-mode torque command value in the feedback mode. Specifically, the torque feedback controller **129***b* calculates the voltage phase command as a function of a deviation of the estimated torque value from the motor-mode torque command value or the generator-mode torque command value using PI feedback techniques.

The operation signal generator **130***b* works to produce the operation signal for the second inverter **102** using the voltage amplitude command, the voltage phase command, and the electrical angle θ. Specifically, the operation signal generator **130***b* calculates the command values for the three-phase windings based on the voltage amplitude command, the voltage phase command, and the electrical angle θ and then generates the switching operation signals for the upper and lower arms for the three-phase windings by means of PWM control based on comparison of levels of signals derived by normalizing the three-phase command voltages using the power supply voltage with a level of a carrier signal, such as a triangle wave signal. The driver **117** then works to turn on or off the switches Sp and Sn for the three-phase windings in the inverters **101** and **102** in response to the switching operation signals derived by the operation signal generators **130***a* and **130***b*.

The operation signal generator **130***b* may alternatively be designed to produce the switching operation signals using pulse pattern information that is map information about relations among the voltage amplitude command, the voltage phase command, the electrical angle θ, and the switching operation signal, the voltage amplitude command, the voltage phase command, and the electrical angle θ.

The rotating electrical machine **10** has a risk that generation of an axial current may result in electrical erosion in the bearing **21** or **22**. For example, when the stator winding **51** is excited or de-excited in response to the switching operation, a small switching time gap (i.e., switching unbalance) may occur, thereby resulting in distortion of magnetic flux, which leads to the electrical erosion in the bearings **21** and **22** retaining the rotating shaft **11**. The distortion of magnetic flux depends upon the inductance of the stator **50** and creates an electromotive force oriented in the axial direction, which results in dielectric breakdown in the bearing **21** or **22** to develop the electrical erosion.

In order to avoid the electrical erosion, this embodiment is engineered to take three measures as discussed below. The first erosion avoiding measure is to reduce the inductance by designing the stator **50** to have a core-less structure and also to shape the magnetic flux in the magnet unit **42** to be smooth to minimize the electrical erosion. The second erosion avoiding measure is to retain the rotating shaft in a cantilever form to minimize the electrical erosion. The third erosion avoiding measure is to unify the annular stator winding **51** and the stator core **52** using molding techniques using a moulding material to minimize the electrical erosion. The first to third erosion avoiding measures will be described below in detail.

In the first erosion avoiding measure, the stator **50** is designed to have no teeth in gaps between the conductor groups **81** in the circumferential direction. The sealing members **57** made of non-magnetic material are arranged in the gaps between the conductor groups **81** instead of teeth (iron cores) (see FIG. **10**). This results in a decrease in inductance of the stator **50**, thereby minimizing the distortion of magnetic flux caused by the switching time gap occurring upon excitation of the stator winding **51** to reduce the electrical erosion in the bearings **21** and **22**. The inductance on the d-axis is preferably less than that on the q-axis.

Additionally, each of the magnets **91** and **92** is magnetically oriented to have the easy axis of magnetization which is directed near the d-axis to be more parallel to the d-axis than that near the q-axis (see FIG. **9**). This strengthens the magnetic flux on the d-axis, thereby resulting in a smooth change in surface magnetic flux (i.e., an increase or decrease in magnetic flux) from the q-axis to the d-axis on each magnetic pole of the magnets **91** and **92**. This minimizes a sudden voltage change arising from the switching imbalance to avoid the electrical erosion.

In the second erosion avoiding measure, the rotating electrical machine **10** is designed to have the bearings **21** and **22** located away from the axial center of the rotor **40** toward one of the ends of the rotor **40** opposed to each other in the axial direction thereof (see FIG. **2**). This minimizes the risk of the electrical erosion as compared with a case where a plurality of bearings are arranged outside axial ends of a rotor. In other words, in the structure wherein the rotor has ends retained by the bearings, generation of a high-frequency magnetic flux results in creation of a closed circuit extending through the rotor, the stator, and the bearings (which are arranged axially outside the rotor). This leads to a risk that the axial current may result in electrical erosion in the bearings. In contrast, the rotor **40** are retained by the plurality of bearings **21** and **22** in the cantilever form, so that the above closed circuit does not occur, thereby minimizing the electrical erosion in the bearings **21** and **22**.

In addition to the above one-side layout of the bearings **21** and **22**, the rotating electrical machine **10** also has the following structure. In the magnet holder **41**, the intermediate portion **45** extending in the radial direction of the rotor **40** is equipped with the contact avoider which axially extends to avoid physical contact with the stator **50** (see FIG. **2**). This enables a closed circuit through which the axial current flows through the magnet holder **41** to be lengthened to increase the resistance thereof. This minimizes the risk of the electrical erosion of the bearings **21** and **22**.

The retainer **23** for the bearing unit **20** is secured to the housing **30** and located on one axial end side of the rotor **40**, while the housing **30** and the unit base **61** (i.e., a stator holder) are joined together on the other axial end of the rotor **40** (see FIG. **2**). These arrangements properly achieve the structure in which the bearings **21** and **22** are located only on the one end of the length of the rotating shaft **11**. Additionally, the unit base **61** is connected to the rotating shaft **11** through the housing **30**, so that the unit base **61** is located electrically away from the rotating shaft **11**. An insulating member such as resin may be disposed between the unit base **61** and the housing **30** to place the unit base **61** and the rotating shaft **11** electrically farther away from each other. This also minimizes the risk of the electrical erosion of the bearings **21** and **22**.

The one-side layout of the bearings **21** and **22** in the rotating electrical machine **10** in this embodiment decreases the axial voltage applied to the bearings **21** and **22** and also decreases the potential difference between the rotor **40** and the stator **50**. A decrease in the potential difference applied to the bearings **21** and **22** is, thus, achieved without use of conductive grease in the bearings **21** and **22**. The conductive grease usually contains fine particles such as carbon particles, thus leading to a risk of generation of acoustic noise. In order to alleviate the above problem, this embodiment uses a non-conductive grease in the bearings **21** and **22** to minimize the acoustic noise in the bearings **21** and **22**. For instance, in a case where the rotating electrical machine **10** is used with an electrical vehicle, it is usually required to take a measure to eliminate the acoustic noise. This embodiment is capable of properly taking such a measure.

In the third erosion avoiding measure, the stator winding **51** and the stator core **52** are unified together using a moulding material to minimize a positional error of the stator winding **51** in the stator **50** (see FIG. **11**). The rotating electrical machine **10** in this embodiment is designed not to have inter-conductor members (e.g., teeth) between the conductor groups **81** arranged in the circumferential direction of the stator winding **51**, thus leading to a concern about the positional error or misalignment of the stator winding **51**. The misalignment of the conductor of the stator winding **51** may be minimized by unifying the stator winding **51** and the stator core **52** in the mold. This eliminates risks of the distortion of magnetic flux arising from the misalignment of the stator winding **51** and the electrical erosion in the bearings **21** and **22** resulting from the distortion of the magnetic flux.

The unit base **61** serving as a housing to firmly fix the stator core **52** is made of carbon fiber reinforced plastic (CFRP), thereby minimizing electrical discharge to the unit base **61** as compared with when the unit base **61** is made of aluminum, thereby avoiding electrical erosion.

An additional erosion avoiding measure may be taken to make at least one of the outer race **25** and the inner race **26** of each of the bearings **21** and **22** using a ceramic material or alternatively to install an insulating sleeve outside the outer race **25**.

Other embodiments will be described below in terms of differences between themselves and the first embodiment.

Second Embodiment

In this embodiment, the polar anisotropic structure of the magnet unit **42** of the rotor **40** is changed and will be described below in detail.

The magnet unit **42** is, as clearly illustrated in FIGS. **22** and **23**, made using a magnet array referred to as a Halbach array. Specifically, the magnet unit **42** is equipped with the first magnets **131** and the second magnets **132**. The first magnets **131** have a magnetization direction (i.e., an orientation of a magnetization vector thereof) oriented in the radial direction of the magnet unit **42**. The second magnets **132** have a magnetization direction (i.e., an orientation of the magnetization vector thereof) oriented in the circumferential direction of the magnet unit **42**. The first magnets **131** are arrayed at a given interval away from each other in the circumferential direction. Each of the second magnets **132** is disposed between the first magnets **131** arranged adjacent each other in the circumferential direction. The first magnets **131** and the second magnets **132** are each implemented by a rare-earth permanent magnet, such as a neodymium magnet.

The first magnets **131** are arranged away from each other in the circumferential direction so as to have N-poles and S-poles which are created in radially inner portions thereof and face the stator **50**. The N-poles and the S-poles are arranged alternately in the circumferential direction. The second magnets **132** are arranged to have N-poles and S-poles alternately located adjacent the first magnets **131** in the circumferential direction. The cylinder **43** which surrounds the magnets **131** and **132** may be formed as a soft magnetic core made of a soft magnetic material and which functions as a back core. The magnet unit **42** in this embodiment are designed to have the easy axis of magnetization oriented in the same way as in the first embodiment relative to the d-axis and the q-axis in the d-q axis coordinate system.

The magnetic members **133** each of which is made of a soft magnetic material are disposed radially outside the first magnets **131**, in other words, close to the cylinder **43** of the magnet holder **41**. Each of the magnetic members **133** may be made of magnetic steel sheet, soft iron, or a dust core material. Each of the magnetic members **133** has a length identical with that of the first magnet **131** (especially, a length of an outer periphery of the first magnet **131**) in the circumferential direction. An assembly made up of each of the first magnets **131** and a corresponding one of the magnetic members **133** has a thickness identical with that of the second magnet **132** in the radial direction. In other words, each of the first magnets **131** has the thickness smaller than that of the second magnet **132** by that of the magnetic member **133** in the radial direction. The magnets **131** and **132** and the magnetic members **133** are firmly secured to each other using, for example, adhesive agent. In the magnet unit **42**, the radial outside of the first magnets **131** faces away from the stator **50**. The magnetic members **133** are located on the opposite side of the first magnets **131** to the stator **50** in the radial direction (i.e., farther away from the stator **50**).

Each of the magnetic members **133** has the key **134** in a convex shape which is formed on the outer periphery thereof and protrudes radially outside the magnetic member **133**, in other words, protrudes into the cylinder **43** of the magnet holder **41**. The cylinder **43** has the key grooves **135** which are formed in an inner peripheral surface thereof in a concave shape and in which the keys **134** of the magnetic members **133** are fit. The protruding shape of the keys **134** is contoured to conform with the recessed shape of the key grooves **135**. As many of the key grooves **135** as the keys **134** of the magnetic members **133** are formed. The engagement between the keys **134** and the key grooves **135** serves to eliminate misalignment or a positional deviation of the first magnets **131**, the second magnets **132**, and the magnet holder **41** in the circumferential direction (i.e. a rotational direction). The keys **134** and the key grooves **135** (i.e., convexities and concavities) may be formed either on the cylinders **43** of the magnet holder **41** or in the magnetic members **133**, respectively. Specifically, the magnetic members **133** may have the key grooves **135** in the outer periphery thereof, while the cylinder **43** of the magnet holder **41** may have the keys **134** formed on the inner periphery thereof.

The magnet unit **42** has the first magnets **131** and the second magnets **132** alternately arranged to increase the magnetic flux density in the first magnets **131**. This results in concentration of magnetic flux on one surface of the magnet unit **42** to enhance the magnetic flux close to the stator **50**.

The layout of the magnetic members **133** radially arranged outside the first magnets **131**, in other words, farther away from the stator **50** reduces partial magnetic saturation occurring radially outside the first magnets **131**, thereby alleviating a risk of demagnetization in the first magnets **131** arising from the magnetic saturation. This results in an increase in magnetic force produced by the magnet unit **42**. In other words, the magnet unit **42** in this embodiment is viewed to have portions which are usually subjected to the demagnetization and replaced with the magnetic members **133**.

FIGS. **24**(*a*) and **24**(*b*) are illustrations which demonstrate flows of magnetic flux in the magnet unit **42**. FIG. **24**(*a*) illustrates a conventional structure in which the magnet unit **42** is not equipped with the magnetic members **133**. FIG. **24**(*b*) illustrates the structure in this embodiment in which the magnet unit **42** is equipped with the magnetic members **133**. FIGS. **24**(*a*) and **24**(*b*) are linearly developed views of the cylinder **43** of the magnet holder **41** and the magnet unit **42**. Lower sides of FIGS. **24**(*a*) and **24**(*b*) are close to the stator **50**, while upper sides thereof are farther away from the stator **50**.

In the structure shown in FIG. **24**(*a*), a magnetic flux acting surface of each of the first magnets **131** and a side surface of each of the second magnets **132** are placed in contact with the inner peripheral surface of the cylinder **43**. A magnetic flux acting surface of each of the second magnets **132** is placed in contact with the side surface of one of the first magnets **131**. Such layout causes a combined magnetic flux to be created in the cylinder **43**. The combined magnetic flux is made up of a magnetic flux F**1** which passes outside the second magnet **132** and then enters the surface of the first magnets **131** contacting the cylinder **43** and a magnetic flux which flows substantially parallel to the cylinder **43** and attracts a magnetic flux F**2** produced by the second magnet **132**. This leads to a risk that the magnetic saturation may occur near the surface of contact between the first magnet **131** and the second magnet **132** in the cylinder **43**.

In the structure in FIG. **24**(*b*) wherein each of the magnetic members **133** is disposed between the magnetic flux acting surface of the first magnet **131** and the inner periphery of the cylinder **43** farther away from the stator **50**, the magnetic flux is permitted to pass through the magnetic member **133**. This minimizes the magnetic saturation in the cylinder **43** and increases resistance against the demagnetization.

The structure in FIG. **24**(*b*), unlike FIG. **24**(*a*), functions to eliminate the magnetic flux F**2** facilitating the magnetic saturation. This effectively enhances the permeance in the whole of the magnetic circuit, thereby ensuring the stability in properties of the magnetic circuit under elevated temperature.

As compared with radial magnets used in conventional SPM rotors, the structure in FIG. **24**(*b*) has an increased length of the magnetic path passing through the magnet. This results in a rise in permeance of the magnet which enhances the magnetic force to increase the torque. Further, the magnetic flux concentrates on the center of the d-axis, thereby increasing the sine wave matching percentage. Particularly, the increase in torque may be achieved effectively by shaping the waveform of the current to a sine or trapezoidal wave under PWM control or using 120° excitation switching ICs.

In a case where the stator core **52** is made of magnetic steel sheets, the thickness of the stator core **52** in the radial direction thereof is preferably half or greater than half the thickness of the magnet unit **42** in the radial direction. For instance, it is preferable that the thickness of the stator core **52** in the radial direction is greater than half the thickness of the first magnets **131** arranged at the pole-to-pole center in the magnet unit **42**. It is also preferable that the thickness of the stator core **52** in the radial direction is smaller than that of the magnet unit **42**. In this case, a magnet magnetic flux is approximately 1 T, while the saturation magnetic flux density in the stator core **52** is 2 T. The leakage of magnetic flux to inside the inner periphery of the stator core **52** is avoided by selecting the thickness of the stator core **52** in the radial direction to be greater than half that of the magnet unit **42**.

Magnets arranged to have the Halbach structure or the polar anisotropic structure usually have an arc-shaped magnetic path, so that the magnetic flux may be increased in proportion to a thickness of ones of the magnets which handle a magnetic flux in the circumferential direction. In such a structure, the magnetic flux flowing through the stator core **52** is thought of as not exceeding the magnetic flux flowing in the circumferential direction. In other words, when the magnetic flux produced by the magnets is 1 T, while ferrous metal whose saturation magnetic flux density is 2 T is used to make the stator core **52**, a light weight and compact electrical rotating machine may be produced by selecting the thickness of the stator core **52** to be greater than half that of the magnets. The demagnetizing field is usually exerted by the stator **50** on the magnetic field produced by the magnets, so that the magnetic flux produced by the magnets will be 0.9 T or less. The magnetic permeability of the stator core may, therefore, be properly kept by selecting the thickness of the stator core to be half that of the magnets.

Modifications of the above structure will be described below.

First Modification

In the above embodiment, the outer peripheral surface of the stator core **52** has a curved surface without any irregularities. The plurality of conductor groups **81** are arranged at a given interval away from each other on the outer peripheral surface of the stator core **52**. This layout may be changed. For instance, the stator core **52** illustrated in FIG. **25** is equipped with the circular ring-shaped yoke **141** and the protrusions **142**. The yoke **141** is located on the opposite side (i.e., a lower side, as viewed in the drawing) of the stator winding **51** to the rotor **40** in the radial direction. Each of the protrusions **142** protrudes into a gap between a respective two of the straight sections **83** arranged adjacent each other in the circumferential direction. The protrusions **142** are arranged at a given interval away from each other in the circumferential direction radially outside the yoke **141**, i.e., close to the rotor **40**. Each of the conductor groups **81** of the stator winding **51** engages the protrusions **142** in the circumferential direction, in other words, the protrusions **142** are used as positioners to position and array the conductor groups **81** in the circumferential direction. The protrusions **142** Correspond to inter-conductor members.

A radial thickness of each of the protrusions **142** from the yoke **141**, in other words, a distance W, as illustrated in FIG. **25**, between the inner surface **320** of the straight sections **82** which is placed in contact with the yoke **141** and the top of the protrusion **412** in the radial direction of the yoke **141** is selected to be smaller than half a radial thickness (as indicated by H1 in the drawing) of the straight sections **83** arranged adjacent the yoke **141** in the radial direction. In other words, non-conductive members (i.e., the sealing members **57**) preferably each occupy three-fourths of a dimension (i.e., thickness) T**1** (i.e., twice the thickness of the conductors **82**, in other words, a minimum distance between the surface **320** of the conductor group **81** placed in contact with the stator core **52** and the surface **330** of the conductor group **81** facing the rotor **40**) of the conductor groups (i.e., conductors) **81** in the radial direction of the stator winding **51** (i.e., the stator core **52**). Such selection of the thickness of the protrusions **142** Causes each of the protrusions **142** not to function as a tooth between the conductor groups **81** (i.e., the straight sections **83**) arranged adjacent each other in the circumferential direction, so that there are no magnetic paths which would usually be formed by the teeth. The protrusions **142** need not necessarily to be arranged between a respective circumferentially adjacent two of all the conductor groups **81**, but however, a single protrusion **142** may be disposed at least only between two of the conductor groups **81** which are arranged adjacent each other in the circumferential direction. For instance, the protrusions **142** may be disposed away from each other in the circumferential direction at equal intervals each of which corresponds to a given number of the conductor groups **81**. Each of the protrusions **142** may be designed to have any shape, such as a rectangular or arc-shape.

The straight sections **83** may alternatively be arranged in a single layer on the outer peripheral surface of the stator core **52**. In a broad sense, the thickness of the protrusions **142** from the yoke **141** in the radial direction may be smaller than half that of the straight sections **83** in the radial direction.

If an imaginary circle whose center is located at the axial center of the rotating shaft **11** and which passes through the radial centers of the straight sections **83** placed adjacent the yoke **141** in the radial direction is defined, each of the protrusions **142** may be shaped to protrude only within the imaginary circle, in other words, not to protrude radially outside the imaginary circle toward the rotor **40**.

The above structure in which the protrusions **142** have the limited thickness in the radial direction and do not function as teeth in the gaps between the straight sections **83** arranged adjacent each other in the circumferential direction enables the adjacent straight sections **83** to be disposed closer to each other as compared with a case where teeth are provided in the gaps between the straight sections **83**. This enables a sectional area of the conductor body **82***a* to be increased, thereby reducing heat generated upon excitation of the stator winding **51**. The absence of the teeth enables magnetic saturation to be eliminated to increase the amount of electrical current delivered to the stator winding **51**. It is, however, possible to alleviate the adverse effects arising from an increase in amount of heat generated by the increase in electrical current delivered to the stator winding **51**. The stator winding **51**, as described above, has the turns **84** which are shifted in the radial direction and equipped with the interference avoiding portions with the adjacent turns **84**, thereby enabling the turns **84** to be disposed away from each other in the radial direction. This enhances the heat dissipation from the turns **84**. The above structure is enabled to optimize the heat dissipating ability of the stator **50**.

The radial thickness of the protrusions **142** may not be restricted by the dimension H1 in FIG. **25** as long as the yoke **141** of the stator core **52** and the magnet unit **42** (i.e., each of the magnets **91** and **92**) of the rotor **40** are arranged at a given distance away from each other. Specifically, the radial thickness of the protrusions **142** may be larger than or equal to the dimension H1 in FIG. **25** as long as the yoke **141** and the magnet unit **42** arranged 2 mm or more away from each other. For instance, in a case where the radial thickness of the straight section **83** is larger than 2 mm, and each of the conductor groups **81** is made up of the two conductors **82** stacked in the radial direction, each of the protrusions **142** may be shaped to occupy a region ranging to half the thickness of the straight section **83** not contacting the yoke **141**, i.e., the thickness of the conductor **82** located farther away from the yoke **141**. In this case, the above beneficial advantages will be obtained by increasing the conductive sectional area of the conductor groups **81** as long as the radial thickness of the protrusions **142** is at least H**1**×3/2.

The stator core **52** may be designed to have the structure illustrated in FIG. **26**. FIG. **26** omits the sealing members **57**, but the sealing members **57** may be used. FIG. **26** illustrates the magnet unit **42** and the stator core **52** as being arranged linearly for the sake of simplicity.

In the structure of FIG. **26**, the stator **50** has the protrusions **142** as inter-conductor members each of which is arranged between a respective two of the conductors **82** (i.e., the straight sections **83**) located adjacent each other in the circumferential direction. The stator **50** is equipped with the portions **350** each of which magnetically operates along with one of the magnetic poles (i.e., an N-pole or an S-pole) of the magnet unit **42** when the stator winding **51** is excited. The portions **350** extend in the circumferential direction of the stator **50**. If each of the portions **350** has a length Wn in the circumferential direction of the stator **50**, the sum of widths of the protrusions **142** lying in a range of this length Wn (i.e., the total dimension of the protrusions **412** in the circumferential direction of the stator **50** in the range of length Wn) is defined as Wt, the saturation magnetic flux density of the protrusions **412** is defined as Bs, a width of the magnet unit **42** equivalent to one of the magnetic poles of the magnet unit **42** in the circumferential direction of the magnet unit **42** is defined as Wm, and the remanent flux density in the magnet unit **42** is defined as Br, the protrusions **142** are made of a magnetic material meeting a relation of $Wt \times Bs \leq Wm \times Br$ - - - (1)

The range Wn is defined to contain ones of the conductor groups **81** which are arranged adjacent each other in the circumferential direction and which overlap in time of excitation thereof with each other. It is advisable that a reference (i.e., a border) used in defining the range Wn be set to the center of the gap **56** between the conductor groups **81**. For instance, in the structure illustrated in FIG. **26**, the plurality of conductor groups **81** lying in the range Wn include the first, the second, the third, and the fourth conductor groups **81**, as numbered from the magnetic center of the N-pole, where the first and the second conductor groups **81** are closest to the magnetic center of the N-pole. The range Wn is defined to include the total of those four conductor groups **81**. Ends (i.e., outer limits) of the range Wn are defined to lie at the centers of the gaps **56**.

In FIG. **26**, the range Wn contains half of the protrusion **142** inside each of the ends thereof. The total of the four protrusions **142** lie in the range Wn. If the width of each of the protrusions **142** (i.e., a dimension of the protrusion **142** in the circumferential direction of the stator **50**, in other words, an interval between the adjacent conductor groups **81**) is defined as A, the sum of widths Wt of the protrusions **142** lying in the range Wn meets a relation of $Wt = \frac{1}{2}A + A + A + A + \frac{1}{2}A = 4A$.

Specifically, the three-phase windings of the stator winding **51** in this embodiment are made in the form of distributed windings. In the stator winding **51**, the number of the protrusions **142** for each pole of the magnet unit **42**, that is, the number of the gaps **56** each between the adjacent conductor groups **81** is selected to be "the number of phases×Q" where Q is the number of the conductors **82** for each phase which are placed in contact with the stator core **52**. In other words, in the case where the conductors **82** are stacked in the radial direction of the rotor **40** to constitute each of the conductor groups **81**, Q is the number of inner ones of the conductors **82** of the conductor groups **81** for each phase. In this case, when the three-phase windings of the stator winding **51** are excited in a given sequence, the protrusions **142** for two of the three-phases within each pole are magnetically excited. The total circumferential width Wt of the protrusions **142** excited upon excitation of the stator winding **51** within a range of each pole of the magnet unit **42**, therefore, meets a relation of "the number of the phases excited×Q×A=2×2×A where A is the width of each of the protrusions **142** (i.e., the gap **56**) in the circumferential direction.

The total width Wt is determined in the above way. Additionally, the protrusions **142** of the stator core **52** are made of magnetic material meeting the above equation (1). The total width Wt is also viewed as being equivalent to a circumferential dimension of where the relative magnetic permeability is expected to become greater than one within each pole. The total width Wt may alternatively be determined as a circumferential width of the protrusions **142** in each pole with some margin. Specifically, since the number of the protrusions **142** for each pole of the magnet unit **42** is given by the number of phases×Q, the width of the protrusions **412** in each pole (i.e., the total width Wt) may be given by the number of phases×Q×A=3×2×A=6A.

The distributed winding, as referred to herein, means that there is a pair of poles (i.e., the N-pole and the S-pole) of the stator winding **51** for each pair of magnetic poles. The pair of poles of the stator winding **51**, as referred to herein, is made of the two straight sections **83** in which electrical current flows in opposite directions and the turn **84** electrically connecting them together. Note that a short pitch winding or a full pitch winding may be viewed as an equivalent of the distributed winding as long as it meets the above conditions.

Next, the case of a concentrated winding will be described below. The concentrated winding, as referred to herein, means that the width of each pair of magnetic poles is different from that of each pair of poles of the stator winding **51**. An example of the concentrated winding includes a structure in which there are three conductor groups **81** for each pair of magnetic poles, in which there are three conductor groups **81** for two pairs of magnetic poles, in which there are nine conductor groups **81** for four pairs of magnetic poles, or in which there are nine conductor groups **81** for five pairs of magnetic poles.

In the case where the stator winding **51** is made in the form of the concentrated winding, when the three-phase windings of the stator winding **51** are excited in a given sequence, a portion of the stator winding **51** for two phases is excited. This causes the protrusions **142** for two phases to be magnetically excited. The circumferential width Wt of the protrusions **142** which is magnetically excited upon excitation of the stator winding in a range of each pole of the magnet unit **42** is given by Wt=A×2. The width Wt is determined in this way. The protrusions **142** are made of magnetic material meeting the above equation (1). In the above described case of the concentrated winding, the sum of widths of the protrusions **142** arranged in the circumferential direction of the stator **50** within a region surrounded by the conductor groups **81** for the same phase is defined as A. The dimension Wm in the concentrated winding is given by [an entire circumference of a surface of the magnet unit **42** facing the air gap]×[the number of phases]÷[the number of the distributed conductor groups **81**].

Usually, a neodymium magnet, a samarium-cobalt magnet, or a ferrite magnet whose value of BH is higher than or equal to 20[MGOe (kJ/m^3)] has Bd=1.0 T or more. Iron has Br=2.0 T or more. The protrusions **142** of the stator core **52** may, therefore, be made of magnetic material meeting a relation of $Wt < \frac{1}{2} \times Wm$ for realizing a high-power motor.

In a case where each of the conductors **82** is, as described later, equipped with the outer coated layer **182**, the conductors **82** may be arranged in the circumferential direction of the stator core with the outer coated layers **182** placed in contact with each other. In this case, the width Wt may be viewed to be zero or equivalent to thicknesses of the outer coated layers **182** of the conductors **82** contacting with each other.

The structure illustrated in FIG. **25** or **26** is designed to have inter-conductor members (i.e., the protrusions **142**) which are too small in size for the magnet-produced magnetic flux in the rotor **40**. The rotor **40** is implemented by a surface permanent magnet rotor which has a flat surface and a low inductance, and does not have a salient pole in terms of a magnetic resistance. Such a structure enables the inductance of the stator **50** to be decreased, thereby reducing a risk of distortion of the magnetic flux caused by the switching time gap in the stator winding **51**, which minimizes the electrical erosion of the bearings **21** and **22**.

Second Modification

The stator **50** equipped with the inter-conductor members made to meet the above equation may be designed to have the following structure. In FIG. **27**, the stator core **52** is equipped with the teeth **143** as inter-conductor members which are formed in an outer peripheral portion (an upper portion, as viewed in the drawing) of the stator core **52**. The teeth **143** protrude from the yoke **141** and are arranged at a given interval away from each other in the circumferential direction of the stator core **52**. Each of the teeth **143** has a thickness identical with that of the conductor group **81** in the radial direction. The teeth **143** have side surfaces placed in contact with the conductors **82** of the conductor groups **81**. The teeth **143** may alternatively be located away from the conductors **82** through gaps.

The teeth **143** are shaped to have a restricted width in the circumferential direction. Specifically, each of the teeth **143** has a stator tooth which is very thin for the volume of magnets. Such a structure of the teeth **143** serves to achieve saturation by the magnet-produced magnetic flux at 1.8T or more to reduce the permeance, thereby decreasing the inductance.

If a surface area of a magnetic flux acting surface of the magnet unit **42** facing the stator **50** for each pole is defined as Sm, and the remanent flux density of the magnet unit **42** is defined as Br, the magnetic flux in the magnet unit **42** will be $Sm \times Br$. A surface area of each of the teeth **143** facing the rotor **40** is defined as St. The number of the conductors **83** for each phase is defined as m. When the teeth **143** for two phases within a range of one pole are magnetically excited upon excitation of the stator winding **51**, the magnetic flux in the stator **50** is expressed by $St \times m \times 2 \times Bs$. The decrease in inductance may be achieved by selecting the dimensions of the teeth **143** to meet a relation of $St \times m \times 2 \times Bs < Sm \times Br$ - - - (2).

In a case where the dimension of the magnet unit **42** is identical with that of the teeth **143** in the axial direction, the above equation (2) may be rewritten as an equation (3) of $Wst \times m \times 2 \times Bs < Wm \times Br$ where Wm is the circumferential width of the magnet unit **42** for each pole, and Wst is the circumferential width of the teeth **143**. For example, when Bs=2 T, Br=1 T, and m=2, the equation (3) will be $Wst < Wm/8$. In this case, the decrease in inductance may be achieved by selecting the width Wst of the teeth **143** to be smaller than one-eighth (⅛) of the width Wm of the magnet unit **42** for one pole. When m is one, the width Wst of the teeth **143** is preferably selected to be smaller than one-fourth (¼) of the width Wm of the magnet unit **42** for one pole.

"$Wst \times m \times 2$" in the equation (3) corresponds to a circumferential width of the teeth **143** magnetically excited upon excitation of the stator winding **51** in a range of one pole of the magnet unit **42**.

The structure in FIG. **27** is, like in FIGS. **25** and **26**, equipped with the inter-conductor members (i.e., the teeth **143**) which are very small in size for the magnet-produced magnetic flux in the rotor **40**. Such a structure is capable of reducing the inductance of the stator **50** to alleviate a risk of distortion of the magnetic flux arising from the switching time gap in the stator winding **51**, which minimizes the probability of the electrical erosion of the bearings **21** and **22**. Note that the definitions of parameters, such as Wt, Wn, A, and Bs, associated with the stator **50** or parameters, such as Wm and Br, associated with the magnet unit **42** may refer to those in the above described first modification.

Third Modification

The above embodiment has the sealing members **57** which cover the stator winding **51** and occupy a region including all of the conductor groups **81** radially outside the stator core **52**, in other words, lie in a region where the thickness of the sealing members **57** is larger than that of the conductor groups **81** in the radial direction. This layout of the sealing members **57** may be changed. For instance, the sealing members **57** may be, as illustrated in FIG. **28**, designed so that the conductors **82** protrude partially outside the sealing members **57**. Specifically, the sealing members **57** are arranged so that portions of the conductors **82** that are radially outermost portions of the conductor groups **81** are exposed outside the sealing members **57** toward the stator **50**. In this case, the thickness of the sealing members **57** in the radial direction may be identical with or smaller than that of the conductor groups **81**.

Fourth Modification

The stator **50** may be, as illustrated in FIG. **29**, designed not to have the sealing members **57** covering the conductor groups **81**, i.e., the stator winding **51**. In this case, a gap is created between the adjacent conductor groups **81** arranged in the circumferential direction without a inter-conductor member therebetween. In other words, no inter-conductor member is disposed between the conductor groups **81** arranged in the circumferential direction. Air may be arranged in the gaps between the conductor groups **81**. The air may be viewed as a non-magnetic member or an equivalent thereof whose Bs is zero (0).

Fifth Modification

The inter-conductor members of the stator **50** may be made of a non-magnetic material other than resin. For instance, a non-metallic material, such as SUS304 that is austenitic stainless steel.

Sixth Modification

The stator **50** may be designed not to have the stator core **52**. Specifically, the stator **50** is made of the stator winding **51** shown in FIG. **12**. The stator winding **51** of the stator **50** may be covered with a sealing member. The stator **50** may alternatively be designed to have an annular winding retainer made from non-magnetic material such as synthetic resin instead of the stator core **52** made from soft magnetic material.

Seventh Modification

The structure in the first embodiment uses the magnets **91** and **92** arranged in the circumferential direction to constitute the magnet unit **42** of the rotor **40**. The magnet unit **42** may be made using an annular permanent magnet. For instance, the annular magnet **95** is, as illustrated in FIG. **30**, secured to a radially inner periphery of the cylinder **43** of the magnet holder **41**. The annular magnet **95** is equipped with a plurality of different magnetic poles whose magnetic polarities are arranged alternately in the circumferential direction of the annular magnet **95**. The magnet **95** lies integrally both on the d-axis and the q-axis. The annular magnet **95** has a magnetic orientation directed in the radial direction on the d-axis of each magnetic pole and a magnetic orientation directed in the circumferential direction on the q-axis between the magnetic poles, thereby creating arc-shaped magnetic paths.

The annular magnet **95** may be designed to have an easy axis of magnetization directed parallel or nearly parallel to the d-axis near the d-axis and also to have an easy axis of magnetization directed perpendicular or near perpendicular to the q-axis near the q-axis, thereby creating the arc-shaped magnetic paths.

Eighth Modification

This modification is different in operation of the controller **110** from the above embodiment or modifications. Only differences from those in the first embodiment will be described below.

The operations of the operation signal generators **116** and **126** illustrated in FIG. **20** and the operation signal generators **130***a* and **130***b* illustrated in FIG. **21** will first be discussed below using FIG. **31**. The operations executed by the operation signal generators **116**, **126**, **130***a*, and **130***b* are basically identical with each other. Only the operation of the operation signal generator **116** will, therefore, be described below for the sake of simplicity.

The operation signal generator **116** includes the carrier generator **116***a*, the U-phase comparator **116***b*U, the V-phase comparator **116***b*V, and the W-phase comparator **116***b*W. The carrier generator **116***a* produces and outputs the carrier signal SigC in the form of a triangle wave signal.

The U-, V-, and W-phase comparators **116***b*U, **116***b*V, and **116***b*W receive the carrier signal SigC outputted by the carrier generator **116***a* and the U-, V-, and W-phase command voltages produced by the three-phase converter **115**. The U-, V-, and W-phase command voltages are produced, for example, in the form of a sine wave and outputted 120° out of electrical phase with each other.

The U-, V-, and W-phase comparators **116***b*U, **116***b*V, and **116***b*W compare the U-, V-, and W-phase command voltages with the carrier signal SigC to produce operation signals for the switches Sp and Sn of the upper and lower arms in the first inverter **101** for the U-, V-, and W-phase windings under PWM (Pulse Width Modulation) control. Specifically, the operation signal generator **116** works to produce operation signals for the switches Sp and Sn of the upper and lower arms for the U-, V-, and W-phase windings under the PWM control based on comparison of levels of signals derived by normalizing the U-, V-, and W-phase command voltages using the power supply voltage with a level of the carrier signal SigC. The driver **117** is responsive to the operation signals outputted by the operation signal generator **116** to turn on or off the switches Sp and Sn in the first inverter **101** for the U-, V-, and W-phase windings.

The controller **110** alters the carrier frequency fc of the carrier signal SigC, i.e., a switching frequency for each of the switches Sp and Sn. The carrier frequency fc is altered to be higher in a low torque range or a high-speed range in the rotating electrical machine **10** and alternatively lower in a high torque range in the rotating electrical machine **10**. This altering is achieved in order to minimize a deterioration in ease of control of electrical current flowing through each of the U-, V-, and W-phase windings.

In brief, the core-less structure of the stator **50** serves to reduce the inductance in the stator **50**. The reduction in inductance usually results in a decrease in electrical time constant in the rotating electrical machine **10**. This leads to a risk that a ripple of current flowing through each of the phase windings may be increased, thereby resulting in the deterioration in ease of control of the current flowing through the phase winding, which causes control divergence. The adverse effects of the above deterioration on the ease of control usually become higher when the current (e.g., an effective value of the current) flowing through the winding lies in a low current region than when the current lies in a high current range. In order to alleviate such a problem, the controller **110** in this embodiment is designed to alter the carrier frequency fc.

How to alter the carrier frequency fc will be described below with reference to FIG. **32**. This operation of the operation signal generator **116** is executed by the controller **110** cyclically at a given interval.

First, in step S**10**, it is determined whether electrical current flowing through each of the three-phase windings **51***a* lies in the low current range. This determination is made to determine whether torque now produced by the rotating electrical machine **10** lies in the low torque range. Such a determination may be achieved according to the first method or the second method, as discussed below.

First Method

The estimated torque value of the rotating electrical machine **10** is calculated using the d-axis current and the q-axis current converted by the d-q converter **112**. If the estimated torque value is determined to be lower than a torque threshold value, it is concluded that the current flowing through the winding **51***a* lies in the low current range. Alternatively, if the estimated torque value is determined to be higher than or equal to the torque threshold value, it is concluded that the current lies in the high current range. The torque threshold value is selected to be half, for example, the degree of starting torque (also called locked rotor torque) in the rotating electrical machine **10**.

Second Method

If an angle of rotation of the rotor **40** measured by an angle sensor is determined to be higher than or equal to a speed threshold value, it is determined that the current flowing through the winding **51***a* lies in the low current range, that is, in the high speed range. The speed threshold value may be selected to be a rotational speed of the rotating electrical machine **10** when a maximum torque produced by the rotating electrical machine **10** is equal to the torque threshold value.

If a NO answer is obtained in step S**10**, meaning that the current lies in the high current range, then the routine proceeds to step S**11** wherein the carrier frequency fc is set to the first frequency fL.

Alternatively, if a YES answer is obtained in step S**10**, then the routine proceeds to step S**12** wherein the carrier frequency fc is set to the second frequency fH that is higher than the first frequency fL.

As apparent from the above discussion, the carrier frequency fc when the current flowing through each of the three-phase windings lies in the low current range is selected to be higher than that when the current lies in the high current range. The switching frequency for the switches Sp and Sn is, therefore, increased in the low current range, thereby minimizing a rise in current ripple to ensure the stability in controlling the current.

When the current flowing through each of the three-phase windings lies in the high current range, the carrier frequency fc is selected to be lower than that when the current lies in the low current range. The current flowing through the winding in the high current range usually has an amplitude larger than that when the current lies in the low current range, so that the rise in current ripple arising from the reduction in inductance has a low impact on the ease of control of the current. It is, therefore, possible to set the carrier frequency fc in the high current range to be lower than that in the low current range, thereby reducing a switching loss in the inverters **101** and **102**.

This modification is capable of realizing the following modes.

If a YES answer is obtained in step S**10** in FIG. **32** when the carrier frequency fc is set to the first frequency fL, the carrier frequency fc may be changed gradually from the first frequency fL to the second frequency fH.

Alternatively, if a NO answer is obtained in step S**10** when the carrier frequency fc is set to the second frequency fH, the carrier frequency fc may be changed gradually from the second frequency fH to the first frequency fL.

The operation signals for the switches may alternatively be produced using SVM (Space Vector Modulation) instead of the PWM. The above alteration of the switching frequency may also be made.

Ninth Modification

In each of the embodiments, two pairs of conductors making up the conductor groups **81** for each phase are, as illustrated in FIG. **33**(*a*), arranged parallel to each other. FIG. **33**(*a*) is a view which illustrates an electrical connection of the first and second conductors **88***a* and **88***b* that are the two pairs of conductors. The first and second conductors **88***a* and **88***b* may alternatively be, as illustrated in FIG. **33**(*b*), connected in series with each other instead of the connection in FIG. **33**(*a*).

Three or more pairs of conductors may be stacked in the form of multiple layers. FIG. **34** illustrates four pairs of conductors: the first to fourth conductors **88***a* to **88***d* which are stacked. The first conductor **88***a*, the second conductor **88***b*, the third conductor **88***c*, and the fourth conductor **88***d* are arranged in this order from the stator core **52** in the radial direction.

The third and fourth conductors **88***c* and **88***d* are, as illustrated in FIG. **33**(*c*), connected in parallel to each other. The first conductor **88***a* is connected to one of joints of the third and fourth conductors **88***c* and **88***d*. The second conductor **88***b* is connected to the other joint of the third and fourth conductors **88***c* and **88***d*. The parallel connection of conductors usually results in a decrease in current density of those conductors, thereby minimizing thermal energy produced upon energization of the conductors. Accordingly, in the structure in which a cylindrical stator winding is installed in a housing (i.e., the unit base **61**) with the coolant path **74** formed therein, the first and second conductors **88***a* and **88***b* which are connected in non-parallel to each other are arranged close to the stator core **52** placed in contact with the unit base **61**, while the third and fourth conductors **88***c* and **88***d* which are connected in parallel to each other are disposed farther away from the stator core **52**. This layout equalizes the cooling ability of the conductors **88***a* to **88***d* stacked in the form of multiple layers.

The conductor group **81** including the first to fourth conductors **88***a* to **88***d* may have a thickness in the radial direction which is smaller than a circumferential width of the conductor groups **81** for one phase within a region of one pole.

Tenth Modification

The rotating electrical machine **10** may alternatively be designed to have an inner rotor structure (i.e., an inward rotating structure). In this case, the stator **50** may be mounted, for example, on a radial outside within the housing **30**, while the rotor **40** may be disposed on a radial inside within the housing **30**. The inverter unit **60** may be mounted one or both axial sides of the stator **50** or the rotor **40**. FIG. **35** is a transverse sectional view of the rotor **40** and the stator **50**. FIG. **36** is an enlarged view which partially illustrates the rotor **40** and the stator **50** in FIG. **35**.

The inner rotor structure in FIGS. **35** and **36** is substantially identical with the outer rotor structure in FIGS. **8** and **9** except for the layout of the rotor **40** and the stator **50** in the radial direction. In brief, the stator **50** is equipped with the stator winding **51** having the flattened conductor structure and the stator core **52** with no teeth. The stator winding **51** is installed radially inside the stator core **52**. The stator core **52**, like the outer rotor structure, has any of the following structures.

(A) The stator **50** has the inter-conductor members each of which is disposed between the conductor portions in the circumferential direction. As the inter-conductor members, magnetic material is used which meets a relation of $Wt \times Bs \leq Wm \times Br$ where Wt is a width of the inter-conductor members in the circumferential direction within one magnetic pole, Bs is the saturation magnetic flux density of the inter-conductor members, Wm is a width of the magnet unit equivalent to one magnetic pole in the circumferential direction, and Br is the remanent flux density in the magnet unit.

(B) The stator **50** has the inter-conductor members each of which is disposed between the conductor portions in the circumferential direction. The inter-conductor members are each made of a non-magnetic material.

(C) The stator **50** has no inter-conductor member disposed between the conductor portions in the circumferential direction.

The same is true of the magnets **91** and **92** of the magnet unit **42**. Specifically, the magnet unit **42** is made up of the magnets **91** and **92** each of which is magnetically oriented to have the easy axis of magnetization which is directed near the d-axis to be more parallel to the d-axis than that near the q-axis which is defined on the boundary of the magnetic poles. The details of the magnetization direction in each of the magnets **91** and **92** are the same as described above. The magnet unit **42** may be the annular magnet **95** (see FIG. **30**).

FIG. **37** is a longitudinal sectional view of the rotating electrical machine **10** designed to have the inner rotor structure. FIG. **37** corresponds to FIG. **2**. Differences from the structure in FIG. **2** will be described below in brief. In FIG. **37**, the annular stator **50** is retained inside the housing **30**. The rotor **40** is disposed inside the stator **50** with an air gap therebetween to be rotatable. The bearings **21** and **22** are, like in FIG. **2**, offset from the axial center of the rotor **40** in the axial direction of the rotor **40**, so that the rotor **40** is retained in the cantilever form. The inverter **60** is mounted inside the magnet holder **41** of the rotor **40**.

FIG. **38** illustrates the inner rotor structure of the rotating electrical machine **10** which is different from that described above. The housing **30** has the rotating shaft **11** retained by the bearings **21** and **22** to be rotatable. The rotor **40** is secured to the rotating shaft **11**. Like the structure in FIG. **2**, each of the bearings **21** and **22** is offset from the axial center of the rotor **40** in the axial direction of the rotor **40**. The rotor **40** is equipped with the magnet holder **41** and the magnet unit **42**.

The rotating electrical machine **10** in FIG. **38** is different from that in FIG. **37** in that the inverter unit **60** is not located radially inside the rotor **40**. The magnet holder **41** is joined to the rotating shaft **11** radially inside the magnet unit **42**.

The stator **50** is equipped with the stator winding **51** and the stator core **52** and secured to the housing **30**.

Eleventh Modification

The inner rotor structure of a rotating electrical machine which is different from that described above will be discussed below. FIG. **39** is an exploded view of the rotating electrical machine **200**. FIG. **40** is a sectional side view of the rotating electrical machine **200**. In the following discussion, a vertical direction is based on the orientation of the rotating electrical machine **200**.

The rotating electrical machine **200**, as illustrated in FIGS. **39** and **40**, includes the stator **203** and the rotor **204**. The stator **203** is equipped with the annular stator core **201** and the multi-phase stator winding **202**. The rotor **204** is disposed inside the stator core **201** to be rotatable. The stator **203** works as an armature. The rotor **204** works as a field magnet. The stator core **201** is made of a stack of silicone steel plates. The stator winding **202** is installed in the stator core **201**. Although not illustrated, the rotor **204** is equipped with a rotor core and a plurality of permanent magnet arranged in the form of a magnet unit. The rotor core has formed therein a plurality of holes which are arranged at equal intervals away from each other in the circumferential direction of the rotor core. The permanent magnets which are magnetized to have magnetization directions changed alternately in adjacent magnetic poles are disposed in the holes of the rotor core. The permanent magnets of the magnet unit may be designed, like in FIG. **23**, to have a Halbach array structure or a similar structure. The permanent magnets of the magnet unit may alternatively be made of anisotropic magnets, as described with reference to FIG. **9** or **30**, in which the magnetic orientation (i.e., the magnetization direction) extends in an arc-shape between the d-axis which is defined on the magnetic center and the q-axis which is defined on the boundary of the magnetic poles.

The stator **203** may be made to have one of the following structures.

(A) The stator **203** has the inter-conductor members each of which is disposed between the conductor portions in the circumferential direction. As the inter-conductor members, magnetic material is used which meets a relation of $Wt \times Bs \leq Wm \times Br$ where Wt is a width of the inter-conductor members in the circumferential direction within one magnetic pole, Bs is the saturation magnetic flux density of the inter-conductor members, Wm is a width of the magnet unit equivalent to one magnetic pole in the circumferential direction, and Br is the remanent flux density in the magnet unit.

(B) The stator **203** has the inter-conductor members each of which is disposed between the conductor portions in the circumferential direction. The inter-conductor members are each made of a non-magnetic material.

(C) The stator **203** has no inter-conductor member disposed between the conductor portions in the circumferential direction.

The rotor **204** has the magnet unit which is made up of a plurality of magnets each of which is magnetically oriented to have the easy axis of magnetization which is directed near the d-axis to be more parallel to the d-axis than that near the q-axis which is defined on the boundary of the magnetic poles.

The annular inverter case **211** is disposed on one end side of an axis of the rotating electrical machine **200**. The inverter case **211** has a lower surface placed in contact with an upper surface of the stator core **201**. The inverter case **211** has disposed therein a plurality of power modules **212** constituting an inverter circuit, the smoothing capacitors **213** working to reduce a variation in voltage or current (i.e., a ripple) resulting from switching operations of semiconductor switches, the control board **214** equipped with a controller, the current sensor **215** working to measure a phase current, and the resolver stator **216** serving as a rotational speed sensor for the rotor **204**. The power modules **212** are equipped with IGBTs serving as semiconductor switches and diodes.

The inverter case **211** has the power connector **217** which is disposed on a circumferential edge thereof for connection with a dc circuit for a battery mounted in a vehicle. The inverter case **211** also has the signal connector **218** which is disposed on the circumferential edge thereof for achieving transmission of signals between the rotating electrical machine **200** and a controller installed in the vehicle. The inverter case **211** is covered with the top cover **219**. The dc power produced by the battery installed in the vehicle is inputted into the power connector **217**, converted by the switches of the power modules **212** to an alternating current, and then delivered to phase windings of the stator winding **202**.

The bearing unit **221** and the annular rear case **222** are disposed on the opposite end side of the axis of the stator core to the inverter case **211**. The bearing unit **221** retains a rotation axis of the rotor **204** to be rotatable. The rear case **222** has the bearing unit **221** disposed therein. The bearing unit **221** is equipped with, for example, two bearings and offset from the center of the length of the rotor **204** toward one of the ends of the length of the rotor **204**. The bearing unit **221** may alternatively be engineered to have a plurality of bearings disposed on both end sides of the stator core **201** opposed to each other in the axial direction, so that the bearings retain both the ends of the rotation shaft. The rear case **222** is fastened to a gear case or a transmission of the vehicle using bolts, thereby securing the rotating electrical machine **200** to the vehicle.

The inverter case **211** has formed therein the cooling flow path **211*a*** through which cooling medium flows. The cooling flow path **211*a*** is defined by closing an annular recess formed in a lower surface of the inverter case **211** by an upper surface of the stator core **201**. The cooling flow path **211*a*** surrounds a coil end of the stator winding **202**. The cooling flow path **211*a*** has the module cases **212*a*** of the power modules **212** disposed therein. Similarly, the rear case **222** has formed therein the cooling flow path **222*a*** which surrounds a coil end of the stator winding **202**. The cooling flow path **222*a*** is defined by closing an annular recess formed in an upper surface of the rear case **222** by a lower surface of the stator core **201**. Note that the definitions of parameters, such as Wt, Wn, Wm, and Bs, associated with the stator **50** or parameters, such as θ**11**, θ**12**, X**1**, X**2**, Wm, and Br, associated with the magnet unit **42** may refer to those in the above described first embodiment or the first modification.

Twelfth Modification

The above discussion has referred to the revolving-field type of rotating electrical machines, but a revolving armature type of rotating electrical machine may be embodied. FIG. **41** illustrates the revolving armature type of rotating electrical machine **230**.

The rotating electrical machine **230** in FIG. **41** has the bearing **232** retained by the housings **231*a*** and **231*b***. The bearing **232** retains the rotating shaft **233** to be rotatable. The bearing **232** is made of, for example, an oil-impregnated bearing in which a porous metal is impregnated with oil. The rotating shaft **233** has secured thereto the rotor **234** which works as an armature. The rotor **234** includes the rotor core

235 and the multi-phase rotor winding 236 secured to an outer periphery of the rotor core 235. The rotor core 235 of the rotor 234 is designed to have the slot-less structure. The multi-phase rotor winding 236 has the flattened conductor structure as described above. In other words, the multi-phase rotor winding 236 is shaped to have an area for each phase which has a dimension in the circumferential direction which is larger than that in the radial direction.

The stator 237 is disposed radially outside the rotor 234. The stator 237 works as a field magnet. The stator 237 includes the stator core 238 and the magnet unit 239. The stator core 238 is secured to the housing 231*a*. The magnet unit 239 is attached to an inner periphery of the stator core 238. The magnet unit 239 is made up of a plurality of magnets arranged to have magnetic poles alternately arrayed in the circumferential direction. Like the magnet unit 42 Described above, the magnet unit 239 is magnetically oriented to have the easy axis of magnetization which is directed near the d-axis to be more parallel to the d-axis than that near the q-axis that is defined on a boundary between the magnetic poles. The magnet unit 239 is equipped with magnetically oriented sintered neodymium magnets whose intrinsic coercive force is 400 [kA/m] or more and whose remanent flux density is 1.0 [T] or more.

The rotating electrical machine 230 in this embodiment is engineered as a two-pole three-coil brush coreless motor. The multi-phase rotor winding 236 is made of three coils. The magnet unit 239 is designed to have two poles. A ratio of the number of poles and the number of coils in typical brush motors is 2:3, 4:10, or 4:21 depending upon intended use.

The rotating shaft 233 has the commutator 241 secured thereto. A plurality of brushes 242 are arranged radially outside the commutator 241. The commutator 241 is electrically connected to the multi-phase rotor winding 236 through the conductors 234 embedded in the rotating shaft 233. The commutator 241, the brushes 242, and the conductors 243 are used to deliver dc current to the multi-phase rotor winding 236. The commutator 241 is made up of a plurality of sections arrayed in a circumferential direction thereof depending upon the number of phases of the multi-phase rotor winding 236. The brushes 242 may be connected to a dc power supply, such as a storage battery, using electrical wires or using a terminal block.

The rotating shaft 233 has the resinous washer 244 disposed between the bearing 232 and the commutator 241. The resinous washer 244 serves as a sealing member to minimize leakage of oil seeping out of the bearing 232, implemented by an oil-impregnated bearing, to the commutator 241.

Thirteenth Modification

Each of the conductors 82 of the stator winding 51 of the rotating electrical machine 10 may be designed to have a stack of a plurality of insulating coatings or layers laid on each other. For instance, each of the conductors 82 may be made by covering a bundle of a plurality of insulating layer-coated conductors (i.e., wires) with an insulating layer, so that the insulating layer (i.e., an inner insulating layer) of each of the conductors 82 is covered with the insulating layer (i.e., an outer insulating layer) of the bundle. The outer insulating layer is preferably designed to have an insulating ability greater than that of the inner insulating layer. Specifically, the thickness of the outer insulating layer is selected to be larger than that of the inner insulating layer. For instance, the outer insulating layer has a thickness of 100 μm, while the inner insulating layer has a thickness of 40 μm. Alternatively, the outer insulating layer may have a permittivity lower than that of the inner insulating layer. Each of the conductors 82 may have any of the above structure. Each wire is preferably made of a collection of conductive members or fibers.

As apparent from the above discussion, the rotating electrical machine 10 becomes useful in a high-voltage system of a vehicle by increasing the insulation ability of the outermost layer of the conductor 82. The above structure enables the rotating electrical machine 10 to be driven in low pressure conditions such as high-altitude areas.

Fourteenth Modification

Each of the conductors 82 equipped with a stack of a plurality of insulating layers may be designed to have at least one of a linear expansion coefficient and the degree of adhesion strength different between an outer one and an inner one of the insulating layers. The conductors 82 in this modification are illustrated in FIG. 42.

In FIG. 42, the conductor 82 includes a plurality of (four in the drawing) wires 181, the outer coated layer 182 (i.e., an outer insulating layer) with which the wires 181 are covered and which is made of, for example, resin, and the intermediate layer 183 (i.e., an intermediate insulating layer) which is disposed around each of the wires 181 within the outer coated layer 182. Each of the wires 181 includes the conductive portion 181*a* made of copper material and the conductor-coating layer (i.e., an inner insulating layer) made of electrical insulating material. The outer coated layer 182 serves to electrically insulate between phase-windings of the stator winding. Each of the wires 181 is preferably made of a collection of conductive members or fibers.

The intermediate layer 183 has a linear expansion coefficient higher than that of the coated layer 181*b*, but lower than that of the outer coated layer 182. In other words, the linear expansion coefficient of the conductor 82 is increased from an inner side to an outer side thereof. Typically, the outer coated layer 182 is designed to have a linear expansion coefficient higher than that of the coated layer 181*b*. The intermediate layer 183, as described above, has a linear expansion coefficient intermediate between those of the coated layer 181*b* and the outer coated layer 182 and thus serves as a cushion to eliminate a risk that the inner and outer layers may be simultaneously broken.

Each of the wires 181 of the conductor 82 has the conductive portion 181*a* and the coated layer 181*b* adhered to the conductive portion 181*a*. The coated layer 181*b* and the intermediate layer 183 are also adhered together. The intermediate layer 183 and the outer coated layer 182 are adhered together. Such joints have a strength of adhesion decreasing toward an outer side of the conductor 82. In other words, the strength of adhesion between the conductive portion 181*a* and the coated layer 181*b* is lower than that between the coated layer 181*b* and the intermediate layer 183 and between the intermediate layer 183 and the outer coated layers 182. The strength of adhesion between the coated layer 181*b* and the intermediate layer 183 may be higher than or identical with that between the intermediate layer 183 and the outer coated layers 182. Usually, the strength of adhesion between, for example, two coated layers may be measured as a function of a tensile strength required to peel the coated layers away from each other. The strength of adhesion of the conductor 82 is selected in the above way to minimize the risk that the inner and outer layers may be broken together arising from a temperature difference between inside and outside the conductor 82 when heated or cooled.

Usually, the heat generation or temperature change in the rotating electrical machine results in copper losses arising from heat from the conductive portion **181***a* of the wire **181** and from an iron core. These two types of loss result from the heat transmitted from the conductive portion **181***a* in the conductor **82** or from outside the conductor **82**. The intermediate layer **183** does not have a heat source. The intermediate layer **183** has the strength of adhesion serving as a cushion for the coated layer **181***b* and the outer coated layer **182**, thereby eliminating the risk that the coated layer **181***b* and the outer coated layer **182** may be simultaneously broken. This enables the rotating electrical machine to be used in conditions, such as in vehicles, wherein a resistance to high pressure is required, or the temperature greatly changes.

In addition, the wire **181** may be made of enamel wire with a layer (i.e., the coated layer **181***b*) coated with resin, such as PA, PI or PAI. Similarly, the outer coated layer **182** outside the wire **181** is preferably made of PA, PI, and PAI and has a large thickness. This minimizes a risk of breakage of the outer coated layer **182** caused by a difference in linear expansion coefficient. Instead of use of PA, PI, PAI to make the outer coated layer **182** having a large thickness, material, such as PPS, PEEK, fluororesin, polycarbonate, silicone, epoxy, polyethylene naphthalate, or LCP which has a dielectric permittivity lower than that of PI or PAI is preferably used to increase the conductor density of the rotating electrical machine. The use of such resin enhances the insulating ability of the outer coated layer **182** even when it has a thickness smaller than or equal to that of the coated layer **181***b* and increases the occupancy of the conductive portion. Usually, the above resin has the degree of electric permittivity higher than that of an insulating layer of enamel wire. Of course, there is an example where the state of formation or additive results in a decrease in electric permittivity thereof. Usually, PPS and PEEK is higher in linear expansion coefficient than an enamel-coated layer, but lower than another type of resin and thus is useful only for the outer of the two layers.

The strength of adhesion of the two types of coated layers arranged outside the wire **181** (i.e., the intermediate insulating layer and the outer insulating layer) to the enamel coated layer of the wire **181** is preferably lower than that between the copper wire and the enamel coated layer of the wire **181**, thereby minimizing a risk that the enamel coated layer and the above two types of coated layers are simultaneously broken.

In a case where the stator is equipped with a water cooling mechanism, a liquid cooling mechanism, or an air cooling mechanism, thermal stress or impact stress is thought of as being exerted first on the outer coated layers **182**. The thermal stress or the impact stress is decreased by partially bonding the insulating layer of the wire **181** and the above two types of coated layers together even if the insulation layer is made of resin different from those of the above two types of coated layers. In other words, the above described insulating structure may be created by placing a wire (i.e., an enamel wire) and an air gap and also arranging a fluororesin, polycarbonate, silicone, epoxy, polyethylene naphthalate, or LCP. In this case, adhesive which is made from epoxy, low in electric permittivity, and also low in linear expansion coefficient is preferably used to bond the outer coated layer and the inner coated layer together. This eliminates breakage of the coated layers caused by friction arising from vibration of the conductive portion or breakage of the outer coated layer due to the difference in linear expansion coefficient as well as the mechanical strength.

The outermost layer which serves to ensure the mechanical strength or securement of the conductor **82** having the above structure is preferably made from resin material, such as epoxy, PPS, PEEK, or LCP which is easy to shape and similar in dielectric constant or linear expansion coefficient to the enamel coated layer, typically in a final process for a stator winding.

Typically, the resin potting is made using urethane or silicone. Such resin, however, has a linear expansion coefficient approximately twice that of other types of resin, thus leading to a risk that thermal stress is generated when the resin is subjected to the resin potting, so that it is sheared. The above resin is, therefore, unsuitable for use where requirements for insulation are severe and 60V or more. The final insulation process to make the outermost layer using injection moulding techniques with epoxy, PPS, PEEK, or LCP satisfies the above requirements.

Other modifications will be listed below.

The distance DM between a surface of the magnet unit **42** which faces the armature and the axial center of the rotor in the radial direction may be selected to be 50 mm or more. For instance, the distance DM, as illustrated in FIG. **4**, between the radial inner surface of the magnet unit **42** (i.e., the first and second magnets **91** and **92**) and the center of the axis of the rotor **40** may be selected to be 50 mm or more.

The small-sized slot-less structure of the rotating electrical machine whose output is several tens or hundreds watt is known which is used for models. The inventors of this application have not seen examples where the slot-less structure is used with large-sized industrial rotating electrical machines whose output is more than 10 kW. The inventors have studied the reason for this.

Modern major rotating electrical machines are categorized into four main types: a brush motor, a squirrel-cage induction motor, a permanent magnet synchronous motor, and a reluctance motor.

Brush motors are supplied with exciting current using brushes. Large-sized brush motors, therefore, have an increased size of brushes, thereby resulting in complex maintenance thereof. With the remarkable development of semiconductor technology, brushless motors, such as induction motors, have been used instead. In the field of small-sized motors, a large number of coreless motors have also come on the market in terms of low inertia or economic efficiency.

Squirrel-cage induction motors operate on the principle that a magnetic field produced by a primary stator winding is received by a secondary stator core to deliver induced current to bracket-type conductors, thereby creating magnetic reaction field to generate torque. In terms of small-size and high-efficiency of the motors, it is inadvisable that the stator and the rotor be designed not to have iron cores.

Reluctance motors are motors designed to use a change in reluctance in an iron core. It is, thus, inadvisable in principle that the iron core be omitted.

In recent years, permanent magnet synchronous motors have used an IPM (Interior Permanent Magnet) rotor. Especially, most large-sized motors use an IPM rotor unless there are special circumstances.

IPM motors has properties of producing both magnet torque and reluctance torque. The ratio between the magnet torque and the reluctance torque is timely controlled using an inverter. For these reasons, the IMP motors are thought of as being compact and excellent in ability to be controlled.

According to analysis by the inventors, torque on the surface of a rotor producing the magnet torque and the reluctance torque is expressed in FIG. **43** as a function of the distance DM between the surface of the magnet unit which faces the armature and the center of the axis of the rotor, that is, the radius of a stator core of a typical inner rotor indicated on the horizontal axis.

The potential of the magnet torque, as can be seen in the following equation (eq1), depends upon the strength of magnetic field created by a permanent magnet, while the potential of the reluctance torque, as can be seen in the following equation (eq2), depends upon the degree of inductance, especially, on the q-axis.

$$\text{The magnet torque} = k \cdot \Psi \cdot Iq \quad \text{(eq1)}$$

$$\text{The reluctance torque} = k \cdot (Lq - Ld) \cdot Iq \cdot Id \quad \text{(eq2)}$$

Comparison between the strength of magnetic field produced by the permanent magnet and the degree of inductance of a winding using the distance DM shows that the strength of magnetic field created by the permanent magnet, that is, the amount of magnetic flux Ψ is proportional to a total area of a surface of the permanent magnet which faces the stator. In case of a cylindrical stator, such a total area is a cylindrical surface area of the permanent magnet. Technically speaking, the permanent magnet has an N-pole and an S-pole, and the amount of magnetic flux Ψ is proportional to half the cylindrical surface area. The cylindrical surface area is proportional to the radius of the cylindrical surface and the length of the cylindrical surface. When the length of the cylindrical surface is constant, the cylindrical surface area is proportional to the radius of the cylindrical surface.

The inductance Lq of the winding depends upon the shape of the iron core, but its sensitivity is low and rather proportional to the square of the number of turns of the stator winding, so that it is strongly dependent upon the number of the turns. The inductance L is expressed by a relation of $L=\mu \cdot N\hat{}2 \times S/\delta$ where μ is permeability of a magnetic circuit, Nis the number of turns, S is a sectional area of the magnetic circuit, and δ is an effective length of the magnetic circuit. The number of turns of the winding depends upon the size of space occupied by the winding. In the case of a cylindrical motor, the number of turns, therefore, depends upon the size of space occupied by the winding of the stator, in other words, areas of slots in the stator. The slot is, as demonstrated in FIG. **44**, rectangular, so that the area of the slot is proportional to the product of a and b where a is the width of the slot in the circumferential direction, and b is the length of the slot in the radial direction.

The width of the slot in the circumferential direction becomes large with an increase in diameter of the cylinder, so that the width is proportional to the diameter of the cylinder. The length of the slot in the radial direction is proportional to the diameter of the cylinder. The area of the slot is, therefore, proportional to the square of the diameter of the cylinder. It is apparent from the above equation (eq2) that the reluctance torque is proportional to the square of current in the stator. The performance of the rotating electrical machine, therefore, depends upon how much current is enabled to flow in the rotating electrical machine, that is, depends upon the areas of the slots in the stator. The reluctance is, therefore, proportional to the square of the diameter of the cylinder for a cylinder of constant length. Based on this fact, a relation of the magnetic torque and the reluctance torque with the distance DM is shown by plots in FIG. **43**.

The magnet torque is, as shown in FIG. **43**, increased linearly as a function of the distance DM, while the reluctance torque is increased in the form of a quadratic function as a function of the distance DM. FIG. **43** shows that when the distance DM is small, the magnetic torque is dominant, while the reluctance torque becomes dominant with an increase in diameter of the stator core. The inventors of this application have arrived at the conclusion that an intersection of lines expressing the magnetic torque and the reluctance torque in FIG. **43** lies near 50 mm that is the radius of the stator core. It seems that it is difficult for a motor whose output is 10 kW and whose stator core has a radius much larger than 50 mm to omit the stator core because the use of the reluctance torque is now mainstream. This is one of reasons why the slot-less structure is not used in large-sized motors.

The rotating electrical machine using an iron core in the stator always faces a problem associated with magnetic saturation of the iron core. Particularly, radial gap type rotating electrical machines have a longitudinal section of the rotating shaft which is of a fan shape for each magnetic pole, so that the further inside the rotating electrical machine, the smaller the width of a magnetic circuit, so that inner dimensions of teeth forming slots in the core become a factor of the limit of performance of the rotating electrical machine. Even if a high performance permanent magnet is used, generation of magnetic saturation in the permanent magnet will lead to a difficulty in producing a required degree of performance of the permanent magnet. It is necessary to design the permanent magnet to have an increased inner diameter in order to eliminate a risk of occurrence of the magnetic saturation, which results in an increase size of the rotating electrical machine.

For instance, a typical rotating electrical machine with a distributed three-phase winding is designed so that three to six teeth serve to produce a flow of magnetic flux for each magnetic pole, but encounters a risk that the magnetic flux may concentrate on a leading one of the teeth in the circumferential direction, thereby causing the magnetic flux not to flow uniformly in the three to six teeth. For instance, the flow of magnetic flux concentrates on one or two of the teeth, so that the one or two of the teeth in which the magnetic saturation is occurring will move in the circumferential direction with rotation of the rotor, which may lead to a factor causing slot ripple.

For the above reasons, it is required to omit the teeth in the slot-less structure of the rotating electrical machine whose distance DM is 50 mm or more to eliminate the risk of generation of the magnetic saturation. The omission of the teeth, however, results in an increase in magnetic resistance in magnetic circuits of the rotor and the stator, thereby decreasing torque produced by the rotating electrical machine. The reason for such an increase in magnetic resistance is that there is, for example, a large air gap between the rotor and the stator. The slot-less structure of the rotating electrical machine whose distance DM is 50 mm or more, therefore, has room for improvement for increasing the output torque. There are numerous beneficial advantages to use the above torque-increasing structure in the slot-less structure of rotating electrical machines whose distance DM is 50 mm or more.

Not only the outer rotor type rotating electrical machines, but also the inner rotor type rotating electrical machines are preferably designed to have the distance DM of 50 mm or more between the surface of the magnet unit which faces the armature and the center of the axis of the rotor in the radial direction.

The stator winding **51** of the rotating electrical machine **10** may be designed to have only the single straight section **83** of the conductor **82** arranged in the radial direction. Alternatively, a plurality of straight sections **83**, for example, three, four, five, or six straight sections **83** may be stacked on each other in the radial direction.

For example, the structure illustrated in FIG. **2** has the rotating shaft **11** extending outside the ends of length of the rotating electrical machine **10**, but however, may alternatively be designed to have the rotating shaft **11** protruding outside only one of the ends of the rotating electrical machine **10**. In this case, it is advisable that a portion of the rotating shaft **11** which is retained by the bearing unit **20** in the cantilever form be located on one of the ends of the rotating electrical machine, and that the rotating shaft **11** protrude outside such an end of the rotating electrical machine. This structure has the rotating shaft **11** not protruding inside the inverter unit **60**, thus enabling a wide inner space of the inverter unit **60**, i.e., the cylinder **71** to be used.

The above structure of the rotating electrical machine **10** uses non-conductive grease in the bearings **21** and **22**, but however, may alternatively be designed to have conductive grease in the bearings **21** and **22**. For instance, conductive grease containing metallic particles or carbon particles may be used.

A bearing or bearings may be mounted on only one or both axial ends of the rotor **40** for retaining the rotating shaft **11** to be rotatable. For example, the structure of FIG. **1** may have a bearing or bearings mounted on only one side or opposite sides of the inverter unit **60** in the axial direction.

The magnet holder **41** of the rotor **40** of the rotating electrical machine **10** has the intermediate portion **45** equipped with the inner shoulder **49***a* and the annular outer shoulder **49***b*, however, the magnet holder **41** may alternatively be designed to have the flat intermediate portion **45** without the shoulders **49***a* and **49***b*.

The conductor body **82***a* of each of the conductors **82** of the stator winding **51** of the rotating electrical machine **10** is made of a collection of the wires **86**, however, may alternatively be formed using a square conductor having a rectangular cross section. The conductor **82** may alternatively be made using a circular conductor having a circular cross section or an oval cross section.

The rotating electrical machine **10** has the inverter unit **60** arranged radially inside the stator **50**, but however, may alternatively be designed not to have the inverter **60** disposed inside the stator **50**. This enables the stator **50** to have a radial inner void space in which parts other than the inverter unit **60** may be mounted.

The rotating electrical machine **10** may be designed not to have the housing **30**. In this case, the rotor **40** or the stator **50** may be retained by a wheel or another part of a vehicle.

In-Wheel Motor for Vehicle

Embodiments in which a rotating electrical machine is incorporated into a hub of a wheel of a vehicle, such as, an automotive vehicle in the form of an in-wheel motor will be described below. FIG. **45** is a perspective view which illustrates the tire wheel assembly **400** engineered to have an in-wheel motor structure and a surrounding structure. FIG. **46** is a longitudinal sectional view which illustrates the tire wheel assembly **400** and the surrounding structure. FIG. **47** is a perspective exploded view of the tire wheel assembly **400**. These views are perspective illustrations of the tire wheel assembly **400**, as viewed from inside the vehicle. The vehicle may use the in-wheel motor structure in different modes. For instance, in a case where the vehicle is equipped with four wheels: two front wheel and two rear wheels, either or both of the front wheels and the rear wheel may be engineered to have the in-wheel motor structure in this embodiment. Alternatively, the in-wheel motor structure may also be used with a vehicle equipped with a front or a rear single wheel. The wheel motor, as referred to herein, is designed as a vehicle power unit.

The tire wheel assembly **400**, as illustrated in FIGS. **45** to **47**, includes the tire **401** that is a known air inflated tire, the wheel **402** fit in the tire **401**, and the rotating electrical machine **500** secured inside the wheel **402**. The rotating electrical machine **500** is equipped with a stationary portion including a stator and a rotating portion including a rotor. The rotating electrical machine **500** is firmly attached at the stationary portion to the vehicle body and also attached at the rotating portion to the wheel **402**. The tire **401** and the wheel **402** are rotated with rotation of the rotating portion of the rotating electrical machine **500**. The structure of the rotating electrical machine **500** including the stationary portion and the rotating portion will be described later in detail.

The tire wheel assembly **400** also has peripheral devices: a suspension, a steering device, and a brake device mounted thereon. The suspension retains the tire wheel assembly **400** secured to a vehicle body, not shown. The steering device works to turn the tire wheel assembly **400**. The brake device works to apply a brake to the tire wheel assembly **400**.

The suspension is implemented by an independent suspension, such as trailing arm suspension, a strut-type suspension, a wishbone suspension, or a multi-link suspension. In this embodiment, the suspension includes the lower arm **411**, the suspension arm **412**, and the spring **413**. The lower arm **411** extends toward the center of the vehicle body. The suspension arm **412** and the spring **413** extend vertically. The suspension arm **412** may be engineered as a shock absorber whose detailed structure will be omitted in the drawings. The lower arm **411** and the suspension arm **412** are joined to the vehicle body and also joined to the disc-shaped base plate **405** secured to the stationary portion of the rotating electrical machine **500**. The lower arm **411** and the suspension arm **412** are, as clearly illustrated in FIG. **46**, retained coaxially with each other by the rotating electrical machine **500** (i.e., the base plate **405**) using the support shafts **414** and **415**.

The steering device may be implemented by a rack-and-pinion, a ball-and-nut steering system, a hydraulic power steering system, or an electronic power steering system. In this embodiment, the steering device is made up of the rack unit **421** and the tie rod **422**. The rack unit **421** is connected to the base plate **405** of the rotating electrical machine **500** through the tie rod **422**. Rotation of a steering shaft, not shown, will cause the rack unit **421** to be driven, thereby moving the tie rod **422** in a lateral direction of the vehicle. This causes the tire wheel assembly **400** to be turned around the lower arm **411** and the support shafts **414** and **415** of the suspension arm **412**, thereby changing the orientation of the tire wheel assembly **400**.

The brake device may preferably be made of a disc brake or a drum brake. In this embodiment, the brake device includes the disc rotor **431** and the brake caliper **432**. The disc rotor **431** is secured to the rotating shaft **501** of the rotating electrical machine **500**. The brake caliper **432** is secured to the base plate **405** of the rotating electrical machine **500**. The brake caliper **432** has a brake pad which is hydraulically actuated and pressed against the disc rotor **431** to create a brake in the form of mechanical friction, thereby stopping rotation of the tire wheel assembly **400**.

The tire wheel assembly **400** also has mounted thereon the storage duct **440** in which the electrical cable H1 and the cooling pipe H2 extending from the rotating electrical machine **500** are disposed. The storage duct **440** extends from an end of the stationary portion of the rotating electrical machine **500** parallel to an end surface of the rotating electrical machine **500** without physical interference with the suspension arm **412** and is firmly joined to the suspension arm **412**, thereby fixing a location of the joint of the storage duct **440** to the suspension arm **412** relative to the base plate **405**. This minimizes mechanical stress which arises from vibration of the vehicle and acts on the electrical cable H**1** and the cooling pipe H**2**. The electrical cable H**1** is electrically connected to a power supply, not shown, and an ECU, not shown, which are mounted in the vehicle. The cooling pipe H**2** is connected to a radiator, not shown.

The structure of the rotating electrical machine **500** will be described below in detail. This embodiment will refer to an example where the rotating electrical machine **500** is designed as the in-wheel motor. The rotating electrical machine **500** is excellent in operation efficiency and output performance as compared with a conventional electrical motor of a power unit equipped with a speed reducer for use in vehicles. The rotating electrical machine **500** may alternatively be employed as an electrical motor in another application other than the power unit for vehicles if it may be produced at low cost. In such a case, the rotating electrical machine **500** ensures high performance. The operation efficiency, as referred to herein, represents an indication used in fuel economy tests in which automobiles are operated in given driving modes.

The outline of the rotating electrical machine **500** is shown in FIGS. **48** to **51**. FIG. **48** is a side elevation of the rotating electrical machine **500**, as viewed in an axial direction of the rotating shaft **501** (i.e., from inside the vehicle). FIG. **49** is a longitudinal sectional view of the rotating electrical machine **500**, as taken along the line **49-49** in FIG. **48**. FIG. **50** is a transverse sectional view of the rotating electrical machine **500**, as taken along the line **50-50** in FIG. **49**. FIG. **51** is an exploded sectional view of the rotating electrical machine **500**. In the following discussion, a direction in which the rotating shaft **501** extends outside the vehicle body will be referred to as an axial direction, and a direction perpendicular to the length of the rotating shaft **501** will be referred to as a radial direction in FIG. **51**. In FIG. **48**, opposite directions extending in a circular form from a point on a center line which passes through the center of the rotating shaft **501**, in other words, the center of rotation of the rotating portion of the rotating electrical machine **500** and defines the cross section **49** of the rotating electrical machine **500** will be referred to as a circumferential direction. In other words, the circumferential direction is either a clockwise direction or a counterclockwise direction from a point on the cross section **49**. In FIG. **49**, the right side is an outer side of the vehicle, while the left side is an inner side of the vehicle. In other words, when the rotating electrical machine **500** is mounted in the vehicle, the rotor **510** which will be described later in detail is disposed closer to the outer side of the vehicle body than the rotor cover **670** is.

The rotating electrical machine **500** in this embodiment is designed as an outer-rotor surface-magnet rotating electrical machine. The rotating electrical machine **500** includes the rotor **510**, the stator **520**, the inverter unit **530**, the bearing **560**, and the rotor cover **670**. These parts are each arranged coaxially with the rotating shaft **501** provided integrally with the rotor **510** and assembled in a given order in the axial direction to complete the rotating electrical machine **500**.

In the rotating electrical machine **500**, the rotor **510** and the stator **520** are hollow cylindrical and face each other through an air gap. Rotation of the rotating shaft **501** causes the rotor **510** to rotate radially outside the stator **520**. The rotor **510** works as a field generator. The stator **520** works as an armature.

The rotor **510** includes the hollow cylindrical rotor carrier **511** and the annular magnet unit **512** secured to the rotor carrier **511**. The rotating shaft **501** is firmly joined to the rotor carrier **511**.

The rotor carrier **511** includes the cylindrical portion **513**. The magnet unit **512** is firmly attached to an inner circumferential surface of the cylindrical portion **513**. In other words, the magnet unit **512** is surrounded by the cylindrical portion **513** of the rotor carrier **511** from radially outside it. The cylindrical portion **513** has a first end and a second end which are opposed to each other in the axial direction. The first end faces the outside of the vehicle body. The second end faces the base plate **405**. In the rotor carrier **511**, the end plate **514** continues to the first end of the cylindrical portion **513**. In other words, the cylindrical portion **513** and the end plate **514** are formed or joined integrally with each other. The cylindrical portion **513** has an opening in the second end. The rotor carrier **511** may be made by a cold rolled steel plate having a high mechanical strength. For example, the rotor carrier **511** is made of SPCC (steel plate cold commercial) or SPHC (steel plate hot commercial) which has a thickness larger than SPCC. The rotor carrier **511** may alternatively be made of forging steel or carbon fiber reinforced plastic (CFRP).

The length of the rotating shaft **501** is larger than a dimension of the rotor carrier **511** in the axial direction. In other words, the rotating shaft **501** protrudes from the open end of the rotor carrier **511** inwardly in the vehicle to have an end on which the brake device is mounted.

The end plate **514** of the rotor carrier **511** has the center hole **514*a*** passing through a thickness thereof. The rotating shaft **501** passes through the hole **514*a*** of the end plate **514** and is retained by the rotor carrier **511**. The rotating shaft **501** has the flange **502** extending from a joint of the rotor carrier **511** to the rotating shaft **501** in a direction traversing or perpendicular to the length of the rotating shaft **501**. The flange **502** has a surface joined to an outer surface of the end plate **514** which faces outside the vehicle, so that the rotating shaft **501** is secured to the rotor carrier **511**. In the tire wheel assembly **400**, the wheel **402** is joined to the rotating shaft **501** using fasteners, such as bolts, extending from the flange **502** outwardly in the vehicle.

The magnet unit **512** is made up of a plurality of permanent magnets which arranged adjacent each other and whose magnetic polarities are disposed alternately in a circumferential direction of the rotor **510**. The magnet unit **512**, thus, has a plurality of magnetic poles arranged in the circumferential direction. The permanent magnets are secured to the rotor carrier **511** using, for example, adhesive. The magnet unit **512** has the same structure as that of the magnet unit **42** Discussed with reference to FIGS. **8** and **9** and is made of sintered neodymium magnets whose intrinsic coercive force is 400 [kA/m] or more and whose remanent flux density is 1.0 [T] or more.

The magnet unit **512** is, like the magnet unit **42** in FIG. **9**, made of polar anisotropic magnets and includes the first magnets **91** and the second magnets **92** which are different in magnetic polarity from each other. As already described with reference to FIGS. **8** and **9**, each of the magnets **91** and **92**, as can be seen in FIG. **9**, includes the first portion **250** and the two second portions **260** arranged on opposite sides of the first portion **250** in the circumferential direction of the magnet unit **512**. In other words, the first portion **250** is located closer to the d-axis than the second portions **260** are.

The second portions **260** are arranged closer to the q-axis than the first portion **250** is. The direction in which the easy axis of magnetization **300** extends in the first portion **250** is oriented more parallel to the d-axis than the direction in which the easy axis of magnetization **310** extends in the second portions **260**. In other words, the magnet unit **512** is engineered so that an angle θ**11** which the easy axis of magnetization **300** in the first portion **250** makes with the d-axis is selected to be smaller than an angle θ**12** which the easy axis of magnetization **310** in the second portion **260** makes with the q-axis. Annular magnetic paths are, therefore, created according to the directions of easy axes of magnetization. In each of the magnets **91** and **92**, the easy axis of magnetization in a region close to the d-axis may be oriented parallel to the d-axis, while the easy axis of magnetization in a region close to the q-axis may be oriented perpendicular to the q-axis. In brief, the magnet unit **512** is magnetically oriented to have the easy axis of magnetization in the region close to the d-axis (i.e., the center of the magnetic pole) which is oriented more parallel to the d-axis than in the region close to the q-axis (i.e., the boundary between the magnetic poles).

Accordingly, the above described structure of each of the magnets **91** and **92** functions to enhance the magnet magnetic flux thereof on the d-axis and reduce a change in magnetic flux near the q-axis. This enables the magnets **91** and **92** to be produced which have a smooth change in surface magnetic flux from the q-axis to the d-axis on each magnetic pole. The magnet unit **512** may be designed to have the same structure as that of the magnet unit **42** illustrated in FIGS. **22** and **23** or illustrated in FIG. **30**.

The magnet unit **512** may be equipped with a rotor core (i.e., a back yoke) which is made of a plurality of magnetic steel plates stacked in the axial direction and arranged close to the cylindrical portion **513** of the rotor carrier **511**, i.e., near the outer circumference thereof. In other words, the rotor core may be disposed radially inside the cylindrical portion **513** of the rotor carrier **511**, and the permanent magnets (i.e., the magnets **91** and **92**) may be arranged radially inside the rotor core.

Referring back to FIG. **47**, the cylindrical portion **513** of the rotor carrier **511** has formed therein the recesses **513***a* which are arranged at a given interval away from each other in the circumferential direction of the cylindrical portion **513** and extend in the axial direction of the cylindrical portion **513**. The recesses **513***a* are made, for example, using a stamp or a press. The cylindrical portion **513**, as can be seen in FIG. **52**, has convexities or protrusions **513***b* each of which is formed on an inner circumference thereof in alignment with a respective one of the recesses **513** in the radial direction of the cylindrical portion **513**. The magnet unit **512** has formed in the outer circumference thereof the recesses **512***a* each of which is fit on a respective one of the protrusions **513***b* of the cylindrical portion **513**. In other words, the protrusions **513***b* of the cylindrical portion **513** are disposed in the recesses **512***a*, thereby holding the magnet unit **512** from moving in the circumferential direction of the rotor carrier **511**. The protrusions **513***b* of the rotor carrier **511**, thus, serve as stoppers to stop the magnet unit **512** from being rotated. The protrusions **513***b* may alternatively be formed in a known way other than the pressing techniques.

FIG. **52** demonstrates magnetic paths which are produced by the magnets of the magnet unit **512** and indicated by arrows. Each of the magnetic paths extends in an arc-shape and crosses the q-axis that is located at the boundary between the magnetic poles. Each of the magnetic paths is oriented parallel or nearly parallel to the d-axis in the region close to the d-axis. The magnet unit **512** has the recesses **512***b* which are formed in an inner circumferential surface thereof and located on the q-axis. The magnetic paths in the magnet unit **512** have lengths different between a region near the stator **520** (i.e., a lower side in the drawing) and a region far from the stator **520** (i.e., an upper side in the drawing). Specifically, the length of the magnetic path close to the stator **520** is shorter than that of the magnetic path far from the stator **520**. Each of the recesses **512***b* is located on the shortest length of the magnetic path. In other words, in view of an insufficient amount of magnetic flux around the shorter magnetic path, the magnet unit **512** is shaped to have removed portions in which the magnetic flux is weak.

Generally, the effective magnetic flux density Bd of a magnet becomes high with an increase in length of a magnetic circuit passing through the magnet. The permeance coefficient Pc and the effective magnetic flux density Bd of the magnet have a relationship in which when one of them becomes high, the other also becomes high. The structure illustrated in FIG. **52** enables the volume of the magnets to be reduced with a minimized risk of decrease in permeance coefficient Pc that is an indication of the degree of the effective magnetic flux density of the magnets. On the B-H coordinate system, an intersection of a permeance straight line and a demagnetization curve is an operating point according to the configuration of a magnet. The magnetic flux density on the operating point represents the effective magnetic flux density Bd. The rotating electrical machine **500** in this embodiment is engineered to have the stator **520** in which the amount of iron is decreased and highly effective in having the magnetic circuit crossing the q-axis.

The recesses **512***b* of the magnet unit **512** may be used as air paths extending in the axial direction, thereby enhancing the cooling ability of the rotating electrical machine **500**.

Next, the structure of the stator **520** will be described below. The stator **520** includes the stator winding **521** and the stator core **522**. FIG. **53** is an exploded view of the stator winding **521** and the stator core **522**.

The stator winding **521** is made up of a plurality of phase-windings which are of a hollow cylindrical shape. The stator core **522** serving as a base member is arranged radially inside the stator winding **521**. In this embodiment, the stator winding **521** includes three-phase windings: a U-phase winding, a V-phase winding, and a W-phase winding. Each of the U-phase winding, the V-phase winding, and the W-phase winding is made of two layers of the conductor **523**: an outer layer and an inner layer located radially inside the outer layer. The stator **520** is, like the above described stator **50**, designed to have a slot-less structure and the flattened stator winding **521**. The stator **520**, therefore, has substantially the same structure of the stator **50** illustrated in FIGS. **8** to **16**.

The structure of the stator core **522** will be described below. The stator core **522** is, like the above described stator core **52**, made of a plurality of magnetic steel plates stacked in the axial direction in the shape of a hollow cylinder having a given thickness in the radial direction. The stator winding **521** is mounted on a radially outer circumference of the stator core **522** which faces the rotor **510**. The stator core **522** does not have any irregularities on the outer circumferential surface thereof. In the assembly of the stator core **522** and the stator winding **521**, the conductors **523** of the stator winding **521** are arranged adjacent each other in the circumferential direction on the outer circumferential surface of the stator core **522**. The stator core **522** functions as a back core.

The stator **520** may be made to have one of the following structures.

(A) The stator **520** has an inter-conductor members each of which is disposed between the conductors **523** in the circumferential direction. As the inter-conductor members, magnetic material is used which meets a relation of Wt×Bs≤Wm×Br where Wt is a width of the inter-conductor members in the circumferential direction within one magnetic pole, Bs is the saturation magnetic flux density of the inter-conductor members, Wm is a width of the magnet unit **512** equivalent to one magnetic pole in the circumferential direction, and Br is the remanent flux density in the magnet unit **512**.

(B) The stator **520** has the inter-conductor members each of which is disposed between the conductors **523** in the circumferential direction. The inter-conductor members are each made of a non-magnetic material.

(C) The stator **520** has no inter-conductor member disposed between the conductors **523** in the circumferential direction.

The above structure of the stator **520** results in a decrease in inductance as compared with typical rotating electrical machines equipped with teeth (i.e., iron core) which create a magnetic path between conductors of a stator winding. Specifically, the structure of the stator **520** enables the inductance to be one-tenth or less of that in the prior art structure. Usually, the reduction in inductance will result in a reduction in impedance. The rotating electrical machine **500** is, therefore, designed to increase output power relative to input power to increase the degree of output torque. The rotating electrical machine **500** is also enabled to produce a higher degree of output than rotating electrical machines which use a magnet-embedded rotor and output torque using impedance voltage (i.e., reluctance torque).

In this embodiment, the stator winding **521** is formed along with the stator core **522** in the form of a single unit using a resinous molding material (i.e., insulating material). The molding material occupies an interval between a respective adjacent two of the conductors **523** arranged in the circumferential direction. This structure of the stator **520** is equivalent to that described in the above item (B). The conductors **523** arranged adjacent each other in the circumferential direction may have surfaces which face each other in the circumferential direction and are placed in direct contact with each other or opposed to each other through a small air gap therebetween. This structure is equivalent to the above item (C). When the structure in the above item (A) is used, the outer circumferential surface of the stator core **522** is preferably shaped to have protrusions in accordance with orientation of the conductors **523** in the axial direction, that is, a skew angle in a case where the stator winding **521** is of a skew structure.

The structure of the stator winding **521** will be described below with reference to FIGS. **54**(*a*) and **54**(*b*). FIG. **54**(*a*) is a partially developed view which illustrates an assembly of the conductors **523** arranged in the form of an outer one of two layers overlapping each other in the radial direction of the stator winding **521**. FIG. **54**(*b*) is a partially developed which illustrates an assembly of the conductors **523** arranged in the form of an inner one of the two layers.

The stator winding **521** is designed as an annular distributed winding. The stator winding **521** is made up of the conductors **523** arranged in the form of two layers: an outer layer and an inner layer overlapping each other in the radial direction of the stator winding **521**. The conductors **523** of the outer layer are, as can be seen in FIGS. **54**(*a*) and **54**(*b*), skewed at an orientation different from that of the conductors **523** of the inner layer. The conductors **523** are electrically insulated from each other. Each of the conductors **523** is, as illustrated in FIG. **13**, preferably made of an aggregation of wires **86**. For instance, two each of the conductors **523** through which current flows in the same direction for the same phase are arranged adjacent each other in the circumferential direction of the stator winding **521**. Accordingly, in the stator winding **521**, a respective circumferentially arranged two of the conductors **523** in each of the outer and inner layers, that is, a total four of the conductors **523** constitutes one conductor portion of the stator winding **521** for each phase. The conductor portions are provided one in each magnetic pole.

The conductor portion is preferably shaped to have a thickness (i.e., a dimension in the radial direction) which is less than a width thereof (i.e., a dimension in the circumferential direction) for each phase in each pole. In other words, the stator winding **521** is preferably designed to have a flattened conductor structure. For instance, a total eight of the conductors **523**: four arrayed adjacent each other in the circumferential direction in each of the outer and inner layers preferably define each conductor portion for each phase in the stator winding **521**. Alternatively, each of the conductors **523** may be shaped to have a transverse section, as illustrated in FIG. **50**, whose width (i.e., a dimension in the circumferential direction) is larger than a thickness thereof (i.e., a dimension in the radial direction). The stator winding **521** may alternatively be designed to have the same structure as that of the stator winding **51** shown in FIG. **12**. This structure, however, requires the rotor carrier **511** to have an inner chamber in which coil ends of the stator winding **521** are disposed.

The stator winding **521**, as can be seen in FIG. **54**(*a*), has the coil side **525** which overlaps the stator core **522** in the radial direction thereof. The coil side **525** is made up of portions of the conductors **523** which obliquely extend or slant at a given angle to the axis of the stator winding **521** and are arranged adjacent each other in the circumferential direction. The stator winding **521** also has the coil ends **526** located outside the coil side **525** in the axial direction thereof. Each of the coil ends **526** is made up of portions of the conductors **523** which are turned inwardly in the axial direction to make joints of the conductors **523** of the coil side **525**. FIG. **54**(*a*) illustrates the coil side **525** and the coil ends **526** in the outer layer of the conductors **523** of the stator winding **521**. The conductors **523** of the inner layer and the conductors **523** of the outer layer are electrically connected together by the coil ends **526**. In other words, each of the conductors **523** of the outer layer is turned in the axial direction and leads to a respective one of the conductors **523** of the inner layer through the coil end **526**. In brief, a direction in which current flows in the stator winding **521** is reversed between the outer and inner layers of the conductors **523** connected to extend in the circumferential direction.

The stator winding **521** has end regions defining ends thereof opposed to each other in the axial direction and an intermediate region between the end regions. Each of the conductors **523** has skew angles different between each of the end regions and the intermediate region. Specifically, the skew angle is an angle which each of the conductors **523** makes with a line extending parallel to the axis of the stator winding **521**. The conductors **523**, as illustrated in FIG. **55**, have the skew angle θ_{s1} in the intermediate region and the skew angle θ_{s2} in the end regions which is different from the skew angle θ_{s1}. The skew angle θ_{s1} is smaller than the skew angle θ_{s2}. The end regions of the stator winding **521** are defined to partially occupy the coil side **525**. The skew angle θ_{s1} and the skew angle θ_{s2} are angles at which the conductors **523** are inclined in the axial direction of the stator winding **521**. The skew angle θ_{s1} in the intermediate region is preferably selected to be an angle suitable for removing harmonic components of magnetic flux resulting from excitation of the stator winding **521**.

The skew angle of each of the conductors **523** of the stator winding **521** is, as described above, selected to be different between the intermediate region and the end regions. The skew angle θ_{s1} in the intermediate region is set smaller than the skew angle θ_{s2} in the end regions, thereby decreasing the size of the coil ends **526**, but enabling a winding factor of the stator winding **521** to be increased. In other words, it is possible for the stator winding **521** to decrease the length of the coil ends **526**, i.e., portions of the conductors **523** extending outside the stator core **522** in the axial direction without sacrificing a desired winding factor, which enables the rotating electrical machine **500** to be reduced in size and the degree of torque to be increased.

An adequate range of the skew angle θ_{s1} in the intermediate region will be discussed below. In the case where the X conductors **523** where X is the number of the conductors **523** are arranged in one magnetic pole of the stator winding **521**, excitation of the stator winding **521** is thought of as producing an X^{th} harmonic. If the number of phases is defined as S, and the number of the conductors **523** for each phase is defined as m, then X=2×S×m. The inventor of this application has focused the fact that an X^{th} harmonic is equivalent to a combination of an $(X^{-1})^{th}$ harmonic and $(X^{+1})^{th}$ harmonic, and the X^{th} harmonic may be reduced by reducing at least either of the $(X^{-1})^{th}$ harmonic or the $(X^{+1})^{th}$ harmonic and found that the X^{th} harmonic will be reduced by selecting the skew angle θ_{s1} to fall in a range of 360°/(X+1) to 360°/(X−1) in terms of electrical angle.

For instance, if S=3, and m=2, the skew angle θ_{s1} is determined to fall in a range of 360°/13 to 360°/11 in order to decrease the 12^{th} harmonic (i.e., X=12). Specifically, the skew angle θ_{s1} is selected from a range of 27.7° to 32.7°.

The skew angle θ_{s1} of each of the conductors **523** in the intermediate region determined in the above way will facilitate or enhance interlinkage of magnetic fluxes, as produced by N-poles and S-poles of the magnets arranged alternately, in the intermediate regions of the conductors **523**, thereby increasing the winding factor of the stator winding **521**.

The skew angle θ_{s2} in the end regions is determined to be larger than the skew angle θ_{s1} in the intermediate region of the conductors **523**. The skew angle θ_{s2} is selected to meet a relation of $\theta_{s1}<\theta_{s2}<90°$.

In the stator winding **521**, the end of each of the conductors **523** of the inner layer is joined to the end of a respective one of the conductors **523** of the outer layer by welding or bonding techniques. Alternatively, each of the conductors **523** of the inner layer and a respective one of the conductors **523** of the outer layer may be made by a single conductor with a curved or bent portion defining an end joint thereof. In the stator winding **521**, one of the ends of each phase winding, i.e., one of the axially opposed coil ends **526** of each phase winding is electrically connected to a power converter (i.e., an inverter) using, for example, a bus. The structure of the stator winding **521** in which the conductors **523** are joined together in ways different between the coil end **526** closer to the bus bar and the coil end **526** farther away from the bus bar will be described below.

First Structure

The conductors **523** are welded together at the coil ends **526** closer to the bus bars, while they are connected in a way other than welding at the coil ends **526** farther away from the bus bars. For instance, a single conductor may be shaped to have a curved or bent portion which defines the coil end **523** farther away from the bus bar and to make a respective two of the conductors **523**. The end of each phase winding is, as described above, welded to the bus bar at the coil end **526** closer to the bus bar. The coil ends **526** closer to the bus bars may, therefore, be welded together to connect the conductors **523** in a single step. This improves the efficiency in producing the stator winding **521**.

Second Structure

The conductors **523** are connected in a way other than welding at the coil ends **526** closer to the bus bars and welded together at the coil ends **526** farther away from the bus bars. In a case where the conductors **523** are welded together at the coil ends **526** closer to the bus bars, it is necessary to increase an interval between the bus bars and the coil ends **526** in order to avoid a mechanical interference between the welds and the bus bars. The second structure, however, eliminates such a need and enables an interval between the bus bars and the coil ends **526** to be decreased, thereby loosing requirements for an axial dimension of the stator winding **521** or for the bus bars.

Third Structure

The conductors **523** are jointed together at all the coil ends **526** using welding techniques. This structure enables each of the conductors **523** to be made of a shorter length of conductor than the above structures and also eliminates the need for bending or curving conductors to improve the efficiency in completing the stator winding **521**.

Fourth Structure

The stator winding **521** is completed without welding the coil ends **526** of all the conductors **523**. This minimizes or eliminates welded portions of the stator winding **521**, thereby minimizing a risk that electrical insulation of the conductors **532** may be damaged at welds.

The stator winding **521** may be produced by preparing a weaved assembly of conductor strips placed horizontally and then bending them into a cylinder. In this case, the coil ends **526** of the conductor strips may be welded together before the conductor strips are bent. The bending of the conductor strips into a cylinder may be achieved by wrapping the assembly of the conductor strips about a circular cylinder which is identical in diameter with the stator core **522** or alternatively by wrapping the assembly of the conductor trips directly around the stator core **522**.

The stator winding **521** may alternatively be designed to have one of the following structures.

The stator winding **521** illustrated in FIGS. **54**(*a*) and **54**(*b*) may alternatively have the intermediate region and the end regions which are identical in skew angle with each other.

The stator winding **521** illustrated in FIGS. **54**(*a*) and **54**(*b*) may alternatively have the conductors **523** which are arranged adjacent each other in the circumferential direction in the same phase and have ends joined together using connecting conductors extending perpendicular to the axial direction of the stator winding **521**.

The stator winding **521** may be made in the form of 2×n annular layers. For example, the stator winding **521** may be shaped to have 4 or 6 overlapping annular layers.

The structure of the inverter unit **530** working as a power converter unit will be described below with reference to FIGS. **56** and **57** which are exploded sectional views. FIG. **57** illustrates two sub-assemblies of parts of the inverter unit **530** shown in FIG. **56**.

The inverter unit **530** includes the inverter housing **531**, a plurality of electrical modules **532** disposed in the inverter housing **531** and the bus bar module **533** which electrically connects the electrical modules **532** together.

The inverter housing **531** includes the hollow cylindrical outer wall **541**, the hollow cylindrical inner wall **542**, and the bossed member **543**. The inner wall **542** is smaller in outer diameter than the outer wall **541** and arranged radially inside the outer wall **541**. The bossed member **543** is secured to one of axially opposed ends of the inner wall **542**. These members **541**, **542**, and **543** are each preferably made of an electrically conductive material, such as carbon fiber reinforced plastic (CFRP). The inverter housing **531** has the outer wall **541** and the inner wall **542** overlapping each other in the radial direction thereof. The bossed member **543** is, as illustrated in FIG. **57**, attached to the axial end of the inner wall **542**.

The stator core **522** is secured to an outer periphery of the outer wall **541** of the inverter housing **531**, thereby assembling the stator **520** and the inverter unit **530** as a single unit.

The outer wall **541**, as illustrated in FIG. **56**, has a plurality of grooves or recesses **541***a*, **541***b*, and **541**C formed in an inner peripheral surface thereof. The inner wall **542** has a plurality of grooves or recesses **542***a*, **542***b*, and **542**C formed in an outer peripheral surface thereof. When the outer wall **541** and the inner wall **542** are assembled together, three inner chambers: the annular chambers **544***a*, **544***b*, and **544***c* are, as can be seen in FIG. **57**, defined by the recesses **541***a*, **541***b*, and **541**C and the recesses **542***a*, **542***b*, and **542**C. The annular chamber **544***b* located intermediate between the annular chambers **544***a* and **544***c* is used as the coolant path **545** through which cooling water or coolant flows. The annular chambers **544***a* and **544***c* located axially outside the annular chamber **544***b* (i.e., the coolant path **545**) have the sealing members **546** disposed therein. The sealing members **546** hermetically seal the annular chamber **544***b* (i.e., the coolant path **545**). The coolant path **545** will also be discussed later in detail.

The bossed member **543** includes the annular disc-shaped end plate **547** and the boss **548** protruding from the end plate **547** into the housing **531**. The boss **548** is of a hollow cylindrical shape. Specifically, the inner wall **542** has a first end and a second end which is opposed to the first end in the axial direction and closer to a protruding end of the rotating shaft **501** (i.e., the inside of the vehicle). The bossed member **543** is, as can be seen in FIG. **51**, secured to the second end of the inner wall **542**. In the tire wheel assembly **400** illustrated in FIGS. **45** to **47**, the base plate **405** is secured to the inverter housing **531** (more specifically, the end plate **547** of the bossed member **543**).

The inverter housing **531** is of a double-walled structure made up of outer and inner peripheral walls overlapping each other in the radial direction of the inverter housing **531**. The outer peripheral wall of the inverter housing **531** is defined by a combination of the outer wall **541** and the inner wall **542**. The inner peripheral wall of the inverter housing **531** is defined by the boss **548**. In the following discussion, the outer peripheral wall defined by the outer wall **541** and the inner wall **542** will also be referred to as an outer peripheral wall WA**1**. The inner peripheral wall defined by the boss **548** will also be referred to as an inner peripheral wall WA**2**.

The inverter housing **531** has an annular inner chamber which is defined between the outer peripheral wall WA**1** and the inner peripheral wall WA**2** and in which the electrical modules **532** are arranged adjacent each other in the circumferential direction thereof. The electrical modules **532** are firmly attached to an inner periphery of the inner wall **542** using adhesive or vises (i.e., screws). The inverter housing **531** will also be referred to as a housing member. The electrical modules **532** will also be referred to as electrical parts or electrical devices.

The bearing **560** is disposed inside the inner peripheral wall WA**2** (i.e., the boss **548**). The bearing **560** retains the rotating shaft **501** to be rotatable. The bearing **560** is designed as a hub bearing which is disposed in the center of the wheel **402** to support the tire wheel assembly **400** to be rotatable. The bearing **560** is located to overlap the rotor **510**, the stator **520**, and the inverter unit **530** in the radial direction thereof. In the rotating electrical machine **500** of this embodiment, the above described magnetic orientation of the rotor **510** enables the magnet unit **512** to have a decreased thickness. The stator **520**, as described above, has a slot-less structure and uses flattened conductors. This enables the magnetic circuit to have a thickness decreased in the radial direction, thereby increasing the volume of space radially inside the magnetic circuit. These arrangements enable the magnetic circuit, the inverter unit **530**, and the bearing **560** to be stacked in the radial direction. The boss **548** also serves as a bearing retainer in which the bearing **560** is disposed.

The bearing **560** is implemented by, for example, a radial ball bearing, as can be seen in FIG. **51**, including the cylindrical inner race **561**, the cylindrical outer race **561** which is larger in diameter than the inner race **561** and arranged radially outside the inner race **561**, and the balls **563** disposed between the inner race **561** and the outer race **562**. The outer race **562** is fit in the bossed member **543**, thereby securing the bearing **560** to the inverter housing **531**. The inner race **561** is fit on the rotating shaft **501**. The inner race **561**, the outer race **562**, and the balls **563** are made of metallic material, such as carbon steel.

The inner race **561** of the bearing **560** includes the cylinder **561***a* in which the rotating shaft **501** is disposed and the flange **561***b* which extends from an end of the cylinder **561***a* in a direction perpendicular to the axis of the bearing **560**. The flange **561***b* is placed in contact with an inner surface of the end plate **514** of the rotor carrier **511**. After the bearing **560** is mounted on the rotating shaft **501**, the rotor carrier **511** is retained or held between the flange **502** of the rotating shaft **501** and the flange **561***b* of the inner race **561**. The angle (i.e., 90° in this embodiment) which the flange **503** of the rotating shaft **501** makes with the axis of the rotating shaft **501** is identical with that which the flange **561***b* of the inner race **561** makes with the axis of the rotating shaft **501**. The rotor carrier **511** is firmly held between the flanges **502** and **561***b*.

The rotor carrier **511** is supported by the inner race **561** of the bearing **560** from inside, thereby ensuring the stability in holding the rotor carrier **511** relative to the rotating shaft **501** at a required angle, which achieves a desired degree of parallelism of the magnet unit **512** to the rotating shaft **501**. This enhances the resistance of the rotor carrier **511** to mechanical vibration even though the rotor carrier **511** is designed to have a size increased in the radial direction.

Next, the electrical modules **532** installed in the inverter housing **531** will be discussed below.

The electrical modules **532** is made up of a plurality of modules each of which includes electrical devices, such as semiconductor switches, and smoothing capacitors which constitute a power converter. Specifically, the electrical modules **532** include the switch modules **532**A equipped with semiconductor switches (i.e., power devices) and the capacitor modules **532**B equipped with smoothing capacitors.

A plurality of spaces **549** are, as illustrated in FIGS. **49** and **50**, secured to the inner peripheral surface of the inner wall **542**. The spaces **549** each have a flat surface to which one of the electrical modules **532** is attached. The inner peripheral surface of the inner wall **542** is curved, while each of the electrical modules **532** has a flat surface to be attached to the inner wall **542**. Each of the spaces **549** is, therefore, shaped to have the flat surface which faces away from the inner wall **542**. The electrical modules **532** are secured to the flat surfaces of the spacers **549**.

The spacers **549** need not necessarily to be interposed between the inner wall **542** and the electrical modules **532**. For example, the inner wall **542** may be shaped to have flat sections. Alternatively, each of the electrical modules **532** may be shaped to have a curved surface attached directly to the inner wall **542**. The electrical modules **532** may alternatively be secured to the inverter housing **531** in non-contact with the inner peripheral surface of the inner wall **542**. For instance, the electrical modules **532** may be fixed on the end plate **547** of the bossed member **543**. The switch modules **532**A may be secured to the inner peripheral surface of the inner wall **542** in non-contact therewith. Similarly, the capacitor modules **532**B may be secured to the inner peripheral surface of the inner wall **542** in non-contact therewith.

In a case where the spacers **549** are disposed on the inner peripheral surface of the inner wall **542**, a combination of the outer peripheral wall WA**1** and the spacers **549** will be referred to as a cylindrical portion. Alternatively, in a case where the spacers **549** are not used, the outer peripheral wall WA**1** itself will be referred to as a cylindrical portion.

The outer peripheral wall WA**1** of the inverter housing **531**, as described already, has formed therein the coolant path **545** in which cooling water flows to cool the electrical modules **532**. Instead of the cooling water, cooling oil may be used. The coolant path **545** is of an annular shape contoured to conform with the configuration of the outer peripheral wall WA**1**. The cooling water passes the electrical modules **532** from an upstream to a downstream side in the coolant path **545**. In this embodiment, the coolant path **545** extends in an annular shape and surrounds or overlaps the electrical modules **532** in the radial direction.

The inner wall **542** has formed therein the inlet path **571** through which the cooling water is inputted into the coolant path **545** and the outlet path **572** through which the cooling water is discharged from the coolant path **545**. The inner wall **542**, as described already, has the electrical modules **532** disposed on the inner peripheral surface thereof. Only one of intervals each between a respective circumferentially adjacent two of the electrical modules **532** is shaped to be larger than the others. In such a large interval, a portion of the inner wall **542** protrudes radially inwardly to form the bulging portion **573**. The bulging portion **573** has formed therein the inlet path **571** and the outlet path **572** which are arranged adjacent each other in the circumferential direction of the inner wall **542**.

FIG. **58** illustrates the layout of the electrical modules **532** in the inverter housing **531**. FIG. **58** represents the same longitudinal section of the rotating electrical machine **500** as in FIG. **50**.

The electrical modules **532** are, as can be seen in FIG. **58**, arranged at the first interval INT**1** or the second interval INT**2** away from each other in the circumferential direction of the rotating electrical machine **500**. Only selected two of the electrical modules **532** are, as clearly illustrated in FIG. **58**, located at the second interval INT**2** away from each other. The second interval INT**2** is selected to be larger than the first interval INT**1**. Each of the intervals INT**1** and INT**2** is, for example, a distance between the centers of an adjacent two of the electrical modules **532** arranged in the circumferential direction. The bulging portion **573** is located in the interval INT**2** between the electrical modules **532**. In other words, the intervals between the electrical modules **532** include a longer interval (i.e., the second interval INT**2**) in which the bulging portion **573** lies.

Each of the intervals INT**1** and INT**2** may be given by an arc-shaped distance between the two adjacent electrical modules **532** along a circle around the center defined on the rotating shaft **501**. Each of the intervals INT**1** and INT**2** may alternatively be expressed, as illustrated in FIG. **58**, by an angular interval θi**1** or θi**2** around the center defined on the rotating shaft **501** where θi**1**<θi**2**).

In the structure illustrated in FIG. **58**, the electrical modules **532** are placed in non-contact with each other in the circumferential direction of the rotating electrical machine **500**, but however, they may be arranged in contact with each other in the circumferential direction except for the second interval INT**2**.

Referring back to FIG. **48**, the end plate **547** of the bossed member **543** has formed therein the inlet/outlet port **574** in which ends of the inlet path **571** and the outlet path **572** are formed. The inlet path **571** and the outlet path **572** connect with the circulation path **575** through which the cooling water is circulated. The circulation path **575** is defined by a coolant pipe. The circulation path **575** has the pump **576** and the heat dissipating device **577** installed therein. The pump **576** is actuated to circulate the cooling water in the coolant path **545** and the circulation path **575**. The pump **576** is implemented by an electrically powered pump. The heat dissipating device **577** is made of a radiator working to release thermal energy of the cooling water to air.

The stator **520** is, as illustrated in FIG. **50**, arranged outside the outer peripheral wall WA**1**. The electrical modules **532** are arranged inside the outer peripheral wall WA**1**. Accordingly, thermal energy generated by the stator **520** is transferred to the outer peripheral wall WA**1** from outside, while thermal energy generated by the electrical modules **532** is transferred to the outer peripheral wall WA**1** from inside. The cooling water flowing through the coolant path **545**, therefore, simultaneously absorbs the thermal energy generated by both the stator **520** and the electrical modules **532**, thereby facilitating dissipation of heat from the rotating electrical machine **500**.

The electrical structure of the power converter will be described below with reference to FIG. **59**.

The stator winding **521** is, as illustrated in FIG. **59**, made up of a U-phase winding, a V-phase winding, and a W-phase winding. The stator winding **521** connects with the inverter **600**. The inverter **600** is made of a bridge circuit having as many upper and lower arms as the phases of the stator winding **521**. The inverter **600** is equipped with a series-connected part made up of the upper arm switch **601** and the lower arm switch **602** for each phase. Each of the switches **601** and **602** is turned on or off by a corresponding one of the driver circuits **603** to energize or deenergize a corresponding one of the phase windings. Each of the switches **601** and **602** is made of, for example, a semiconductor switch, such as a MOSFET or IGBT. The capacitor **604** is also connected to each of the series-connected parts made up of the switches **601** and **602** to output electrical charge required to achieve switching operations of the switches **601** and **602**.

The control device **607** serves as a controller and is made up of a microcomputer equipped with a CPU and memories. The control device **607** analyzes information about parameters sensed in the rotating electrical machine **500** or a request for a motor mode or a generator mode in which the rotating electrical machine **500** operates to control switching operations of the switches **601** and **602** to excite or deexcite the stator winding **521**. For instance, the control device **607** performs a PWM operation at a given switching frequency (i.e., carrier frequency) or an operation using a rectangular wave to turn on or off the switches **601** and **602**. The control device **607** may be designed as a built-in controller installed inside the rotating electrical machine **500** or an external controller located outside the rotating electrical machine **500**.

The rotating electrical machine **500** in this embodiment has a decreased electrical time constant because the stator **520** is engineered to have a decreased inductance. It is, therefore, preferable to increase the switching frequency (i.e., carrier frequency) and enhance the switching speed in the rotating electrical machine **500**. In terms of such requirements, the capacitor **604** serving as a charge supply capacitor is connected parallel to the series-connected part made up of the switches **601** and **602** for each phase of the stator winding **521**, thereby reducing the wiring inductance, which deals with electrical surges even through the switching speed is enhanced.

The inverter **600** is connected at a high potential terminal thereof to a positive terminal of the dc power supply **605** and at a low potential terminal thereof to a negative terminal (i.e., ground) of the dc power supply **605**. The smoothing capacitor **606** is connected to the high and low potential terminals of the inverter **600** in parallel to the dc power supply **605**.

Each of the switch modules **532**A includes the switches **601** and **602** (i.e., semiconductor switching devices generating heat), the driver circuits **603** (i.e., electric devices constituting the driver circuits **603**), and the charge supply capacitor **604**. Each of the capacitor modules **532**B includes the smoothing capacitor **606** generating heat. The structure of the switch modules **532**A is shown in FIG. **60**.

Each of the switch modules **532**A, as illustrated in FIG. **60**, includes the module case **611**, the switches **601** and **602** for one of the phases of the stator winding **521**, the driver circuits **603**, and the charge supply capacitor the charge supply capacitor **604**. Each of the driver circuits **603** is made of a dedicated IC or a circuit board and installed in the switch module **532**A.

The module case **611** is made from insulating material, such as resin. The module case **611** is secured to the outer peripheral wall WA**1** with a side surface thereof contacting the inner peripheral surface of the inner wall **542** of the inverter unit **530**. The module case **611** has, for example, resin molded therein. In the module case **611**, the switches **601** and **602**, the driver circuits **603**, and the capacitor **604** are electrically connected together using wires **612**. The switch modules **532**A are, as described above, attached to the outer peripheral wall WA**1** through the spacers **549**, but however, FIG. **60** emits the spacers **549** for the brevity of illustration.

In a condition where the switch modules **532**A are firmly attached to the outer peripheral wall WA**1**, a portion of each of the switch modules **532**A which is closer to the outer peripheral wall WA**1**, i.e., the coolant path **545** is more cooled. In terms of such ease of cooling, the order in which the switches **601** and **602**, the driver circuits **603**, and the capacitor **604** are arranged is determined. Specifically, the switches **601** and **602** have the largest amount of heat generation. The capacitor **604** has an intermediate amount of heat generation. The driver circuits **603** have the smallest amount of heat generation. Accordingly, the switches **601** and **602** are located closest to the outer peripheral wall WA**1**. The driver circuits **603** are located farther away from the outer peripheral wall WA**1**. The capacitor **604** is interposed between the switches **601** and **602** and the driver circuit **603**. In other words, the switches **601** and **602**, the capacitor **604**, the driver circuit **603** are arranged in this order close to the outer peripheral wall WA**1**. An area of each of the switch modules **532**A which is attached to the inner wall **542** is preferably smaller in size than an area of the inner peripheral surface of the inner wall **542** which is contactable with the switch modules **532**A.

Although not illustrated in detail, the capacitor modules **532**B have the capacitor **606** disposed in a module case similar in configuration and size to the switch modules **532**A. Each of the capacitor modules **532**B is, like the switch modules **532**A, secured to the outer peripheral wall WA**1** with the side surface of the module case **611** placed in contact with the inner peripheral surface of the inner wall **542** of the inverter housing **531**.

The switch modules **532**A and the capacitor modules **532**B need not necessarily be arranged coaxially with each other inside the outer peripheral wall WA**1** of the inverter housing **531**. For instance, the switch modules **532**A may alternatively be disposed radially inside or outside the capacitor modules **532**B.

When the rotating electrical machine **500** is operating, the switch modules **532**A and the capacitor modules **532**B transfer heat generated therefrom to the coolant path **545** through the inner wall **542** of the outer peripheral wall WA**1**, thereby cooling the switch modules **532**A and the capacitor modules **532**B.

Each of the electrical modules **532** may be designed to have formed therein a flow path into which coolant is delivered to cool the electrical module **532**. The cooling structure of the switch modules **532**A will be described below with reference to FIGS. **61**(*a*) and **61**(*b*). FIG. **61**(*a*) is a longitudinal sectional view of each of the switch modules **532**A along a line passing through the outer peripheral wall WA**1**. FIG. **61**(*b*) is a sectional view taken along the line **61**B-**61**B in FIG. **61**(*a*).

Like in FIG. **60**, the switch module **532**A, as illustrated in FIGS. **61**(*a*) and **61**(*b*), includes the module case **611**, the switches **601** and **602** for a corresponding one of the phases of the stator winding **521**, the driver circuits **603**, the capacitor **604**, and a cooling device made of a pair of pipes **621** and **622** and the coolers **623**. The pipe **621** of the cooling device is designed as an inlet pipe through which cooling water is delivered from the coolant path **545** in the outer peripheral wall WA**1** to the coolers **623**. The pipe **622** of the cooling device is designed as an outlet pipe through which the cooling water is discharged from the coolers **623** to the coolant path **545**. The cooler **623** is prepared for an object to be cooled. The cooling device may, therefore, be designed to have a single cooler **623** or a plurality of coolers **623**. In the structure shown in FIGS. **61**(*a*) and **61**(*b*), the two coolers **623** are arranged at a given interval away from each other in a direction perpendicular to the length of the coolant path **545**, in other words, the radial direction of the inverter unit **530**. The pipes **621** and **622** connect with the coolers **623**.

Each of the coolers **623** has an inner void. Each of the coolers **623** may be equipped with inner fins for enhancing the cooling ability.

In the structure equipped with the two coolers **623** which will also be referred to as a first cooler **623** and a second cooler **623** where the first cooler **623** is located closer to the outer peripheral wall WA**1** than the second cooler **623** is, a first space between the first cooler **623** and the outer peripheral wall WA**1**, a second space between the first and second coolers **623**, and a third space located inside the second cooler **623** away from the outer peripheral wall WA**1** are locations where electrical devices are disposed. The second space, the first space, and the third space have a higher degree of cooling capability in this order. In other words, the second space is a location which has the highest degree of cooling ability. The first space close to the outer peripheral wall WA**1** (i.e., the coolant path **545**) is higher in cooling capability than the third space farther away from the outer peripheral wall WA**1**. In view of this relation in cooling capability, the switches **601** and **602** are arranged in the second space between the first and second coolers **623**. The capacitor **604** is arranged in the first space between the first cooler **623** and the outer peripheral wall WA**1**. The driver circuits **603** are arranged in the third space located farther away from the outer peripheral wall WA**1**. Although not illustrated, the driver circuits **603** may alternatively be disposed in the first space, while the capacitor **604** may be disposed in the third space.

In either case, in the module case **611**, the switches **601** and **602** are electrically connected to the driver circuits **603** using the wires **612**, while the switches **601** and **602** are connected to the capacitor **604** using the wires **612**. The switches **601** and **602** are located between the driver circuits **603** and the capacitor **604**, so that the wires **612** extending from the switches **601** and **602** to the driver circuit **603** are oriented in a direction opposite a direction in which the wires **612** extending from the switches **601** and **602** to the capacitor **604**.

The pipes **621** and **622** are, as can be seen in FIG. **61**(*b*), arranged adjacent each other in the circumferential direction, that is, from an upstream side to a downstream side of the coolant path **545**. The cooling water, therefore, enters the coolers **623** from the pipe **621** located on the upstream side and is then discharged from the pipe **622** located on the downstream side. The stopper **624** is preferably disposed between the inlet pipe **621** and the outlet pipe **621** in the coolant path **545** to stop flow of the cooling water in order to facilitate entry of cooling water into the cooling device. The stopper **624** may be designed as a shutter or block to close the coolant path **545** or an orifice to decrease a transverse sectional area of the coolant path **545**.

FIGS. **62**(*a*) to **62**(*c*) illustrate a modified form of the cooling structure of the switch modules **532**A. FIG. **62**(*a*) is a longitudinal section of the switch module **532**A along a line traversing the outer peripheral wall WA**1**. FIG. **62**(*b*) is a sectional view taken along the line **62**B-**62**B in FIG. **62**(*a*).

The structure in FIGS. **62**(*a*) and **62**(*b*) has the inlet pipe **621** and the outlet pipe **622** which are different in layout from those illustrated in FIGS. **62**(*a*) and **62**(*b*). Specifically, the inlet and outlet pipes **621** and **622** are arranged adjacent each other in the axial direction. The coolant path **545**, as clearly illustrated in FIG. **62**(*c*), includes an inlet section leading to the inlet pipe **621** and an outlet section leading to the outlet pipe **622**. The inlet section and the outlet section are physically separate from each other in the axial direction and hydraulically connected through the pipes **621** and **622** and the coolers **623**.

Each of the switch modules **532**A may alternatively be designed to have one of the following structures.

The structure in FIG. **63**(*a*) is, unlike in FIG. **61**(*a*), equipped with the single cooler **263**. In the module case **611**, a space (which will be referred to as a first space) between the cooler **623** and the outer peripheral wall WA**1** in the radial direction of the module case **611** has a higher degree of cooling capability. A space (which will be referred to as a second space) located inside the cooler **623** farther away from the outer peripheral wall WA**1** has a lower degree of cooling capability. In view of this relation in cooling capability, the structure in FIG. **63**(*a*) has the switches **601** and **602** arranged in the first space close to the outer peripheral wall WA**1** outside the cooler **623**. The capacitor **604** is arranged in the second space located inside the cooler **623**. The driver circuits **603** are disposed farther away from the cooler **623**.

Each of the switch modules **532**A is, as described above, designed to have the switches **601** and **602**, the driver circuits **603**, and the capacitor **604** disposed within the module case **611** for one of the phases of the stator winding **521**, but may be modified to have the switches **601** and **602** and the driver circuits **603** or the capacitor **604** disposed in the module case **611** for one of the phases of the stator winding **521**.

In FIG. **63**(*b*), the module case **611** has the inlet pipe **621**, the outlet pipe **622**, and the two coolers **623** mounted therein. One of the coolers **623** located closer to the outer peripheral wall WA**1** will be referred to as a first cooler. One of the coolers **623** located farther away from the outer peripheral wall WA**1** will be referred to as a second cooler. The switches **601** and **602** are arranged between the first and second coolers **623**. The capacitor **604** or the driver circuits **603** are arranged close to the outer peripheral wall WA**1** outside the first cooler **623**. The switches **601** and **602** and the driver circuit **603** are assembled as a single semiconductor module which is disposed in the module case **611** along with the capacitor **604**.

In the structure of the switch module **532**A illustrated in FIG. **63**(*b*), the capacitor **604** is located outside or inside one of the first and second coolers **623** on the opposite side of the one of the first and second coolers **623** to the switches **601** and **602**. In the illustrated example, the capacitor **604** is located between the first cooler **623** and the outer peripheral wall WA**1**. The switch module **532**A may alternatively be designed to have two capacitors **604** disposed on the both sides of the first cooler **623** in the radial direction of the stator winding **521**.

The structure in this embodiment delivers cooling water into only the switch modules **532**A other than the capacitor module **532**B through the coolant path **545**, but may alternatively be designed to supply the cooling water to both the modules **532**A and **532**B through the coolant path **545**.

It is also possible to bring cooling water into direct contact with the electrical modules **532** to cool them. For instance, the electrical modules **532** may be, as illustrated in FIG. **64**, embedded in the outer peripheral wall WA**1** to achieve a direct contact of the outer surface of the electrical modules **532** with the cooling water. In this case, each of the electrical modules **532** may be partially exposed to the cooling water flowing in the coolant path **545**. Alternatively, the coolant path **545** may be shaped to have a size increased to be larger than that in FIG. **58** in the radial direction to arrange the electrical modules **532** fully within the coolant path **545**. In the case where the electrical modules **532** are embedded in the coolant path **545**, the module case **611** of each of the electrical modules **532** may be equipped with fins disposed in the coolant path **545**, that is, exposed to the cooling water to enhance the ability to cool the electrical modules **532**.

The electrical modules **532**, as described above, include the switch modules **532**A and the capacitor modules **532**B which are different in amount of heat generation from the switch modules **532**A. In terms of such a difference, it is possible to modify the layout of the electrical modules **532** in the inverter housing **531** in the following way.

For instance, the switch modules **532**A are, as illustrated in FIG. **65**, arranged away from each other in the circumferential direction of the stator **520** and located as a whole closer to the upstream side of the coolant path **545** (i.e., the inlet path **571**) than to the downstream side (i.e., the outlet path **572**) of the coolant path **545**. The cooling water entering the inlet path **571** is first used to cool the switch modules **532**A and then used to cool the capacitor modules **532**B. In the structure illustrated in FIG. **65**, the inlet and outlet pipes **621** and **622** are, like in FIGS. **62**(*a*) and **62**(*b*), arranged adjacent each other in the axial direction, but however, may be, like in FIGS. **61**(*a*) and **61**(*b*), oriented adjacent each other in the circumferential direction.

The electrical structure of the electrical modules **532** and the bus bar module **533** will be described below. FIG. **66** is a transverse section taken along the line **66**-**66** in FIG. **49**. FIG. **67** is a transverse section taken along the line **67**-**67** in FIG. **49**. FIG. **68** is a perspective view which illustrates the bus bar module **533**. Electrical connections of the electrical modules **532** and the bus bar module **533** will be discussed with reference to FIGS. **66** to **68**.

The inverter housing **531** has the three switch modules **532**A (which will also be referred to below as a first module group) which are, as illustrated in FIG. **66**, arranged adjacent each other circumferentially next to the bulging portion **573** on the inner wall **542** in which the inlet path **571** and the outlet path **572** are formed in communication with the coolant path **545**. The six capacitor modules **532**B are also arranged circumferentially adjacent each other next to the first module group. In summary, the inverter housing **531** has ten regions (i.e., the number of the modules **532**A and **532**B plus one) defined on the inner peripheral surface of the outer peripheral wall WA**1**. The ten regions are arranged adjacent each other in the circumferential direction of the inverter housing **531**. The electrical modules **532** are disposed, one in each of ninth of the regions, while the bulging portion **573** occupies the remaining one of the regions. The three switch modules **532**A will also be referred to as a U-phase module, a V-phase module, and a W-phase module.

Each of the electrical modules **532** (i.e., the switch modules **532**A and the capacitor modules **532**B) is, as illustrated in FIGS. **66**, **56**, and **57**, equipped with a plurality of module terminals **615** extending from the module case **611**. The module terminals **615** serve as input/output terminals through which electrical signals are inputted into or outputted from the electrical modules **532**. The module terminals **615** each have a length extending in the axial direction of the inverter housing **531**. More specifically, the module terminals **615**, as can be seen in FIG. **51**, extend from the module case **611** toward the bottom of the rotor carrier **511** (i.e., the outside of the vehicle).

The module terminals **615** of the electrical modules **532** are connected to the bus bar module **533**. The switch modules **532**A and the capacitor modules **532**B are different in number of the module terminals **615** from each other. Specifically, each of the switch modules **532**A is equipped with the four module terminals **615**, while each of the capacitor modules **532**B is equipped with the two module terminals **615**.

The bus bar module **533**, as clearly illustrated in FIG. **68**, includes the annular ring **631**, the three external terminals **632**, and the winding connecting terminals **633**. The external terminals **632** extend from the annular ring **631** and achieve connections with external devices, such as a power supply and an ECU (Electronic Control Unit). The winding connecting terminals **633** are connected to ends of the phase windings of the stator winding **521**. The bus bar module **533** will also be referred to as a terminal module.

The annular ring **631** is located radially inside the outer peripheral wall WA**1** of the inverter housing **531** and adjacent one of axially opposed ends of each of the electrical modules **532**. The annular ring **631** includes an annular body made from an electrical insulating material, such as resin, and a plurality of bus bars embedded in the annular body. The bus bars connect with the module terminals **615** of the electrical modules **532**, the external terminals **632**, and the phase windings of the stator winding **521**, which will be also described later in detail.

The external terminals **632** include the high-potential power terminal **632**A connecting with a power unit, the low-potential power terminal **632**B connecting with the power unit, and the single signal terminal **632**C connecting with the external ECU. The external terminals **632** (i.e., **632**A to **632**C) are arranged adjacent each other in the circumferential direction of the annular ring **631** and extend in the axial direction of the annular ring **631** radially inside the annular ring **631**. The bus bar module **533** is, as illustrated in FIG. **51**, mounted in the inverter housing **531** together with the electrical modules **532**. Each of the external terminals **632** has an end protruding outside the end plate **547**. Specifically, the end plate **547** of the bossed member **543**, as illustrated in FIGS. **56** and **57**, has the hole **547***a* formed therein. The cylindrical grommet **635** is fit in the hole **547***a*. The external terminals **632** pass through the grommet **635**. The grommet **635** also functions as a hermetically sealing connector.

The winding connecting terminals **633** connect with ends of the phase windings of the stator winding **521** and extend radially outward from the annular ring **631**. Specifically, the winding connecting terminals **633** include the winding connecting terminal **633**U connecting with the end of the U-phase winding of the stator winding **521**, the winding connecting terminal **633**V connecting with the end of the V-phase winding of the stator winding **521**, and the winding connecting terminal **633**W connecting with the end of the W-phase winding of the stator winding **521**. Each of the winding connecting terminals **633** is, as illustrated in FIG. **70**, the current sensor **634** which measure an electrical current flowing through a corresponding one of the U-phase winding, the V-phase winding, and the W-phase winding.

The current sensor **634** may be arranged outside the electrical module **532** around the winding connecting terminal **633** or installed inside the electrical module **532**.

Connections between the electrical modules **532** and the bus bar module **533** will be described below in detail with reference to FIGS. **69** and **70**. FIG. **69** is a development view of the electrical modules **532** which schematically illustrates electrical connections of the electrical modules **532** with the bus bar module **533**. FIG. **70** is a view which schematically illustrate electrical connections of the electrical modules **532** arranged in an annular shape with the bus bar module **533**. In FIG. **69**, power supply lines are expressed by solid lines, while signal transmission lines are expressed by chain lines. FIG. **70** shows only the power supply lines.

The bus bar module **533** includes the first bus bar **641**, the second bus bar **642**, and the third bus bars **643** as power supply bus bars. The first bus bar **641** is connected to the high-potential power terminal **632**A. The second bus bar **642** is connected to the low-potential power terminal **632**B. The three third bus bars **643** are connected to the U-phase winding connecting terminals **633**U, the V-phase winding connecting terminals **633**V, and the W-phase winding connecting terminals **633**W.

The winding connecting terminals **633** and the third bus bars **643** usually generate heat due to the operation of the rotating electrical machine **10**. A terminal block, not shown, may, therefore, be disposed between the winding connecting terminals **633** and the third bus bars **643** in contact with the inverter housing **531** equipped with the coolant path **545**. Alternatively, the winding connecting terminals **633** and/or the third bus bars **643** may be bent in a crank form to achieve physical contact with the inverter housing **531** equipped with the coolant path **545**.

The above structure serves to release heat generated by the winding connecting terminals **633** or the third bus bars **643** to cooling water flowing in the coolant path **545**.

FIG. **70** depicts the first bus bar **641** and the second bus bar **642** as completely circular bus bars, but however, may alternatively be of a C-shape. Each of the winding connecting terminals **633**U, **633**V, and **633**W may alternatively be connected directly to a corresponding one of the switch modules **532**A (i.e., the module terminals **615**) without use of the bus bar module **533**.

Each of the switch modules **532**A is equipped with the four module terminals **615** including a positive terminal, a negative terminal, a winding terminal, and a signal terminal. The positive terminal is connected to the first bus bar **641**. The negative terminal is connected to the second bus bar **642**. The winding terminal is connected to one of the third bus bars **643**.

The bus bar module **533** is also equipped with the fourth bus bars **644** as signal transmission bus bars. The signal terminal of each of the switch modules **532**A is connected to one of the fourth bus bars **644**. The fourth bus bar **644** are connected to the signal terminal **632**C.

In this embodiment, each of the switch modules **532**A receives a control signal transmitted from an external ECU through the signal terminal **632**C. Specifically, the switches **601** and **602** in each of the switch modules **532**A are turned on or off in response to the control signal inputted through the signal terminal **632**C. Each of the switch modules **532**A is, therefore, connected to the signal terminal **632**C without passing through a control device installed in the rotating electrical machine **500**. The control signals may alternatively be, as illustrated in FIG. **71**, produced by the control device of the rotating electrical machine **500** and then inputted to the switch modules **532**A.

The structure of FIG. **71** has the control board **651** on which the control device **652** is mounted. The control device **652** is connected to the switch modules **532**A. The signal terminal **632**C is connected to the control device **652**. For instance, an external ECU serving as a host control device outputs a command signal associated with the motor mode or the generation mode to the control device **652**. The control device **652** then controls on-off operations of the switches **601** and **602** of each of the switch modules **532**A.

In the inverter unit **530**, the control board **651** may be arranged closer to the outside of the vehicle (i.e., the bottom of the rotor carrier **511**) than the bus bar module **533** is. The control board **651** may alternatively be disposed between the electrical modules **532** and the end plate **547** of the bossed member **543**. The control board **651** may be located to overlap at least a portion of each of the electrical modules **532** in the axial direction.

Each of the capacitor modules **532**B is equipped with two module terminals **615** serving as a positive terminal and a negative terminal. The positive terminal is connected to the first bus bar **641**. The negative terminal is connected to the second bus bar **642**.

Referring back to FIGS. **49** and **50**, the inverter housing **531** has disposed therein the bulging portion **573** which is equipped with the inlet path **571** and the outlet path **572** for cooling water. The inlet path **571** and the outlet path **572** are aligned with the electrical modules **532** arranged adjacent each other in the circumferential direction of the inverter housing **531**. The external terminals **632** are arranged adjacent the bulging portion **573** in the radial direction of the inverter housing **531**. In other words, the bulging portion **573** and the external terminals **632** are located at the same angular position in the circumferential direction of the inverter housing **531**. In this embodiment, the external terminals **632** are disposed radially inside the bulging portion **573**. As the inverter housing **531** is viewed from inside the vehicle, the inlet/outlet port **574** and the external terminals **632** are, as clearly illustrated in FIG. **48**, aligned with each other in the radial direction of the end plate **547** of the bossed member **543**.

The bulging portion **573** and the external terminals **632** are, as clearly illustrated in FIG. **66**, arranged adjacent the electrical modules **532** in the circumferential direction, thereby enabling the inverter unit **530** to be reduced in size, which also enables the rotating electrical machine **500** to be reduced in size.

Referring back to the structure of the tire wheel assembly **400** in FIGS. **45** and **47**, the cooling pipe H**2** is joined to the inlet/outlet port **574**. The electrical cable H**1** is joined to the external terminals **632**. The electrical cable H**1** and the cooling pipe H**2** are arranged inside the storage duct **440**.

In the inverter housing **531**, the three switch modules **532**A are arranged adjacent each other next to the external terminals **632** in the circumferential direction. The six capacitor modules **532**B are arranged next to the array of the switch modules **532**A in the circumferential direction. Such layout may be modified in the following way. For instance, the array of the three switch modules **532**A may be arranged at a location farthest away from the external terminals **632**, that is, diametrically opposed to the external terminals **632** across the rotating shaft **501**. Alternatively, the switch modules **532**A may be arranged at an increased interval away from each other in the circumferential direction, so that the capacitor modules **532**B may be disposed between the switch modules **532**A.

The layout of the switch modules **532**A located farthest away from the external terminals **632**, that is, diametrically opposed to the external terminals **632** across the rotating shaft **501** minimizes a risk of failure in operation of the switch modules **532**A caused by mutual inductance between the external terminals **632** and the switch modules **532**A.

Next, the structure of the resolver **660** working as an angular position sensor will be described below.

The inverter housing **531**, as illustrated in FIGS. **49** to **51**, has disposed therein the resolver **660** which measures the electrical angle θ of the rotating electrical machine **500**. The resolver **660** functions as an electromagnetic induction sensor and includes the resolver rotor **661** secured to the rotating shaft **501** and the resolver stator **662** which radially faces an outer circumference of the resolver rotor **661**. The resolver rotor **661** is made of a ring-shaped disc fit on the rotating shaft **501** coaxially with the rotating shaft **501**. The resolver stator **662** includes the circular stator core **663** and the stator coil **664** wound around teeth of the stator core **663**. The stator coil **664** includes a single-phase exciting coil and two-phase output coils.

The exciting coil of the stator coil **664** is energized by a sine wave excitation signal to generate magnetic flux which interlinks with the output coils. This causes a positional relation of the exciting coil with the two output coils to be changed cyclically as a function of an angular position of the resolver rotor **661** (i.e., a rotation angle of the rotating shaft **501**), so that the number of magnetic fluxes interlining with the output coils is changed cyclically. In this embodiment, the exciting coil and the output coils are arranged so that voltages, as developed at the output coils, are out of phase by $\pi/2$. Output voltage generated by the output coils will, therefore, be waves derived by modulating the excitation signal with modulating waves $\sin\theta$ and $\cos\theta$. Specifically, if the excitation signal is expressed by $\sin\Omega t$, the modulated waves will be $\sin\theta \times \sin\Omega t$ and $\cos\theta \times \sin\Omega t$.

The resolver **660** is equipped with a resolver digital converter. The resolver digital converter works to perform wave detection using the modulated wave and the excitation signal to calculate the electrical angle θ. For instance, the resolver **660** is connected to the signal terminal **632**C. An output of the resolver digital converter is inputted to an external device through the signal terminal **632**C. In a case where a control device is installed in the rotating electrical machine **500**, the output of the resolver digital converter is inputted to the control device.

The structure of the resolver **660** installed in the inverter housing **531** will be described below.

The bossed member **543** of the inverter housing **531**, as illustrated in FIGS. **49** and **51**, has formed thereon the hollow cylindrical boss **548**. The boss **548** has the protrusion **548***a* formed on an inner periphery thereof in the shape of an inner shoulder. The protrusion **548***a* projects in a direction perpendicular to the axial direction of the inverter housing **531**. The resolver stator **662** is secured using screws in contact with the protrusion **548***a*. In the boss **548**, the bearing **650** is arranged on an opposite side of the protrusion **548***a* to the resolver **660**.

Within the boss **548**, the housing cover **666** is arranged on an opposite side of the resolver **660** to the protrusion **548***a* in the axial direction. The housing cover **666** is made of an annular ring shaped disc and closes an inner chamber of the boss **548** in which the resolver **660** is disposed. The housing cover **666** is made from an electrically conductive material, such as a carbon fiber reinforced plastic (CFRP). The housing cover **666** has formed in the center thereof the center hole **666***a* through which the rotating shaft **501** passes. The center hole **666***a*, as clearly illustrated in FIG. **49**, has disposed therein the sealing member **667** which hermetically seal an air gap between the center hole **666***a* and the outer periphery of the rotating shaft **501**. The sealing member **667** hermetically seals the inner chamber of the boss **548** in which the resolver **660** is disposed. The sealing member **667** may be designed as a slidable seal made from resin.

The inner chamber in which the resolver **660** is disposed is surrounded or defined by the annular boss **548** of the bossed member **543** and which has axially-opposed ends closed by the bearing **560** and the housing cover **666**. The outer circumference of the resolver **660** is, therefore, surrounded by the conductive material, thereby minimizing adverse effects of electromagnetic noise on the resolver **660**.

The inverter housing **531** is, as described above in FIG. **57**, designed to have a double-walled structure equipped with the outer peripheral wall WA**1** and the inner peripheral wall WA**2**. The stator **520** is arranged radially outside the outer peripheral wall WA**1**. The electrical modules **532** are arranged between the outer peripheral wall WA**1** and the inner peripheral wall WA**2**. The resolver **660** is disposed radially inside the inner peripheral wall WA**2**. The inverter housing **531** is made from conductive material. The stator **520** and the resolver **660** are, therefore, isolated from each other through a conductive wall (i.e., a conductive double wall), that is, the outer peripheral wall WA**1** and the inner peripheral wall WA**2**, thereby minimizing a risk of magnetic interference between the stator **520** (i.e., the magnetic circuit) and the resolver **660**.

The rotor cover **670** which is arranged in the open end of the rotor carrier **511** will be described below in detail.

The rotor carrier **511**, as illustrated in FIGS. **49** and **50**, has the end open in the axial direction. The rotor cover **670** which is made of a substantially ring-shaped disc is disposed on the open end, i.e., partially covers the open end. The rotor cover **670** is secured to the rotor carrier **511** using, for example, welding techniques or vises (i.e., screws). The rotor cover **670** is preferably shaped to have a portion smaller in size (i.e. diameter) than the inner periphery of the rotor carrier **511** to hold the magnet unit **512** from moving in the axial direction. The rotor cover **670** has an outer diameter identical with that of the rotor carrier **511**, but has an inner diameter slightly greater than an outer diameter of the inverter housing **531**. The outer diameter of the inverter housing **531** is equal to the inner diameter of the stator **520**.

The stator **520** is, as described above, attached to the outer circumference of the inverter housing **531**. Specifically, the stator **520** and the inverter housing **531** joined together. The inverter housing **531** has a portion protruding in the axial direction from the joint of the stator **520** and the inverter housing **531**. Such a protrusion of the inverter housing **531** is, as clearly illustrated in FIG. **49**, surrounded by the rotor cover **670**. The sealing member **671** is disposed between the inner circumference of the rotor cover **670** and the outer periphery of the inverter housing **531** to hermetically seal an air gap therebetween. The sealing member **671**, therefore, hermetically closes an inner chamber of the rotor cover **670** in which the magnet unit **512** and the stator **520** are disposed. The sealing member **671** may be made of a slidable seal made from resin.

The above embodiment offers the following beneficial advantages.

The rotating electrical machine **500** has the outer peripheral wall WA**1** of the inverter housing **531** arranged radially inside the magnetic circuit made up of the magnet unit **512** and the stator winding **521** and also has the coolant path **545** formed in the outer peripheral wall WA**1**. The rotating electrical machine **500** also has the plurality of electrical modules **532** arranged along the inner circumference of the outer peripheral wall WA**1**. This enables the magnetic circuit, the coolant path **545**, and the power converter to be arranged in a stacked shape in the radial direction of the rotating electrical machine **500**, thereby permitting an axial dimension of the rotating electrical machine **500** to be reduced and also achieving effective layout of parts in the rotating electrical machine **500**. The rotating electrical machine **500** also ensures the stability in cooling the electrical modules **532** composing the power converter, thereby enabling the rotating electrical machine **500** to operate with high efficiency and to be reduced in size thereof.

The electrical modules **532** (i.e., the switch modules **532**A and the capacitor modules **532**B) equipped with heat generating devices, such as semiconductor switches or capacitors are placed in direct contact with the inner peripheral surface of the outer peripheral wall WA**1**, thereby causing heat, as generated by the electrical modules **532**, to be transferred to the outer peripheral wall WA**1**, so that the electrical modules **532** are well cooled.

In each of the switch modules **532**A, the coolers **623** are disposed outside the switches **601** and **602**. In other words, the switches **601** and **602** are arranged between the coolers **623**. The capacitor **604** is placed on an opposite side of at least one of the coolers **623** to the switches **601** and **602**, thereby enhancing the cooling of the capacitor **604** as well as the switches **601** and **602**.

In each of the switch modules **532**A, the coolers **623** are, as described above, placed on both sides of the switches **601** and **602**. The driver circuit **603** is arranged on an opposite side of at least one of the coolers **623** to the switches **601** and **602**, while the capacitor **604** is arranged on the other opposite side of the cooler **623**, thereby enhancing the cooling of the driver circuit **603** and the capacitor **604** as well as the switches **601** and **602**.

For instance, each of the switch modules **532**A is designed to have the coolant path **545** which delivers cooling water into the modules to cool the semiconductor switches. Specifically, each module **532**A is cooled by the outer peripheral wall WA**1** through which the cooling water passes and also by the cooling water flowing in the module **532**A. This enhances the cooling of the switch modules **532**A.

The rotating electrical machine **500** is equipped with a cooling system in which cooling water is delivered into the coolant path **545** from the external circulation path **575**. The switch modules **532**A are placed on an upstream side of the coolant path **545** close to the inlet path **571**, while the capacitor modules **532**B are arranged downstream of the switch modules **532**A. Generally, the cooling water flowing through the coolant path **545** has a lower temperature on the upstream side than the downstream side. The switch modules **532**A are, therefore, cooled better than the capacitor modules **532**B.

The electrical modules **532** are, as described above, arranged at shorter intervals (i.e., the first intervals INT**1**) or a longer interval (i.e., the second interval INT**2**) away from each other in the circumferential direction of the rotating electrical machine **500**. In other words, the intervals between the electrical modules **532** include a single longer interval (i.e., the second interval INT**2**). The bulging portion **573** which is equipped with the inlet path **571** and the outlet path **572** lies in the longer interval. These arrangements enable the inlet path **571** and the outlet path **572** of the coolant path **545** to be arranged radially inside the outer peripheral wall WA**1**. Usually, it is required to increase the volume or flow rate of cooling water in order to enhance the cooling efficiency. Such a requirement may be met by increasing an area of an opening of each of the inlet path **571** and the outlet path **572**. This is achieved in this embodiment by placing the bulging portion **573** in the longer interval (i.e., the second interval INT**2**) between the electrical modules **532**, which enables the inlet path **571** and the outlet path **572** to be shaped to have required sizes.

The external terminals **632** of the bus bar module **533** are arranged adjacent the bulging portion **573** in the radial direction of the rotor **510** radially inside the outer peripheral wall WA**1**. In other words, the external terminals **632** is placed together with the bulging portion **573** within the larger interval (i.e., the second interval INT**2**) between the electrical modules **532** arranged adjacent each other in the circumferential direction of the rotor **510**. This achieves a suitable layout of the external terminals **632** without physical interference with the electrical modules **532**.

The outer-rotor type rotating electrical machine **500** is, as described above, engineered to have the stator **520** attached to the radially outer circumference of the outer peripheral wall WA**1** and also have the plurality of electrical modules **532** arranged radially inside the outer peripheral wall WA**1**. This layout causes heat generated by the stator **520** to be transferred to the outer peripheral wall WA**1** from radially outside and also causes heat generated by the electrical modules **532** to be transferred to the outer peripheral wall WA**1** from radially inside. The stator **520** and the electrical modules **532** are simultaneously cooled by cooling water flowing through the coolant path **545**, thereby facilitating dissipation of thermal energy generated by heat-producing parts installed in the rotating electrical machine **500**.

The electrical modules **532** arranged radially inside the outer peripheral wall WA**1** and the stator winding **521** arranged radially outside the outer peripheral wall WA**1** are electrically connected together using the winding connecting terminals **633** of the bus bar module **533**. The winding connecting terminals **633** are disposed away from the coolant path **545** in the axial direction of the rotating electrical machine **500**. This facilitates electrical connections of the electrical modules **532** to the stator winding **521** even in a structure in which the coolant path **545** extends in an annular form in the outer peripheral wall WA**1**, in other words, the outside and the inside of the outer peripheral wall WA**1** are isolated from each other by the coolant path **545**.

The rotating electrical machine **500** in this embodiment is designed to have a decreased size of teeth or no teeth (i.e., iron cores) between the conductors **523** of the stator **520** arranged adjacent each other in the circumferential direction to reduce a limitation on a torque output which results from magnetic saturation occurring between the conductors **532**. The rotating electrical machine **500** also has the conductors **523** of a thin flat shape to enhance a degree of torque output. This structure enables a region radially inside the magnetic circuit to be increased in size by reducing the thickness of the stator **520** without altering the outer diameter of the rotating electrical machine **500**. The region is used to have the outer peripheral wall WA**1** equipped with the coolant path **545** disposed therein and enables the electrical modules **532** to be placed radially inside the outer peripheral wall WA**1**.

The rotating electrical machine **500** is equipped with the magnet unit **512** in which magnet-produced magnetic fluxes are concentrated on the d-axis to enhance a degree of output torque. Such a structure of the magnet unit **512** enables a radial thickness thereof to be reduced and the region radially inside the magnetic circuit to be, as described above, increased in volume thereof. The region is used to have the outer peripheral wall WA**1** with the coolant path **545** disposed therein and also have the plurality of electrical modules **532** to be placed radially inside the outer peripheral wall WA**1**.

The above region also be used to have the bearing **560** and the resolver **660** arranged therein in addition to the magnetic circuit, the outer peripheral wall WA**1**, and the electrical modules **532**.

The tire wheel assembly **400** using the rotating electrical machine **500** as an in-wheel motor is attached to the vehicle body using the base plate **405** secured to the inverter housing **531** and a mount mechanism, such as suspensions. The rotating electrical machine **500** is designed to have a reduced size, thus occupying a decreased size of space in the vehicle body. This enables the volume of space required for installation of a power unit, such as a storage battery in the vehicle or the volume of a passenger compartment of the vehicle to be increased.

Modified forms of the in-wheel motor will be described below.

First Modification of In-Wheel Motor

The rotating electrical machine **500** has the electrical modules **532** and the bus bar module **533** arranged radially inside the outer peripheral wall WA**1** of the inverter unit **530** and also has the stator **520** arranged radially outside the outer peripheral wall WA**1**. Locations of the bus bar modules **533** relative to the electrical modules **532** are optional. The phase windings of the stator winding **521** may be connected to the bus bar module **533** radially across the outer peripheral wall WA**1** using winding connecting wires (e.g., the winding connecting terminals **633**) whose locations are optional.

For example, the bus bar module **533** or the winding connecting wires may be arranged in the following layouts.

(α1) The bus bar module **533** may be located closer to the outer side of the vehicle, that is, the bottom of the rotor carrier **511** than the electrical modules **532** are in the axial direction of the rotating electrical machine **500**.

(α2) The bus bar module **533** may be located closer to the inner side of the vehicle, that is, farther away from the rotor carrier **511** than the electrical modules **532** is in the axial direction.

The winding connecting wires may be placed on the following location.

(β1) The winding connecting wires may be arranged close to the outer side of the vehicle, that is, the bottom of the rotor carrier **511** in the axial direction of the rotating electrical machine **500**.

(β2) The winding connecting wires may be located closer to the inner side of the vehicle, that is, far away from the rotor carrier **511**.

Four types of locations of the electrical modules **532**, the bus bar module **533**, and the winding connecting wires will be described below with reference to FIGS. **72**(*a*) to **72**(*d*). FIGS. **72**(*a*) to **72**(*d*) are longitudinal sectional views which partially illustrate modified forms of the rotating electrical machine **500**. The same reference numbers as employed in the above embodiments refer to the same parts, and explanation thereof in detail will be omitted here. The winding connecting wires **637** are electrical conductors connecting of the phase windings of the stator winding **521** with the bus bar module **533** and correspond to the above described winding connecting terminals **633**.

In the structure illustrated in FIG. **72**(*a*), a locational relation of the bus bar module **533** to the electrical modules **532** corresponds to the above described layout (α1). The winding connecting wires **637** are arranged in the above layout (β1). Specifically, connections of the electrical modules **532** to the bus bar module **533** and connections of the stator winding **521** to the bus bar module **533** are made on the outer side of the vehicle (i.e., close to the bottom of the rotor carrier **511**). This layout is identical with that in FIG. **49**.

The structure in **72**(*a*) enables the coolant path **545** to be formed in the outer peripheral wall WA**1** without any physical interference with the winding connecting wires **637** and also facilitates the layout of the winding connecting wires **637** connecting the stator winding **521** and the bus bar module **533** together.

In the structure illustrated in FIG. **72**(*b*), a locational relation of the bus bar module **533** to the electrical modules **532** corresponds to the above described layout (α1). The winding connecting wires **637** are arranged in the above layout (β2). Specifically, connections of the electrical modules **532** to the bus bar module **533** are made on the outer side of the vehicle (i.e., close to the bottom of the rotor carrier **511**, while the stator winding **521** and the bus bar module **533** are connected close to the inner side of the vehicle (i.e., far away from the rotor carrier **511**).

The structure in FIG. **72**(*b*) enables the coolant path **545** to be formed in the outer peripheral wall WA**1** without any physical interference with the winding connecting wires **637**.

In the structure illustrated in FIG. **72**(*c*), a locational relation of the bus bar module **533** to the electrical modules **532** corresponds to the above described layout (α2). The winding connecting wires **637** are arranged in the above layout (β1). Specifically, connections of the electrical modules **532** to the bus bar module **533** are made on the inner side of the vehicle (i.e., far away from the bottom of the rotor carrier **511**, while the stator winding **521** and the bus bar module **533** are connected close to the outer side of the vehicle (i.e., close to the rotor carrier **511**).

In the structure illustrated in FIG. **72**(*d*), a locational relation of the bus bar module **533** to the electrical modules **532** corresponds to the above described layout (α2). The winding connecting wires **637** are arranged in the above layout (β2). Specifically, connections of the electrical modules **532** to the bus bar module **533** and connections of the stator winding **521** to the bus bar module **533** are made on the inner side of the vehicle (i.e., far away from the bottom of the rotor carrier **511**).

The structure in FIG. **72**(*c*) or **72**(*d*) in which the bus bar module **533** is arranged farther away from the rotor carrier **511** than the electrical modules **532**, thereby facilitating layout of electrical wires leading to, for example, an electrical device, such as a fan motor, if installed in the rotor carrier **511**. The structure also enables the bus bar module **533** to be placed close to the resolver **660** mounted closer to the inner side of the vehicle than the bearings **563** are, thereby facilitating layout of electrical wires leading to the resolver **660**.

Second Modification of In-Wheel Motor

Modified forms of a mount structure of the resolver rotor **661** will be described below. Specifically, the rotating shaft **501**, the rotor carrier **511**, and the inner race **561** of the bearing **560** are rotated together in the form of a rotating unit. The structure in which the resolver rotor **611** is mounted to the rotating unit will be described below.

FIGS. **73**(*a*) to **73**(*c*) are structural views which illustrate modifications of the mount structure for attaching the resolver rotor **661** to the rotating unit. In any of the modifications, the resolver **660** is arranged within a hermetically sealed space which is surrounded by the rotor carrier **511** and the inverter housing **531** and protected from splashing of water or mud. FIG. **73**(*a*) shows the same structure of the bearing **560** as that in FIG. **49**. The structures in FIGS. **73**(*b*) and **73**(*c*) have the bearing **560** which is different in structure from that illustrated in FIG. **49** and arranged away from the end plate **514** of the rotor carrier **511**. FIGS. **73**(*a*) to **73**(*c*) each demonstrate two available locations where the resolver rotor **661** is mounted. Although not clearly illustrated, the boss **548** of the bossed member **543** may be extended to or near the outer circumference of the resolver rotor **661** to have the resolver stator **662** secured to the boss **548**.

In the structure illustrated in FIG. **73**(*a*) the resolver rotor **661** is attached to the inner race **561** of the bearing **560**. Specifically, the resolver rotor **661** is secured to a surface of the flange **561***b* of the inner race **561** which faces in the axial direction or an end surface of the cylinder **561***a* of the inner race **561** which faces in the axial direction.

In the structure illustrated in FIG. **73**(*b*), the resolver rotor **661** is attached to the rotor carrier **511**. Specifically, the resolver rotor **661** is secured to an inner peripheral surface of the end plate **514** of the rotor carrier **511**. The rotor carrier **511** has the hollow cylinder **515** extending from an inner circumferential edge of the end plate **514** along the rotating shaft **501**. The resolver rotor **661** may alternatively be secured to an outer periphery of the cylinder **515** of the rotor carrier **511**. In the latter case, the resolver rotor **661** is disposed between the end plate **514** of the rotor carrier **511** and the bearing **560**.

In the structure illustrated in FIG. **73**(*c*), the resolver rotor **661** is attached to the rotating shaft **501**. Specifically, the resolver rotor **661** is mounted on the rotating shaft **501** between the end plate **514** of the rotor carrier **511** and the bearing **560** or on the opposite side of the bearing **560** to the rotor carrier **511**.

Third Modification of In-Wheel Motor

Modifications of the structures of the inverter housing **531** and the rotor cover **670** will be described below with reference to **74**(*a*) and **74**(*b*) which are longitudinal sectional view schematically illustrating the structure of the rotating electrical machine **500**. The same reference number as employed in the above embodiments refer to the same parts. The structure in FIG. **74**(*a*) substantially corresponds to that illustrated in FIG. **49**. The structure in FIG. **74**(*b*) substantially corresponds to a partially modified form of that in **74**(*a*).

In the structure illustrated in FIG. **74**(*a*), the rotor cover **670** secured to an open end of the rotor carrier **511**. The rotor cover **670** surrounds the outer peripheral wall WA**1** of the inverter housing **531**. In other words, the rotor cover **670** has an inner circumferential end surface facing the outer peripheral surface of the outer peripheral wall WA**1**. The sealing member **671** is disposed between the inner circumferential end surface of the rotor cover **670** and the outer peripheral surface of the outer peripheral wall WA**1**. The housing cover **666** is disposed inside the boss **548** of the inverter housing **531**. The sealing member **667** is disposed between the housing cover **666** and the rotating shaft **501**. The external terminals **632** of the bus bar module **533** extend through the wall of the inverter housing **531** downward, as viewed in FIG. **74**(*a*).

The inverter housing **531** has formed therein the inlet path **571** and the outlet path **572** which communicate with the coolant path **545**. The inverter housing **531** has also formed thereon the inlet/outlet port **574** in which open ends of the inlet path **571** and the outlet path **572** lie.

In the structure illustrated in FIG. **74**(*b*), the inverter housing **531** (i.e., the bossed member **543**) has the annular protrusion **681** formed thereon in the shape of a flange. The annular protrusion **681** extends substantially parallel to the rotating shaft **501** inwardly in the inverter housing **531** (i.e., in the vehicle). The rotor cover **670** surrounds the protrusion **681** of the inverter housing **531**. In other words, the rotor cover **670** has an inner end surface facing the outer periphery of the protrusion **681**. The sealing member **671** is interposed between the inner end surface of the rotor cover **670** and the outer periphery of the protrusion **681**. The external terminals **632** of the bus bar module **533** extend through the wall of the boss **548** of the inverter housing **531** into the inner space of the boss **548** and also pass through the wall of the housing cover **666** toward the inside of the vehicle (downward, as viewed in FIG. **74**(*b*)).

The inverter housing **531** has formed therein the inlet path **571** and the outlet path **572** which communicate with the coolant path **545**. The inlet path **571** and the outlet path **572** extend to the inner periphery of the boss **548** and then connect with the connecting pipes **682** which extend inwardly through the wall of the housing cover **666** (i.e. downward as viewed in FIG. **74**(*b*)). Portion of the pipes **682** extending inside the housing cover **666** (i.e., toward the inside of the vehicle) serve as the inlet/outlet port **574**.

The structure in FIG. **74**(*a*) or **74**(*b*) hermetically seals the inner space of the rotor carrier **511** and the rotor cover **670** and achieves smooth rotation of the rotor carrier **511** and the rotor cover **670** relative to the inverter housing **531**.

Particularly, the structure in FIG. **74**(*b*) is designed to have the rotor cover **670** which is smaller in inner diameter than that in FIG. **74**(*a*). The inverter housing **531** and the rotor cover **670** are, therefore, laid to overlap each other in the axial direction of the rotating shaft **501** inside the electrical modules **532** in the vehicle, thereby minimizing a risk of adverse effects of electromagnetic noise in the electrical modules **532**. The decreased inner diameter of the rotor cover **670** results in a decrease in diameter of a sliding portion of the sealing member **671**, thereby reducing mechanical loss of rotation of the sliding portion.

Fourth Modification of In-Wheel Motor

A modification of the structure of the stator winding **521** will be described below with reference to FIG. **75**.

The stator winding **521** is, as clearly illustrated in FIG. **75**, made of conductors which are shaped to have a rectangular transverse section and wave-wound with a long side thereof extending in the circumferential direction of the stator winding **521**. Each of the three-phase conductors **532** of the stator winding **521** has coil ends and coil sides. The coil sides are arranged at a given interval away from each other and connected together by the coil ends. The coil sides of the conductors **523** which are arranged adjacent each other in the circumferential direction of the stator winding **521** have side surfaces which face in the circumferential direction and placed in contact with each other or at a small interval away from each other.

The coil ends of each of the phase windings of the stator winding **521** are bent in the radial direction. Specifically, the stator winding **521** (i.e., the conductors **523**) is bent inwardly in the radial direction at locations which are different among the U-, V-, and W-phase windings and away from each other in the axial direction, thereby avoiding physical interference with each other. In the illustrated structure, the coil ends of the conductors **523** of the U-, V-, and W-phase windings are, as described above, bent at right angles inwardly in the radial direction of the stator winding **521** at locations axially offset from each other by a distance equivalent to the thickness of the conductors **523**. The coil sides of the conductors **523** which are arranged adjacent each other in the circumferential direction have lengths which extend in the axial direction and are preferably identical with each other.

The production of the stator **520** in which the stator core **522** is installed in the stator winding **521** may be achieved by preparing the hollow cylindrical stator winding **521** which has a slit to make end surfaces facing in the circumferential direction, in other words, to make the stator winding **521** in a substantially C-shape, fitting the stator core **522** inside an inner periphery of the stator winding **521**, and then joining the facing end surfaces to complete the stator winding **521** of a complete hollow cylindrical shape.

Alternatively, the stator **520** may be produced by preparing the stator core **522** made of three discrete core sections arranged adjacent each other in the circumferential direction and then placing the core sections inside the inner periphery of the hollow cylindrical stator winding **521**.

Fifteenth Modification

The rotating electrical machine **700** according to the fifteenth modification will be discussed below.

The rotating electrical machine **700** is employed as a power unit for vehicles. An overview of the rotating electrical machine **700** is shown in FIGS. **76** to **78**. FIG. **76** is a perspective view illustrating the overall structure of the rotating electrical machine **700**. FIG. **77** is a longitudinal sectional view of the rotating electrical machine **700**, and FIG. **78** is an exploded sectional view of the rotating electrical machine **700**.

The rotating electrical machine **700** in this modification is designed as an outer-rotor surface-magnet rotating electrical machine. The rotating electrical machine **700** includes a machine assembly, a housing **831** disposed to surround the machine assembly, and a cover **832**. The machine assembly is comprised of a rotor **710**, a rotating shaft **701** provided integrally with the rotor **710**, a stator **730**, an inner unit **770**, and a bus bar module **810**. The machine assembly, housing **831**, and cover **832** are each arranged coaxially with the rotating shaft **701**, and are assembled to the rotating shaft **701** in a given order in the axial direction to complete the rotating electrical machine **700**.

The rotor **710** is retained by a pair of bearings **791** and **792** that are provided radially inside the inner unit **770** in the cantilever form, and is rotatable while being retained by the bearings **791** and **792**. A connection shaft **705** is integrally joined to the rotating shaft **701**, and the connection shaft **705** is secured to an axle or wheels.

In the rotating electrical machine **700**, each of the rotor **710** and the stator **720** has a hollow cylindrical shape, and the rotor **710** and the stator **720** are disposed to face each other through an air gap. Rotation of the rotating shaft **701** causes the rotor **710** to rotate radially outside the stator **720**. The rotor **710** works as a field generator. The stator **720** works as an armature.

The rotor **710**, as illustrated in FIG. **79**, includes a hollow cylindrical rotor carrier **711**, and an annular magnet unit **712** secured to the rotor carrier **711**.

The rotor carrier **711** is comprised of an end plate **713**, and a hollow cylindrical portion **714**. The cylindrical portion **714** axially extends from the outer periphery of the end plate **713**.

The end plate **713** has a through hole **713*a*** formed therethrough. The rotating shaft **701** passes through the through hole **713*a*** and is retained to the end plate **713** with fasteners, such as bolts.

The rotating shaft **701** has a flange **702** extending from a joint of the rotating shaft **701**, to which the rotor carrier **711** is secured, in a direction traversing or perpendicular to the axial direction of the rotating shaft **701**. The flange **702** has an outer surface joined to an inner surface of the end plate **713**, so that the rotating shaft **701** is secured to the rotor carrier **711**.

The magnet unit **712** includes a hollow cylindrical magnet holder **721**, magnets **722**, and an end plate **723**. The magnets **722** are secured to the inner periphery of the magnet holder **721**. The magnet holder **721** has opposing first and second ends in the axial direction of the rotor **710**, and each magnet **722** similarly has opposing first and second ends in the axial direction of the rotor **710**. The rotor carrier **711** is secured to the first end of each magnet **722**, and the end plate **723** is secured to the second end of each magnet **722**.

The length of the magnet holder **721** in the axial direction of the rotor **710** is set to be identical to that of each magnet **722** in the axial direction of the rotor **710**. The magnets **722** secured to the inner periphery of the magnet holder **721** result in being surrounded by the magnet holder **721**.

The magnet holder **721** and each magnet **722** are secured to the rotor carrier **711** while the first end of the magnet holder **721** and the first end of each magnet **722** are in contact with the rotor carrier **711**. The magnet holder **721** and each magnet **722** are also secured to the rotor carrier **711** while the second end of the magnet holder **721** and the second end of each magnet **722** are in contact with the end plate **723**.

Each of the rotor carrier **711**, magnet holder **721**, and end plate **723** is made from a non-magnetic material, such as aluminum or non-magnetic stainless (for example, SUS304). It is advisable that each of the elements **711**, **721**, and **723** is made from light metal, such as aluminum. Each of the elements **711**, **721**, and **723** may be made of synthetic resin. The elements **711**, **721**, and **723** may be preferably joined to each other by welding or bonding techniques.

FIG. **80** is an enlarged view of a cross-sectional structure of a part of the magnet unit **712**. Easy axes of magnetization of a selected magnet **722** are illustrated by arrows in FIG. **80**.

The magnets **722** are disposed in the magnet unit **712** to have different magnetic poles arranged alternately in a circumferential direction of the rotor **710**. This results in the magnet unit **712** having a plurality of magnetic poles arranged in the circumferential direction of the rotor **710**. Each magnet **722** is made of an anisotropic permanent sintered neodymium magnet whose intrinsic coercive force is 400 [kA/m] or more and whose remanent flux density is 1.0 [T] or more.

The magnets **722** are arranged such that each magnet **722** is disposed between a corresponding circumferentially adjacent pair of d-axes; each of the d-axes represents a center of a corresponding one of the magnetic poles. In other words, the magnets **722** are arranged such that (i) each magnet **722** serves as a corresponding magnetic pole, and (ii) each q-axis represents a center of a corresponding one of the magnets **722** in the circumferential direction of the rotor **710**.

Each magnet **722** has opposing inner and outer surfaces in the radial direction, and the inner surface of each magnet **722** works as a flux input/output surface **724** from which magnetic flux are outputted or into which magnetic flux are inputted.

Each magnet **722** has d-axis side regions and a q-axis side region. Each d-axis side region of the magnet **722** is located to be closer to a corresponding adjacent d-axis than the q-axis side region is, and the q-axis side region of the magnet **722** is located to be closer to the q-axis than the d-axis side regions are.

The direction of the easy axis of magnetization located in each d-axis side region of the magnet **722** is different from the direction of the easy axis of magnetization located in the q-axis side region of the magnet **722**. That is, the direction of the easy axis of magnetization located in each d-axis side region of the magnet **722** is oriented to be parallel to the d-axis, and the direction of the easy axis of magnetization located in the q-axis side region of the magnet **722** is oriented to be perpendicular to the q-axis. This results in a circular-arc magnetic path being created in accordance with the easy axes of magnetization oriented in each magnet **722**.

In other words, each magnet **722** is magnetically oriented to have

(1) A first set of easy axes of magnetization formed in each of the d-axis side regions closer to the corresponding d-axis that is a center of the corresponding magnetic pole

(2) A second set of easy axes of magnetization formed in the q-axis side region closer to the q-axis that is a boundary between a corresponding adjacent pair of the magnetic poles

(3) The easy axes of magnetization formed in each of the d-axis side regions are more parallel to the corresponding one of the d-axes than the easy axes of magnetization formed in the q-axis side region are

Each of the magnets **722** arranged in the circumferential direction of the rotor **710** strengthens the magnetic flux on each adjacent d-axis while minimizing change in magnetic flux on or around the q-axis. This therefore offers each magnet **722** that results in a smooth change in surface magnetic flux from the corresponding q-axis to each d-axis on the corresponding magnetic pole.

The magnets **722** may be arranged such that each d-axis represents a center of a corresponding one of the magnets **722** in the circumferential direction of the rotor **710**. In place of the above structure of the rotor **710** that includes the magnets **722** whose number is identical to the number of magnetic poles, the rotor **710** may be equipped with an assembly of magnets that are joined to one another to form a ring shape.

Each magnet **722** preferably has the following configuration. Each magnet **722** has a thickness, referred to as a radial thickness, in a radial direction of the rotor **710** passing through the corresponding magnet **722**. The flux input/output surface **724** of the magnet **722** has a circular-arc shape, and the circular-arc flux input/output surface **724** has a first segment defined between the q-axis and one of the d-axes, and a second segment defined the q-axis and the other of the d-axes. Each of the first and second segments of the circular-arc flux input/output surface **724** of the magnet **722** has a length that is longer than the radial thickness of the magnet **722**.

Each magnet **722** has, as illustrated in FIG. **81**, an intersection point CP between the q-axis and the flux input/output surface **724**. Let us define the intersection point CP as a center point CP, and also define that a circle X around the center point CP; the circle has the radius that is equal to the radial thickness of the magnet **722**. This circle X, which will be referred to as an orientation circle X, that defines easy axes of magnetization in the magnet **722**.

Each magnet **722** is specially configured such that the magnet **722** occupies a quarter region of the orientation circle X. That is, each magnet **722** has arc-shaped easy axes of magnetization that pass across the q-axis thereof.

One of the easy axes of magnetization of the magnet **722**, which passes through an intersection point between the q-axis and the radially outer surface opposite to the flux input/output surface **724**, passes through the quarter part of the orientation circle X located in the magnet **722**. The one of the easy axes of magnetization of the magnet **722**, which passes through the quarter part of the orientation circle X located in the magnet **722**, results in the strongest magnetic flux.

Each magnet **722** is configured to occupy a quarter region of the orientation circle X as set forth above. This configuration enables magnetic paths to be created in the magnet **722** while the length of a magnetic path passing through the intersection point between the q-axis and the radially outer surface is ensured as the length defined by the quarter part of the orientation circle X.

Each of the first and second segments of the circular-arc flux input/output surface **724** of the magnet **722** has the length that is longer than the radial thickness of the magnet **722**. This configuration may lead to a risk of magnetic flux leakage from the magnet **722** toward the radial outside of the magnet **722**, i.e., the opposite side of the stator **50**.

The rotor **710** according to the fifteenth modification, which includes the magnet holder **721** made of a non-magnetic material, however results in reduction in adverse effects of magnetic flux leakage.

Adjacent corners **725** of the radially outer surfaces of the magnets **722** are each cut to form a recess **725**, **725** located on the corresponding d-axis. Each of the magnets **722** has a recess **726** formed in the radially inner surface thereof and located on the corresponding q-axis.

Each recess **725**, **725** circumferentially extends within a predetermined range around the corresponding d-axis. Each recess **726** also circumferentially extends within a predetermined range around the corresponding q-axis.

The directions of the above easy axes of magnetization of the magnet **722** cause magnetic paths located close to each d-axis and the radially outer surface to be shorter. Similarly, the directions of the above easy axes of magnetization of the magnet **722** cause magnetic paths located close to the q-axis and the radially inner surface to be shorter.

Each magnet **722** is therefore configured such that some portions, which have weaker magnetic fluxes due to the shorter magnetic paths, have been already eliminated, because each of the eliminated portions have difficulty in creating a sufficient amount of magnetic flux.

The magnet holder **721** is disposed on the radial outside of the circumferentially arranged magnets **722**. The magnet holder **721** may be comprised of (i) a radial outside portion disposed on the radial outside of the circumferentially arranged magnets **722**, (ii) an inter-magnet portion disposed in each adjacent pair of magnets **722**, and (iii) a radial inside portion disposed on the radial inside of the circumferentially arranged magnets **722**. In other words, the magnet holder **721** may be configured to enclose the magnets **722**. For the magnet holder **721** comprised of the radial outside and inside portions, the radial outside portion of the magnet holder **721** may preferably have higher strength than the radial inside portion of the magnet holder **721**.

The magnet holder **721** has convexities or protrusions **727** formed on an inner peripheral surface thereof. Each of the protrusions **727** is fit in a corresponding one of the recesses **725**, **725** of the magnets **722**. Engagement of the recesses **725**, **725** of the magnets **722** and the respective protrusions **727** of the magnet holder **721** holds the magnets **722** from moving in the circumferential direction of the rotor **710**. The protrusions **727** of the magnet holder **721**, thus, serve as stoppers for stopping the magnets **722** from being rotated. For the magnet holder **721** comprised of the radial inside portion disposed on the radial inside of the magnets **722**, i.e., disposed closer to the stator **730** than the magnets **722**, the radial inside portion of the magnet holder **721** may have protrusions that are located to fit the respective recesses **726** of the magnets **722**.

Next, the structure of the stator **730** will be described below.

The stator **730** includes a stator winding, i.e., a stator-winding assembly, **731** and a stator core **732**. FIG. **82** is a perspective view illustrating the structure of the stator **730**. FIG. **83** is an exploded view of the stator winding **731** and the stator core **732**. FIG. **84** is a perspective view illustrating only the structure of a U-phase winding in the stator winding **731**. FIG. **85** is a longitudinal sectional view of the stator winding **730**.

The stator core **732** is comprised of a plurality of core sheets **732***a*, each of which is made of a magnetic steel plate, stacked in the axial direction in the shape of a hollow cylinder having a given thickness in the radial direction. The stator winding **731** is mounted on an outer peripheral surface of the stator core **732** which faces the rotor **710**. The stator core **732** does not have any irregularities on the outer peripheral surface thereof. The stator core **732** functions as a back yoke.

The stator core **732** is, for example, comprised of the plurality of core sheets **732***a* stacked in the axial direction; each core sheet **732***a* has been punched out to have an annular plate-like shape. For the stator core **732** having a helical configuration, the stator core **732** may be comprised of an elongated sheet helically wound and stacked in the axial direction to have a hollow cylindrical shape.

The stator core **732** has opposing first and second ends in the axial direction, and has annular surfaces of the respective first and second ends; the circular surfaces will be referred to as end surfaces. First and second end rings **733** are fixedly mounted on the respective lower and upper end surfaces of the stator core **732**. Each of the first and second end rings **733** serves as a retainer to retain the stator winding **731**, which has been installed in the stator core **732**, at a predetermined position in the circumferential direction. The stator core **732** and the first and second end rings **733** constitute a base member **736**.

Each of the first and second end ring **733** has an outer periphery, and the outer periphery of each of the first and second end rings **733** has engagement faces **734** formed on the outer periphery. Each engagement face **734** is inclined with respect to a corresponding tangent to a circle on the outer periphery; the circle has the same center as the corresponding one of the first and second end ring **733**. The engagement faces **734** respectively have equal lengths in the circumferential direction.

As described later, the stator winding **731** includes a coil side portion that is comprised of conductor portions, i.e., straight sections **744** of a coil module **740**. The number of engagement faces **734** according to the fifteenth modification is set to be identical to the number of the straight sections **744**.

The orientation of one engagement face **734** selected from each circumferentially adjacent pair of engagement faces **734** inclined with respect to the corresponding tangent is opposite to the orientation of the other engagement face **734** selected from the corresponding circumferentially adjacent pair of engagement faces **734** inclined with respect to the corresponding tangent, so that each circumferentially adjacent pair of engagement faces **734** forms a tapered protrusion.

That is, each of the first and second end rings **733** has the tapered protrusions formed on the outer periphery thereof. The tapered protrusions of each of the first and second end rings **733** result in recesses **735** being formed between the tapered protrusions.

The tapered protrusions of the first end ring **733** are in alignment with the tapered protrusions of the second end ring **733** in the axial direction, so that the recesses **735** of the first end ring **733** are in alignment with the recesses **735** of the second end ring **733** in the axial direction. The first and second end rings **733** are fixedly mounted on the respective first and second ends of the stator core **732** in the axial direction while the tapered protrusions of one of the end rings **733** is in alignment with the tapered protrusions of the other of the end rings **733** in the axial direction.

The stator core **732** has a predetermined inner diameter and a predetermined outer diameter, and each of the first and second end rings **733** has a predetermined inner diameter that is the same as the inner diameter of the stator core **732**.

Each of the first and second end rings **733** also has a predetermined maximum outer diameter of an imaginary circle connecting the ends of the respective tapered protrusions, and the maximum outer diameter is the same as the outer diameter of the stator core **732**. Each of the first and second end rings **733** also has a minimum inner diameter that is smaller than the outer diameter of the stator core **732**.

Each of the first and second end rings **733** is made of, for example, a non-magnetic material, such as aluminum or copper. Each of the first and second end rings **733** is welded to a corresponding one of the first and second ends of the stator core **732** in the axial direction. Alternatively, each of the first and second end rings **733** may be mechanically secured to a corresponding one of the first and second ends of the stator core **732** with pin fastening, key press-fit, or bolt fastening. Securing the first and second end rings **733** to the stator core **732** minimizes circumferential misalignment of the first and second end rings **733** with the stator core **732**.

The stator **730**, as illustrated in FIG. **85**, includes an axial inside portion serving as the coil side CS that radially faces the magnets **722** of the rotor **710**, a first axial outside portion serving as a coil end CE**1** located on the axial outside of the coil side CS, and a second axial outside portion serving as a coil end CE**2** located on the axial outside of the coil side CS.

The stator core **732** is disposed inside the coil side CS such that the axial length of the stator core **732** occupies the axial length of the coil side CS. The first end ring **733** is disposed to face the coil end CE**1** of the stator **730**, and the second end ring **733** is disposed to face the coil end CE**2** of the stator **730**. How the first and second end rings **733** are engaged with the stator winding **731** will be described later.

The stator winding **731** is comprised of plural-phase windings that are arranged in a predetermined order in the circumferential direction; the plural-phase windings arranged in the circumferential direction has a hollow cylindrical shape, i.e., an annular shape. The stator core **732** is arranged radially inside the stator winding **731**. The stator winding **731** of the fifteenth modification includes, as the plural-phase windings, a U-phase winding, a V-phase winding, and a W-phase winding.

Each-phase winding in the stator winding **731** includes a plurality of winding segments **741** (see FIG. **86**), and each of the winding segments **741** constitute a coil module **740**. That is, the coil module **740** of each phase winding is comprised of a modularized winding segment **741** of the corresponding phase winding.

Arranging the coil modules **740** of the plural-phase windings in the predetermined order in the circumferential direction results in the conductor portions of the plural-phase windings being arranged in the predetermined order; the arranged conductor portions of the plural-phase windings constitute the coil side CS of the stator winding **731**. FIG. **82** illustrates the predetermined order of arrangement of the conductor portions of the U-, V-, and W-phase windings in the coil side CS of the stator winding **731**. FIG. **84** illustrates the coil modules **740** of the U-phase winding extracted from the coil modules of the three-phase windings. The number of magnet poles of the rotating electrical machine **700** according to the fifteenth modification is set to 24, but may be set to a selected number.

The winding segments **741** of the coil modules **740** of each phase winding are connected in parallel or series to each other to thereby constitute the corresponding phase winding. FIG. **86** illustrates electrical connections among the winding segments **741** of each of the U-, V-, and W-phase windings. In FIG. **86**, the winding segments **741** of each of the U-, V-, and W-phase windings are connected in parallel to each other.

The coil modules **740** are, as illustrated in FIG. **85**, attached to the radial outside of the stator core **732**. The stator winding **731** includes a coil side portion constituting the coil side CS of the stator **730**, a first coil end portion constituting the coil end CE**1** of the stator **730**, and a second coil end portion constituting the coil end CE**2** of the stator **730**. The coil modules **740** are attached to the stator core **732** while both end portions of the coil modules **740** in the axial direction project outside of the stator core **732** in the axial direction.

Each coil module **740** has opposing first and second ends in the axial direction, and the first axial end of each coil module **740** is bent to extend in the radial direction to thereby have a substantially L-shape. Each coil module **740** with the first axial end being bent aims to avoid interference from circumferentially adjacent coil modules **40**.

In particular, the coil modules **740** include coil modules **740**A and coil modules **740**B. Each of the coil modules **740**A includes the first axial end being bent radially outside the stator core **732**, and each of the coil modules **740**B includes the first axial end being bent radially inside the stator core **732**. The stator winding **731** is therefore comprised of the two types of coil modules **740**A and **740**B. The coil modules **740**A and **740**B are mounted to the stator core **732** with their bent first axial ends are opposite from one another.

The stator **730** includes first and second restraint rings **760**. The first restraint ring **760** is, as illustrated in FIG. **82**, mounted around a predetermined first axial position of a radial outer portion of the assembly of the coil modules **740** mounted to the stator core **732**. Similarly, the second restraint ring **760** is, as illustrated in FIG. **82**, mounted around a predetermined second axial position of the radial outer portion of the assembly of the coil modules **740** mounted to the stator core **732**. Each of the first and second restraint rings **760** serves as a restraint member that radially restrains the coil modules **740**, i.e., the stator winding **731**. Each of the first and second restraint rings **760** is, for example, designed as a metallic annular ring.

C rings or multiple rings, whose free ends are joined to each other by welding or bonding, may be used as the first and second restraint rings **760**. Each of the first and second restraint rings **760**, which is made of a C ring or a multiple ring, may preferably have elasticity and an outer diameter in their natural condition which is smaller than the outer diameter of the stator winding **731**.

A linear member, such as a string, a cord, or a wire, may be used as the restraint member, and the restraint member may be helically wound around the outer peripheral portion of the stator winding **731**. As one example, a string dampened with varnish may be used as the restraint member. The varnish strengthens the binding force of the string wound around the stator winding **731**.

The following describes the configuration of each coil module **740**.

Each coil module **740** is configured as a sub assembly comprised of the winding segments **741** and a winding holder **742**.

First, the following describes the configuration of the coil module **740**A. In the following discussion, the winding segments **741** of the coil module **740**A will also be referred to as winding segments **741**A, and the winding holder **742** of the coil module **740**A will also be referred to as a winding holder **742**A. Similarly, the winding segments **741** of the coil module **740**B will also be referred to as winding segments **741**B, and the winding holder **742** of the coil module **740**B will also be referred to as a winding holder **742**B.

FIG. **87**(*a*) is a perspective view of the coil module **740**A, and FIG. **87**(*b*) is a perspective view illustrating only the coil segment **741**A of the coil module **740**A. FIG. **87**(*c*) is a perspective view illustrating only the winding holder **742**A of the coil module **740**A, and FIG. **87**(*d*) is a side view of the coil module **740**A.

FIG. **88**(*a*) is a transverse sectional view of the coil module **740**A, which is taken along the line **88**A-**88**A in FIG. **87**(*d*), and FIG. **88**(*b*) is a transverse sectional view of the coil module **740**A, which is taken along the line **88**B-**88**B in FIG. **87**(*d*). The left side of the coil module **740**A illustrated in FIG. **87**(*d*) corresponds to a stator-core side closer to the stator core **732** than the right side of the coil module **740**A is. The lower side of the coil module **740**A illustrated in each of FIGS. **88**(*a*) and **88**(*b*) corresponds to the stator-core side of the coil module **740**A.

The coil module **740**A includes the winding segment **741**A, and the winding holder **742**A. The winding segment **741**A is comprised of a conductive wire **743** that is multiply wound. The winding holder **742**A has insulation performance. The winding segment **741**A is integrally assembled to the winding holder **742**A. The winding holder **742**A is provided to electrically isolate the winding segment **741**A from its surrounding. In particular, the winding holder **742**A aims to electrically insulate between the winding segment **741**A and the stator core **732**.

The coil module **740**A has an elongated annular shape in the axial direction of the stator core **732**.

Specifically, the coil module **740**A is comprised of a pair of straight sections **744** and a bent portion **745**. The straight sections **744** are disposed to extend in parallel to the axial direction. Lower ends of the straight sections **744** in FIG. **87**(*a*) correspond to the first axial ends of the coil module **740**A. The bent portion **745** joins the lower ends of the straight sections **744**, and is bent from the straight sections **744** to extend perpendicularly to the axial direction, so that the coil module **740**A has, as a whole, a substantially L-shape.

The winding segment **741**A is comprised of a pair of intermediate conductor portions **746**, a first link portion **747**, and a second link portion **748**. The intermediate conductor portions **746** are disposed to linearly extend in parallel to each other. Each of the intermediate conductor portions **746** has opposing first and second axial ends respectively correspond to the first and second axial ends of the coil module **740**A. The first link portion **747** links the first axial ends of the respective intermediate conductor portions **746** to each other, and the second link portion **748** links the second axial ends of the respective intermediate conductor portions **746** to each other. The assembly of the intermediate conductor portions **746**, the first link portion **747**, and the second link portion **748** constitutes the winding segment **741**A having an annular shape.

The intermediate conductor portions **746** are arranged at a predetermined number of coil pitches away from each other; the coil pitch corresponds to the width of the intermediate conductor portion **746** in the circumferential direction. This arrangement of the intermediate conductor portions **746** of each phase winding enables at least one intermediate conductor portion **746** of at least one other-phase winding to be arranged between the intermediate conductor portions **746** of the corresponding phase winding.

The intermediate conductor portions **746** of each phase winding according to the fifteenth modification are arranged two coil pitches away from each other. This arrangement of the intermediate conductor portions **746** of each phase winding according to the fifteenth modification enables two intermediate conductor portions **746** of the respective other phase windings to be arranged between the intermediate conductor portions **746** of the corresponding phase winding.

The first link portions **747** of the coil segments **741**A constitute the coil end CE**1**, and the second link portions **748** of the coil segments **741**A constitute the coil end CE**2** (see FIG. **85**). Specifically, the first link portion **747** of a given-phase winding links the intermediate conductor portions **746**, which are located at different positions in the circumferential direction, of the same-phase winding to each other in the coil end CE**1**. Similarly, the second link portion **748** of a given-phase winding links the intermediate conductor portions **746**, which are located at different positions in the circumferential direction, of the same-phase winding to each other in the coil end CE**2**.

The first link portion **747** of the winding segment **741**A corresponds to the bent portion **745** of the coil module **740**A, and the first link portion **747** is thus bent to extend perpendicularly to the intermediate conductor portions **746**, i.e., to the axial direction. In contrast, the second link portion **748** of the winding segment **741**A is configured to face the intermediate conductor portions **746** in the axial direction, and link the second axial ends of the intermediate conductor portions **746** to each other. This results in the winding segment **747**A having, as a whole, a substantially L-shape. In FIG. **87**(*d*), a boundary BD between the coil side CS and the coil end CE**1** and a boundary BD between the coil side CS and the coil end CE**2** are each illustrated by a broken line.

The first link portion **747** of the winding segment **741**A, which constitutes the coil end CE**1**, includes an outward bent portion Y**1** bent radially outwardly. That is, the winding segment **741**A has the outward bent portion Y**1** formed at the first axial end, i.e., at the side of the coil end CE**1**, and bent radially outwardly, and has no radial bent portion formed at the second axial end, i.e., at the side of the coil end CE**2**.

The winding segment **741**A is, as illustrated in FIG. **88**(*a*), comprised of the multiply wound conductive wire **743** to thereby have a substantially rectangular or square shape in its transverse section. FIG. **88**(*a*) illustrates the transverse section of the intermediate conductor portions **746** of the coil module **740**A. As illustrated in FIG. **88**(*a*), the conductive wire **743** are multiply wound in the winding holder **742**A, so that parts of the multiply-wound conductive wire **743** are arrayed in each intermediate conductor portion **746** in both the circumferential and radial directions.

In each of the first and second link portions **747** and **748**, which extends in the circumferential direction, of the winding segment **741**A, parts of the multiply-wound conductive wire **743** are arrayed in both the axial and radial directions.

In particular, the conductive wire **743** according to the fifteenth modification is concentrically wound in the winding holder **742**A to thereby constitute the winding segment **741**A. The conductive wire **743** may be freely wound in the winding holder **742**A. For example, the conductive wire **743** may be multiply wound in the winding holder **742**A in the form of an alpha winding coil.

The conductive wire **743** has both ends **743***a* and **743***b* opposite to each other. From the multiply wound conductor wire **743** of the winding segment **741**A, as illustrated in FIG. **87**(*a*), the ends **743***a* and **743***b*, which will be referred to as winding ends **743***a* and **743***b*, are drawn out from the respective ends of the first link portion **747**, in other words, from the respective ends of the bent portion **745**. One of the winding ends **743***a* and **743***b* represents the start of winding of the multiply wound conductor wire **743**, and the other thereof represents the end of winding of the multiply wound conductor wire **743**. The winding end **743***a* is connected to a current input/output (I/O) terminal, and the winding end **743***b* is connected to the neutral point.

The winding holder **742**A has a bobbin shape, and is made of an insulating material, such as a synthetic resin material. Like the winding segment **741**A, the winding holder **742**A has, as a whole, a substantially L-shape. The winding holder **742**A includes intermediate holder portion disposed to extend along the respective intermediate conductive portions **746** of the winding segment **741**A, a first link holder portion disposed to extend along the first link portion **747** of the winding segment **741**A, and a second link holder portion disposed to extend along the second link portion **748** of the winding segment **741**A.

The winding holder **742**A is disposed to surround each intermediate conductor portion **746** of the winding segment **741**A on three sides as illustrated in the transverse section of each intermediate conductor portion **746** in FIG. **88**(*a*).

Specifically, the winding holder **742**A is comprised of a first wall portion **751**, a second wall portion **752**, and third wall portions **753**. The first wall portion **751** is disposed to be closer to the stator core **732** than the second and third wall portions **752** and **753** are. The second wall portion **752** is disposed to be farther away from the stator core **732** than the first wall portion **751** is. The third wall portions **753** join the first and second wall portions **751** and **752** to each other. The first wall portion **751** serves as a near back-yoke insulation wall, the second wall portion **752** serves as a far back-yoke insulation wall, and each of the third wall portions **753** serves as a circumferential insulation wall. Each of the third wall portions **753** constitutes an inner surface of a corresponding one of the straight sections **744** that are arranged in the circumferential direction. The third wall portions **753** are each oriented toward the center axis of the stator core **732**.

The winding holder **742**A includes a housing chamber **755** defined by the first wall portion **751**, second wall portion **752**, and third wall portions **753**. The winding segment **741**A is installed in the housing chamber **755** of the winding holder **742**A. Each intermediate conductor portion **746** of the winding segment **741**A installed in the housing chamber **755** is insulated from a side closer to the stator core **732**, a side farther away from the stator core **732**, and an inner circumferential side by the first wall section **751**, the second wall section **752**, and the corresponding one of the third wall portions **753**.

This results in each intermediate conductor portion **746** being electrically isolated from the stator core **732** by the first wall portion **751**, being covered with the second wall portion **752** to prevent the corresponding intermediate conductor section **746** from being exposed to the rotor **710**, i.e., the air gap, and being electrically isolated from a circumferentially adjacent intermediate conductor portion **746** by the corresponding third wall portion **753**.

The first wall portion **751** of the winding holder **742**A has a predetermined radial thickness, i.e., a predetermined dimension in the radial direction, which will be referred to as T**11**. The second wall portion **752** of the winding holder **742**A has a predetermined radial thickness, i.e., a predetermined dimension in the radial direction, which will be referred to as T**12**. Each third wall portion **753** of the winding holder **742**A has a predetermined circumferential thickness, i.e., a predetermined dimension in the circumferential direction, which will be referred to as T**13**. It is preferable that the thickness T**12** of the second wall portion **752** is smaller than the thickness T**11** of the first wall portion **751**, which is expressed by T**11**>T**12**. Because the second wall portion **752** is disposed to be closer to at least one magnet **722** that faces the second wall portion **752**, i.e., the air gap, making thinner the second wall section **752** enables a minimum distance between the winding segment **741**A and at least one magnet **722** that faces the second wall portion **752** to be smaller. This contributes to improvement of the rotating electrical machine **700** of the fifteenth modification.

In addition, making thinner the radial thickness T**12** of the second wall portion **752** while keeping unchanged the minimum distance between the winding segment **741**A and at least one magnet **722** that faces the winding segment **741**A enables the air gap between the coil module **740**, that is, a surface of the winding holder **742**A facing at least one magnet **722**, and the at least one magnet **722** to be larger, thus preventing the turning rotor **710** from contacting to the stator **730**.

The radial thickness T**11** of the first wall portion **751**, which is larger than the radial thickness T**12** of the second wall portion **752**, ensures a sufficient insulation distance between the winding segment **741**A and the stator core **732**, resulting in a higher insulation performance of the stator **730**. The radial thickness T**11** of the first wall portion **751** may be equal to the radial thickness T**12** of the second wall portion **752**.

The circumferential thickness T**13** of each third wall portion **753** is preferably set to be equal to the radial thickness T**12** of the second wall portion **752**. The circumferential thickness T**13** of each third wall portion **753** may be set to larger than or smaller than the radial thickness T**12** of the second wall portion **752**.

The first wall portion **751** of the winding holder **742**A, which constitutes radially inner surfaces of the respective straight sections **744** of the coil module **740**A, is disposed to be radially farther away from the bent portion **745** than the second wall portion **752** is. The second wall portion **752** of the winding holder **742**A, which constitutes radially outer surfaces of the respective straight sections **744** of the coil module **740**A, is disposed to be radially closer to the bent portion **745** than the first wall portion **751** is.

The first wall portion **751** has a first circumferentially outer edge and a first circumferential inner edge that are opposite to each other. The first wall portion **751** also has a second circumferential outer edge and a second circumferential inner edge that are opposite to each other. Similarly, the second wall portion **752** has a first circumferential outer edge and a first circumferential inner edge that are opposite to each other. The second wall portion **752** also has a second circumferential outer edge and a second circumferential inner edge that are opposite to each other.

The winding segment **741**A is housed in the housing chamber **755** of the winding holder **742**A while being in contact with or adjacent to the first wall portion **751**, second wall portion **752**, and the third wall portions **753**. In addition, each intermediate conductor portion **746** of the winding segment **741**A housed in the housing chamber **755** of the winding holder **742**A is located circumferentially outside the corresponding third wall portion **753**.

Each of the intermediate conductor portions **746** of the winding segment **741**A is also located circumferentially inside the first and second circumferential outer edges of the first wall portion **751**, and located circumferentially inside the first and second circumferential outer edges of the second wall portion **752**.

One of the third wall portions **753** is disposed to join between (i) the first circumferential inner edge of the first wall portion **751** and (ii) the first circumferential inner edge of the second wall portion **752**. The other of the third wall portions **753** is disposed to join between (i) the second circumferential inner edge of the first wall portion **751** and (ii) the second circumferential inner edge of the second wall portion **752**.

Each of the first and second circumferential outer edges of the first wall portion **751** projects circumferentially outwardly relative to the corresponding intermediate conductor section **746**. Each of the first and second projecting circumferential outer edges of the first wall portion **751** serves as a projecting portion **751***a*.

Similarly, each of the first and second circumferential outer edges of the second wall portion **752** projects circumferentially outwardly relative to the corresponding intermediate conductor section **746**. Each of the first and second projecting circumferential outer ends of the second wall portion **752** serves as a projecting portion **752***a*.

The projecting portion **751***a* of the first circumferential outer edge of the first wall portion **751** and the projecting portion **752***a* of the first circumferential outer edge of the second wall portion **752**, which face each other, form a first circumferential surplus peripheral wall relative to the corresponding intermediate conductor section **746** of the winding segment **741**A.

Similarly, the projecting portion **751***a* of the second circumferential outer edge of the first wall portion **751** and the projecting portion **752***a* of the second circumferential outer edge of the second wall portion **752**, which faces each other, form a second circumferential surplus peripheral wall relative to the corresponding intermediate conductor section **746** of the winding segment **741**A.

The first circumferential surplus peripheral wall defines, thereinside, an empty space SZ in the housing chamber **755**, and the second circumferential surplus peripheral wall defines, thereinside, an empty space SZ in the housing chamber **755**. In each of the first and second empty spaces SZ, the corresponding intermediate conductor section **746** is not housed.

Each of the empty spaces SZ reduces the possibility of the corresponding intermediate conductor portion **746** of the winding segment **741**A housed in the housing chamber **755** protruding outwardly through the corresponding one of the empty spaces SZ.

An insulating material, such as a synthetic resin material, is filled in the housing chamber **755** in which the winding segment **741**A is housed, so that the winding segment **741**A housed in the housing chamber **755** is molded by the insulating material, such as a resin material.

Alternatively, the winding segment **741**A housed in the housing chamber **755** may be impregnated with an adhesive material containing varnish, so that the winding segment **741**A may be encased in the adhesive. If an insulator-coated conductive wire comprised of a conductive wire covered with an insulator is used as the conductive wire **743**, the parts of the conductive wires **743** in the housing chamber **755** may be joined to each other by the insulators being melted.

The coil modules **740**A are attached to an outer peripheral surface of the cylindrical stator core **732**. The first wall portion **751** of each coil module **740**A, which is closer to the stator core **732** than the second wall portion **752** is, has an inner circular-arc surface whose curvature is identical to the curvature of the outer peripheral surface of the stator core **732**. This enhances adhesion between the stator core **732** and each coil module **740**A. The second wall portion **752** of each coil module **740**A, which is farther away from the stator core **732** than the first wall portion **751** is, may have an outer flat surface or an outer circular-arc surface. The second wall portion **752** of each coil module **740**A according to the fifteenth modification for example has an outer circular-arc surface that is concentric with the inner circular-arc surface of the first wall portion **751**.

Each coil module **740**A, which has the bent portion **745** disposed to be closer to the second wall portion **752** than to the first wall portion **751**, is mounted to the stator core **732** with its bent portion **745** being disposed radially outside the corresponding coil module **740**A.

Each coil module **740**A has a circumferentially first minimum distance between the first and second circumferential outer edges of the first wall portion **751**. Each coil module **740**A also has a circumferentially second minimum distance between the first and second circumferential outer edges of the second wall portion **752**. Each coil module **740**A is designed such that the circumferentially second minimum distance is longer than the circumferentially second minimum distance. The bent portion **745** of the coil module **740**A, which is disposed radially outside the coil module **740**A, has a minimum length in the circumferential direction; the minimum length of the bent portion **745** is identical to the circumferentially second minimum distance.

Each of the strait sections **744** of the coil module **740**A has, as illustrated in FIG. **87**(*d*), a radial inner peripheral surface, and has upper and lower protrusions **756** formed on respective upper and lower portions of a radial inner peripheral surface thereof; the upper and lower protrusions **756** protrude toward the radial inside of the coil module **740**A, i.e., toward the stator core **732**.

The lower protrusion **756** of each straight portion **744** is located to be adjacent to the boundary BD between the coil side CS and the coil end CE**1**. The upper protrusion **756** of each straight portion **744** is located to be adjacent to the boundary BD between the coil side CS and the coil end CE**2**.

That is, the lower protrusion **756** is included in the coil end CE**1** including the first link portion **747** and disposed axially outside the boundary BD, and the upper protrusion **756** is included in the coil end CE**2** including the second link portion **748** and disposed axially outside the boundary BD.

As illustrated in the transverse section of the coil module **740**A in FIG. **88**(*b*), the upper and lower protrusions **756** of each straight portion **744** protrude from the first wall portion **751** that is closer to the stator core **732**.

Specifically, the lower protrusion **756** of each straight portion **744** has an inclined surface **756***a* inclined from the corresponding one of the first and second circumferential outer edges of the first wall portion **751** to the corresponding one of the first and second circumferential inner edges of the first wall portion **751**. Similarly, the upper protrusion **756** of each straight portion **744** has an inclined surface **756***a* inclined from the corresponding one of the first and second circumferential outer edges of the first wall portion **751** to the corresponding one of the first and second circumferential inner edges of the first wall portion **751**.

In particular, the inclined surface **756***a* of the lower protrusion **756** of each straight portion **744** is inclined such that the corresponding one of the first and second inner edges of the first wall portion **751** is farther away from the corresponding straight portion **744** than the corresponding one of the first and second outer edges of the first wall portion **751** is.

Similarly, the inclined surface **756***a* of the upper protrusion **756** of each straight portion **744** is inclined such that the corresponding one of the first and second inner edges of the first wall portion **751** is farther away from the corresponding straight portion **744** than the corresponding one of the first and second outer edges of the first wall portion **751** is.

Alternatively, the inclined surface **756***a* of the lower protrusion **756** of each straight portion **744** may be inclined such that the corresponding one of the first and second outer edges of the first wall portion **751** is farther away from the corresponding straight portion **744** than the corresponding one of the first and second inner edges of the first wall portion **751** is. Similarly, the inclined surface **756***a* of the upper protrusion of each straight portion **744** may be inclined such that the corresponding one of the first and second outer edges of the first wall portion **751** is farther away from the corresponding straight portion **744** than the corresponding one of the first and second inner edges of the first wall portion **751** is.

Next, the following describes the configuration of the coil module **740**B.

The coil module **740**B is basically identical to that of the coil module **740**A except for the orientation of the radially extending bent portion **745** being different from the orientation of the radially extending bent portion **745** of the coil module **740**A. This difference causes the configuration of the coil module **740**B to be slightly different from the configuration of the coil module **740**A. Thus, the following describes mainly the different configuration of the coil module **740**B from the configuration of the coil module **740**A.

FIG. **89**(*a*) is a perspective view of the coil module **740**B, and FIG. **89**(*b*) is a side view of the coil module **740**B. FIG. **90**(*a*) is a transverse sectional view of the coil module **740**B, which is taken along the line **90**A-**90**A in FIG. **89**(*b*), and FIG. **90**(*b*) is a transverse sectional view of the coil module **740**B, which is taken along the line **90**B-**90**B in FIG. **89**(*b*). The left side of the coil module **740**B illustrated in FIG. **89**(*b*) corresponds to a stator-core side closer to the stator core **732** than the right side of the coil module **740**B is. The lower side of the coil module **740**B illustrated in each of FIGS. **90**(*a*) and **90**(*b*) corresponds to the stator-core side of the coil module **740**B.

The coil module **740**B includes the winding segment **741**B, and the winding holder **742**B. The winding segment **741**B is comprised of a conductive wire **743** that is multiply wound. The winding holder **742**B has insulation performance. The winding segment **741**B is integrally assembled to the winding holder **742**B.

The coil module **740**B is comprised of a pair of straight sections **744** and a bent portion **745**. The straight sections **744** are disposed to extend in parallel to the axial direction. Lower ends of the straight sections **744** in FIG. **89**(*a*) correspond to the first axial ends of the coil module **740**B. The bent portion **745** joins the lower ends of the straight sections **744**, and is bent from the straight sections **744** to extend perpendicularly to the axial direction, so that the coil module **740**B has, as a whole, a substantially L-shape.

The configuration of the winding segment **741**B is basically identical to that of the winding segment **741**A. Specifically, like the winding segment **741**A, the winding segment **741**B is comprised of a pair of intermediate conductor portions **746**, a first link portion **747**, and a second link portion **748**. The intermediate conductor portions **746** are disposed to linearly extend in parallel to each other. Each of the intermediate conductor portions **746** has opposing first and second axial ends respectively correspond to the first and second axial ends of the coil module **740**B. The first link portion **747** links the first axial ends of the respective intermediate conductor portions **746** to each other, and the second link portion **748** links the second axial ends of the respective intermediate conductor portions **746** to each other. The assembly of the intermediate conductor portions **746**, the first link portion **747**, and the second link portion **748** constitutes the winding segment **741**B having an annular shape.

The orientation of the radially extending bent portion **745** of the coil module **740**B mounted to the stator core **732** is different from the orientation of the radially extending bent portion **745** of the coil module **740**A mounted to the stator core **732** while the bent first axial ends of the coil modules **740**A and **740**B are opposite from one another. The above differences cause the configuration of the coil module **740**B to be slightly different from the configuration of the coil module **740**A.

The first link portion **747** of the winding segment **741**B, which constitutes the coil end CE**2**, includes an inward bent portion Y**2** bent radially inwardly. That is, the winding segment **741**B has the inward bent portion Y**2** formed at the first axial end, i.e., at the second coil end side, and bent radially inwardly, and has no radial bent portion formed at the second axial end, i.e., at the side of the coil end CE**1**.

The conductive wire **743** of the winding segment **741**B has both ends **743***a* and **743***b* opposite to each other. From the multiply wound conductor wire **743** of the winding segment **741**B, the ends **743***a* and **743***b*, which will be referred to as winding ends **743***a* and **743***b*, are drawn out from the respective ends of the second link portion **748**, in other words, from the respective ends of the second axial end with no bent portion.

The above configurations of the coil modules **740**A and **740**B mounted to the stator coil **732** result in the winding ends **743***a* and **743***b* being drawn out from the same axial side, i.e., the side of the coil end CE**1**, of each of the coil modules **740**A and **740**B.

Like the winding holder **742**A, the winding holder **742**B is, as illustrated in FIG. **90**(*a*), comprised of a first wall portion **751**, a second wall portion **752**, and third wall portions **753**. The first wall portion **751** is disposed to be closer to the stator core **732** than the second and third wall portions **752** and **753** are. The second wall portion **752** is disposed to be farther away from the stator core **732** than the first wall portion **751** is. The third wall portions **753** join the first and second wall portions **751** and **752** to each other.

Unlike the configuration of the winding holder **742**A, the first wall portion **751** of the winding holder **742**B, which constitutes radial inner surfaces of the respective straight sections **744** of the coil module **740**B, is disposed to be radially close to the bent portion **745** than the second wall portion **752** is. The second wall portion **752** of the winding holder **742**B, which constitutes radial outer surfaces of the respective straight sections **744** of the coil module **740**B, is disposed to be radially further from the bent portion **745** than the first wall portion **751** is.

Each coil module **740**B, which has the bent portion **745** disposed to be closer to the first wall portion **751** than to the second wall portion **752**, is mounted to the stator core **732** with its bent portion **745** being disposed radially inside the corresponding coil module **740**B.

Each of the strait sections **744** of the coil module **740**B has, as illustrated in FIG. **89**(*b*), a radial inner peripheral surface, and has upper and lower protrusions **756** formed on respective upper and lower portions of the radial inner peripheral surface thereof; the upper and lower protrusions **756** protrude toward the radial inside of the coil module **740**B, i.e., toward the stator core **732**.

The lower protrusion **756** of each straight portion **744** is located to be adjacent to the boundary BD between the coil side CS and the coil end CE**1**. The upper protrusion **756** of each straight portion **744** is located to be adjacent to the boundary BD between the coil side CS and the coil end CE**2**.

That is, the lower protrusion **756** is included in the coil end CE**1** including the second link portion **748** and disposed axially outside the boundary BD, and the upper protrusion **756** is included in the coil end CE**2** including the first link portion **748** and disposed axially outside the boundary BD. The configuration of each of the upper and lower protrusions **756** of the coil module **742**B is substantially identical to that of the corresponding one of the upper and lower protrusions **756** of the coil module **742**A (see FIG. **90**(*b*)).

Next, the following describes the assembly of the stator core **732** and the coil modules **740**A and **740**B mounted thereto. FIG. **91** is a sectional view indicative of a longitudinal section of the stator **730**, and FIG. **92** is a sectional view indicative of a transverse section of the stator **730**, which is taken along the line **92-92** in FIG. **91**. FIG. **93** is a sectional view indicative of the assembly of the stator core **732** and one of the first and second end rings **733** and the coil module **40**A that are separated from each other.

The first and second end rings **733** are, as illustrated in FIG. **91**, fixedly mounted on the respective first and second ends of the stator core **732** in the axial direction. The coil modules **740**A and **740**B are mounted to the stator core **732** while

(1) The lower protrusions **756** of each coil module **740**A are engaged with the first end ring **733**

(2) The upper protrusions **756** of each coil module **740**A are engaged with the second end ring **733**

(3) The lower protrusions **756** of each coil module **740**B are engaged with the first end ring **733**

(4) The upper protrusions **756** of each coil module **740**B are engaged with the second end ring **733**

The upper projections **756** of the coil modules **740**A and **740**B protrude to axially overlap on the upper end surface of the stator core **732** (see FIG. **91**). The lower projections **756** of the coil modules **740**A and **740**B protrude to axially overlap the lower end surface of the stator core **732** (see FIG. **91**). This results in the stator core **732** being sandwiched between the upper protrusions **756** and lower protrusions **756** of the coil modules **740**A and **740**B in the axial direction of the stator core **732**.

The stator core **732** is comprised of the core sheets **732***a* stacked in the axial direction, so that the stator core **732** is sandwiched between the upper protrusions **756** and the lower protrusions **756** in the stack direction of the core sheets **732***a*. This prevents the clearances between the core sheets **732***a* from expanding, thus preventing unintentional expansion of the length of the stator core **732** in the axial direction.

The first and second restraint rings **760** are mounted around an outer periphery of the assembly of the coil modules **740**A and **740**B. The first and second restraint rings **760** restrain the coil modules **740**A and **740**B to cause the lower and upper protrusions **756** to press the first and second end rings **733**, so that the coil modules **740**A and **740**B are pressed to be engaged with the first and second end rings **733**.

In particular, the first restraint ring **760** is mounted around the predetermined first axial position of the radial outer portion of the assembly of the coil modules **740**A and **740**B; the first axial position radially overlaps the engagement positions between the lower protrusions **756** and the first end ring **733**.

Similarly, the second restraint ring **760** is mounted around the predetermined second axial position of the radial outer portion of the assembly of the coil modules **740**A and **740**B; the second axial position radially overlaps the engagement positions between the upper protrusions **756** and the second end ring **733**.

The above arrangement of the first and second restraint rings **760** reliably maintains the engagement condition between the lower protrusions **756** and the first end ring **733**, and also reliably maintains the engagement condition between the upper protrusions **756** and the second end ring **733**.

Each of the first and second restraint rings **760** is disposed radially outside the assembly of the coil modules **740**A and **740**B, that is, disposed to face the radial inner surfaces of the magnets **722** of the rotor **710**. For avoiding physical interference between the rotor **710** and the first and second restraint rings **760**, it is preferable that a radial thickness of each of the first and second restraint rings **760** as thin as possible.

The first restraint ring **760** may be disposed to be at least partially within the coil side CS in the axial direction, or disposed to be completely within the first coil end CE**1** outside the coil side CS in the axial direction. Similarly, the second restraint ring **760** may be disposed to be at least partially within the coil side CS in the axial direction, or disposed to be completely within the second coil end CE**2** outside the coil side CS in the axial direction.

In particular, the first restraint ring **760** may be preferably disposed completely within the first coil end CE**1** in the axial direction, and disposed radially outside the assembly of the coil modules **740**A and **740**B. Similarly, the second restraint ring **760** may be preferably disposed completely within the second coil end CE**2** in the axial direction, and disposed radially outside the assembly of the coil modules **740**A and **740**B. Given number of restraint rings may be disposed at freely selected positions around the assembly of the coil modules **740**A and **740**B.

The first and second restraint rings **760** are mounted to radially outer surfaces of the second wall portions **752** of the winding holder **742**. To describe it in detail, the first and second restraint rings **760** are arranged to be in contact with the winding holder **742** while being separated from the winding segments **741**. This arrangement of the first and second restraint rings **760** prevents, even if metallic rings are used as the first and second restraint rings **760** for enhancing restraint strength of the assembly of the coil modules **740**A and **740**B, a reduction in the electrical insulation of the winding segments **741**.

The inclined surface **756***a* of each lower protrusion **756** of each coil module **740** is, as illustrated in FIGS. **92** and **93**, in contact with a corresponding one of the engagement portions **756** of the first end ring **733**. Similarly, the inclined surface **756***a* of each upper protrusion **756** of each coil module **740** is, as illustrated in FIGS. **92** and **93**, in contact with a corresponding one of the engagement portions **756** of the second end ring **733**. Each inclined surface **756***a* serves as an engagement surface.

Each of the first and second end rings **733** has the engagement faces **734** continuously formed on the outer periphery thereof in the circumferential direction while the orientations of inclination of the circumferentially continuous engagement faces **734** alternate with each other. This results in the recesses **735** being each formed between a corresponding adjacent pair of engagement faces **734** (see FIG. **93**).

In each recess **735** of the first end ring **733**, adjacent lower protrusions **756** of a corresponding pair of coil modules **740**A and **740**B are fit. Similarly in each recess **735** of the second end ring **733**, adjacent upper protrusions **756** of a corresponding pair of coil modules **740**A and **740**B are fit.

Each of the adjacent lower protrusions **756** fit in the corresponding recess **735** of the first end ring **733** has the first inner edge, and the first inner edge of each of the adjacent lower protrusions **756** is located to be in contact with the bottom of the corresponding recess **735** of the first end ring **733**. This results in, in each recess **735** of the first end ring **733**, the third wall portions **753** of the respective adjacent lower protrusions **756** of a corresponding pair of coil modules **740**A and **740**B being in contact with each other in the circumferential direction.

Similarly, each of the adjacent upper protrusions **756** fit in the corresponding recess **735** of the second end ring **733** has the first inner edge, and the first inner edge of each of the adjacent upper protrusions **756** is located to be in contact with the bottom of the corresponding recess **735** of the second end ring **733**. This results in, in each recess **735** of the second end ring **733**, the third wall portions **753** of the respective adjacent upper protrusions **756** of a corresponding pair of coil modules **740**A and **740**B being in contact with each other in the circumferential direction.

In each tapered protrusion formed by a corresponding circumferentially adjacent pair of engagement faces **734** of the first end ring **733**, the first wall portions **751** of a corresponding pair of coil modules **740**A and **740**B are in contact with or adjacent to each other, and the second wall portions **751** of a corresponding pair of coil modules **740***a* and **740***b* are in contact with or adjacent to each other.

Similarly, in each tapered protrusion formed by a corresponding circumferentially adjacent pair of engagement faces **734** of the second end ring **733**, the first wall portions **751** of a corresponding pair of coil modules **740***a* and **740***b* are in contact with or adjacent to each other, and the second wall portions **751** of a corresponding pair of coil modules **740**A and **740**B are in contact with or adjacent to each other.

As described above, the adjacent lower protrusions **756** of each pair of coil modules **740**A and **740**B are arranged to be circumferentially adjacent to each other through a corresponding circumferentially adjacent pair of engagement faces **734** of the first ring **733**. Similarly, the adjacent upper protrusions **756** of each pair of coil modules **740**A and **740**B are arranged to be circumferentially adjacent to each other through a corresponding circumferentially adjacent pair of engagement faces **734** of the second ring **733**.

This arrangement of the lower and upper protrusions **756** prevents the circumferentially adjacent winding segments **741** from rattling, making it possible to therefore efficiently prevent a positional deviation of the stator winding **731** due to mechanical vibration of the stator **730** or electromagnetic force acting on the stator winding **731**.

Additionally, this arrangement of the lower and upper protrusions **756** minimizes the clearance between each circumferentially adjacent pair of intermediate conductor portions **746**, resulting in an improvement of the space factor of the stator winding **731**.

The first and second restraint rings **760**, which are mounted around the outer periphery of the assembly of the coil modules **740**A and **740**B, cause the lower and upper protrusions **756** to press the first and second end rings **733**, so that the inclined surfaces **756***a* of the lower and upper protrusions **756** of the coil modules **740**A and **740**B are pressed to be in contact with the corresponding engagement faces **734** of the first and second end rings **733**. This results in the coil modules **740**A and **740**B being more strongly fastened to the stator core **732**.

The coil modules **740**A and **740**B are arranged in the circumferential direction of the stator core **732** while the winding segments **741** of each coil module, whose straight sections **744** are housed in the housing chamber **755** of the corresponding winding holder **742**, are arranged at given intervals away from each other.

Specifically, the circumferentially adjacent winding segments **741** are separated from one another by the third wall portions **753** of their winding holders **742** or separated from one another by the empty spaces SZ of the housing chambers **745** of their winding holders **742**. This ensures sufficient electrical insulation between the circumferentially adjacent winding segments **741**.

In particular, each winding segment **741** of one phase winding and the one-side winding segment **741** of another phase winding, which are circumferentially adjacent to one another, are separated from each other by a corresponding set of two third wall portions **753** of their winding holders **742**. The double third wall portions **753** intermediating between each winding segment **741** of one phase winding and a one-side winding segment **741** of another phase winding which are circumferentially adjacent to one another, result in a more higher insulation performance of the stator winding **730**.

Additionally, each winding segment **741** of one phase winding and the other-side winding segment **741** of another phase winding, which are circumferentially adjacent to one another, are separated from each other by a corresponding sequence of two empty spaces SZ of the housing chambers **745** of their winding holders **742**. The two empty spaces SZ of the respective housing chambers **755** are continuously arranged in the circumferential direction, and each of the two empty spaces SZ has resin molded therein. This results in a still more higher insulation performance of the stator winding **731**.

Between each intermediate conductor section **746** and a first-side intermediate conductor section **746**, which are circumferentially adjacent to one another, a corresponding sequence of two third wall portions **735** of different winding holders **742** is disposed.

Additionally, between each intermediate conductor section **746** and a second-side intermediate conductor section **746**, which are circumferentially adjacent to one another, a first corresponding sequence of the projecting portions **751***a* and **752***a* and a second corresponding sequence of the projecting portions **751** and **752** of different winding holders **742** are disposed.

Next, the following describes the inner unit **770**.

FIG. **94** is a longitudinal sectional view of the inner unit **770**, and FIG. **95**, which is also a longitudinal sectional view of the inner unit **770**, illustrates the inner unit **770** to which bearings **791** and **792** are assembled to retain the rotating shaft **701**. Hereinafter, the bearing **791** will also be referred to as a first bearing **791**, and the bearing **792** will also be referred to as a second bearing **792**. The rotating shaft **701** has a base end and an extending end opposing the base end in its axial direction. The first bearing **791** is mounted around the base end of the rotating shaft **701**, which is joined to the connection shaft **705**, and the second bearing **792** is mounted around the extending end of the rotating shaft **701**.

The inner unit **770** includes an inner housing **771**. The inner housing **771** is comprised of an outer cylindrical member **772**, an inner cylindrical member **773**, and an end plate **774**.

The outer cylindrical member **772** has a hollow cylindrical shape, and has a given outer diameter. The inner cylindrical member **773** has a hollow cylindrical shape, and has a given outer diameter that is smaller than the outer diameter of the outer cylindrical member **772**. The inner cylindrical member **773** is disposed radially inside the outer cylindrical member **772**. Each of the outer and inner cylindrical members **772** and **773** has opposing first and second ends in its axial direction. The end plate **774**, which has a substantially circular shape, is fixedly mounted to the first end of each of the outer and inner cylindrical members **772** and **773**.

Each of the members **772** to **774** is preferably made of an electrically conductive material, such as carbon fiber reinforced plastic (CFRP). The first cylindrical member **772** and the end plate **774** have the same outer diameter. The assembly of the outer cylindrical member **772** and end plate **774** defines a housing space thereinside, and the inner cylindrical member **772** is disposed in the housing space. The inner cylindrical member **773** is fastened to the outer cylindrical member **772** and the end plate **774** with fasteners, such as bolts.

The stator core **732** is secured to a radially outer periphery of the outer cylindrical member **772** of the inner housing **771**, resulting in the stator **730** and the inner unit **770** being assembled as a single unit.

The inner housing **771** has formed therein a coolant path **777** through which coolant flows; the coolant **777** is disposed between the outer cylindrical member **772** and the inner cylindrical member **773**. The coolant path **777** is formed to extend in an annular shape in the circumferential direction of the inner housing **771**. An unillustrated coolant pipe is communicably coupled to the coolant path **777**. Coolant is configured to enter the coolant path **777** from the coolant pipe, and circulate through the coolant path **777** to recover heat, and be discharged therefrom into the coolant pipe again.

The inner housing **771** has an annular inner chamber formed radially inside the inner cylindrical member **773**. This enables electrical components, such as electrical components, that constitute an inverter serving as a power converter, to be preferably installed. The electrical components for example include one or more electrical module in each of which semiconductor switches and capacitors are packaged. Arranging the electrical modules to be in contact with the inner cylindrical member **773** enables the coolant flowing through the coolant path **777** to cool the electrical modules.

The outer cylindrical member **772** includes a cylindrical boss **780** disposed radially inside the inner cylindrical member **773**. The boss **780** has a hollow cylindrical shape, and the rotating shaft **701** is disposed to pass through the hollow portion of the boss **780**.

The boss **780** serves as a bearing retainer for retaining the bearings **791** and **792**. That is, the bearings **791** and **792** are fixedly disposed in the hollow portion of the boss **780** (see FIG. **95**).

Each of the bearings **791** and **792** is implemented by, for example, a radial ball bearing that is comprised of a cylindrical inner race, a cylindrical outer race arranged radially outside the inner race, and balls disposed between the inner race and outer race. The outer race is fit in the boss **780**, resulting in the boss **780** being assembled to the inner unit **770**.

The boss **780** is comprised of a first cylindrical retainer wall **781** in which the first bearing **791** is fit to be retained, and a second cylindrical retainer wall **782** in which the second bearing **792** is fit to be retained.

The first bearing **791**, which rotatably retains a predetermined first position of the rotating shaft **710**, has a first size determined based on the retaining first position of the rotating shaft **710**. Similarly, the second bearing **792**, which rotatably retains a predetermined second position of the rotating shaft **710** different from the first position of the rotating shaft **710**, has a second size determined based on the retaining second position of the rotating shaft **710**.

The first size of the first bearing **791** and the second size of the second bearing **792** are respectively determined to be different from each other based on the retaining first and second positions of the rotating shaft **710**. This is because the first and second bearings **791** are subjected to vibration and/or centrifugal load of the rotating shaft **710**, which are different therebetween depending on their retaining first and second positions of the rotating shaft **710**.

Specifically, the first bearing **791**, whose retaining first position of the rotating shaft **710** is closer to the base end than to the extending end, has the first size larger than the second size of the second bearing **792**, so that the first bearing **791** has a greater load capacity than the second bearing **792**. For this reason, the first retainer section **781** in which the first bearing **791** is fit to be retained has a larger diameter than the second retainer section **782** in which the second bearing **792** is fit to be retained.

Each of the first and second bearings **791** and **792** has an internal clearance in the radial direction, i.e., a radial internal clearance, and the radial internal clearance of the first bearing **791** is larger than the radial internal clearance of the second bearing **792**. The radial internal clearance of a bearing represents a radial play or an internal radial looseness between the inner race, outer race, and ball in the bearing. The first bearing **791** is subjected to vibration and/or centrifugal load of the rotating shaft **710**, as compared with the second bearing **792**, so that the larger radial internal clearance of the first bearing **791** enhances an effect of absorbing load. This therefore reduces load acting on the boss **780** at the base end of the rotating shaft **701**, thus minimizing deflection of the extending end of the rotor **701**.

The first cylindrical retainer wall **781** has a parallel surface **781***a* extending parallel to the axial direction of the boss **780**, and a perpendicular surface **781***b* extending perpendicular to the axial direction of the boss **780**. The first bearing **791** is fit to be retained in the first retainer section **781** while being in contact with the parallel and perpendicular surfaces **781***a* and **781***b*.

The second cylindrical retainer wall **782** has a parallel surface **782***a* extending parallel to the axial direction of the boss **780**, and a perpendicular surface **782***b* extending perpendicular to the axial direction of the boss **780**. The second bearing **792** is fit to be retained in the second retainer section **782** while being in contact with the parallel and perpendicular surfaces **782***a* and **782***b*.

The second retainer wall **782** has opposing first and second ends; the first end is closer to the extending end of the rotating shaft **701** than the second end is.

The boss **780** has a third retainer wall **783** formed at the first end of the second retainer wall **782**. In the third retainer wall **783**, a resolver **800** serving as a rotation sensor is fit to be retained. The third retainer wall **783** has a larger inner diameter than an inner diameter of the second retainer wall **782**, resulting in the first end of the second retainer wall **782** and the third retainer wall **783** having an outer shoulder.

The resolver **800** includes, as illustrated in FIG. **77**, a resolver rotor **801** secured to the rotating shaft **701**, and a resolver stator **802** disposed radially outside the resolver rotor **801** to face the resolver rotor **801**.

The resolver rotor **801** has an annular disc shape, and is coaxially mounted around the rotating shaft **701**. The resolver stator **802** includes an unillustrated stator core and an unillustrated stator coil, and is retained in the third retainer wall **783**.

The boss **780** has, as illustrated in FIG. **94**, a smaller-diameter wall **784** formed to extend from the first retainer wall **781** in the axial direction, and a smaller-diameter wall **785** formed to extend from the smaller-diameter wall **784** to the second retainer wall **782** in the axial direction.

The smaller-diameter wall **784** defines a hole thereinside; the hole has an inner diameter smaller than an inner diameter of the first retainer wall **781**. The smaller-diameter wall **784** defines a hole thereinside; the hole has an inner diameter smaller than the inner diameter of the smaller-diameter wall **784**. The third retainer wall **783**, which retains the resolver **800**, is located axially outside the second retainer wall **782**, i.e., located to be close to the extending end of the rotating shaft **701**; the third retainer wall **783** has the larger inner diameter than the inner diameter of the second retainer wall **782**. The second and third retainer walls **782** and **783** are adjacent to each other in the axial direction.

Performing a hole drilling process, such a boring process, of the outer cylindrical member **772** from one side of the outer cylindrical member **772** in the axial direction may enable the coaxial second and third retainer walls **782** and **783** to be continuously produced in the outer cylindrical member **772**. This may result in a higher degree of coaxial alignment of the second bearing **792** retained in the second retainer wall **782** and the resolver stator **802** retained in the third retainer wall **783**, thus enhancing a higher degree of coaxial alignment of the resolver rotor **801** and resolver stator **802**. This higher degree of coaxial alignment of the resolver rotor **801** and resolver stator **802** may minimize deflection of the resolver stator **802** relative to the resolver rotor **801**, thus reducing errors in angle measured by the resolver **800**.

Next, the bus bar module **810** will be described below. The bus bar module **810** is made as a winding connecting member which is electrically connected to the conductor segments **741** of the coil modules **740** of the stator winding **731**, connects first ends of the conductor segments **741** of each phase in parallel to each other, and also connects second ends of the conductor segments **741** together at the neutral point. FIG. **96** is a perspective view of the bus bar module **810**. FIG. **97** is a partial longitudinal view of the bus bar module **810**. FIG. **99** is a longitudinal sectional view which illustrates the inner housing **771**, the stator winding **731** made up of the coil modules, the stator core **732**, and the bus bar module **810**.

The bus bar module **810** includes the annular portion **811** of a circular shape, a plurality of connecting terminals **812** (serving as winding connecting terminals), three input-output terminals **813** (serving as device connecting terminals) one provided for each of the phase windings, and the current measuring terminal **814** connecting with current sensors of the phase windings. The connecting terminals **812** extend from the annular portion **811**.

The annular portion **811** is, as can be seen in FIG. **97**, of a circular annular shape and made from an electrically insulating material such as resin. The annular portion **811** has a plurality of bus bars **821** to **824** embedded therein. The bus bars **821** to **824** of the bus bar module **810** are disposed fully inside the annular portion **811** except the connecting terminals **812** and the input-output terminals **813**.

Each of the bus bars **821** to **824** is of an annular shape or a C-shape with an omission of a circumference thereof. The bus bars **821** to **824** include the U-phase bus bar **821**, the V-phase bus bar **822**, the W-phase bus bar **823**, and the neutral point bus bar **823**. The bus bars **821** to **824** are arranged adjacent each other in the axial direction of the bus bar module **810** to have plate surfaces thereof facing each other in the axial direction. The bus bars **821** to **824** may alternatively be arranged adjacent each other in the radial direction of the bus bar module **810** to have the plate surfaces thereof facing each other in the radial direction.

The annular portion **811** has an outer diameter identical with that of the end plate **774**. The outer diameter of the annular portion **811** is smaller than an inner diameter of the stator winding **731**. This dimensional relation achieves a reduction in size of the bus bar module **810**.

The annular portion **811** has a plurality of attachment portions **815** on an inner periphery thereof. Fasteners, such as bolts, are disposed in the attachment portions **815** to achieve a firm joint the bus bar module **810** to the end plate **774** of the inner housing **771**.

The connecting terminals **812** protrude radially outside the annular portion **811** in connection with the bus bars **821** to **824**. The connecting terminals **812** are, as clearly illustrated in FIG. **96** arranged adjacent each other in the circumferential direction of the annular portion **811**. The connecting terminals **812** are located radially outside the annular portion **811** and extend in the axial direction of the annular portion **811**.

The input-output terminals **813** protrude radially inside the annular portion **811** in connection with the bus bars **821** to **824**. FIG. **99** shows the connecting wires **841** which electrically connect between the input-output terminals **813** and the electrical device **840**.

FIG. **98** schematically illustrates the layout of connections of connecting terminals **812** with the bus bars **821** to **824**. In FIG. **98**, a lateral direction corresponds to a circumferential direction of the annular portion **811**. "U" indicates the connecting terminals **812** leading to the U-phase winding. "V" indicates the connecting terminals **812** leading to the V-phase winding. "W" indicates the connecting terminals **812** leading to the W-phase winding. "NE" indicates the connecting terminals **812** leading to the neutral point.

The connecting terminals **812** (NE) connected to the neutral point are alternately arranged such that a selected one of other connecting terminals **812** (U), **812** (V), and **812** (W) is located between each adjacent pair of connecting terminals **812** (NE). The number of connecting terminals **812** is set to be identical to the number of winding ends **743***a* and **743***b* of the winding segments **741** of the coil modules **740**, so that the connecting terminals **812** are respectively connected to the winding ends **743***a* and **743***b*.

The input-output terminals **813** include the input-output terminal **813**U for the U-phase winding, the input-output terminal **813**V for the V-phase winding, and the input-output terminal **813**W for the W-phase winding. The input-output terminals **813**U, **813**V, and **813**W are respectively connected to the bus bars **821** to **823** within the annular portion **811**.

The input-output terminals **813** are used to transmit electrical power between the inverter, not shown, and the U-, V-, and W-phase windings of the stator winding **731**.

The connecting terminals **812** and/or the winding ends **743***a* and **743***b* are bent or curved in the radial direction, as needed, to achieve contact of the connecting terminals **812** with the winding ends **743***a* and **743***b*. The contacts of the connecting terminals **812** with the winding ends **743***a* and **743***b* are, as clearly illustrated in FIG. **99**, welded or adhered together. The joints of the connecting terminals **812** with the winding ends **743***a* and **743***b* may be electrically insulated by potting material or powder coating material.

The current sensors **816** provided for the respective phases are installed in the annular portion **811**. Electrical current information measured by each current sensor **816** is outputted to an unillustrated controller through a corresponding one of the current measuring terminals **814**.

This embodiment offers the following beneficial advantages.

The annular portion **811** of the bus bar module **810** is firmly secured to the outer peripheral portion of the end plate **774**. This achieves a firm joint of the bus bar module **810** to the inner housing **77** thereby enhancing the resistance of the stator **730** to large mechanical vibrations.

The annular portion **811** of the bus bar module **810** is equipped with the connecting terminals **812** which connect with the phase windings of the stator winding **731** and the input-output terminals **813** which electrically connects with the electrical device **840**. The electrical connection of the phase windings and the inverter is, therefore, achieved using the single bus bar module **810**, thereby resulting in a decreased total number of parts of the rotating electrical machine **700**.

The bus bars **821** to **824** are embedded in the annular portion **811** made from an electrical insulating material and arranged away from each other. This layout enhances the electrical insulation between the bus bars **821** to **824** to minimize a risk of short-circuit between the phase windings.

The connecting terminals **812** are arranged to protrude radially outside the annular portion **811** in connection with the bus bars **821** to **824**. The input-output terminals **813** are arranged to protrude radially inside the annular portion **811** in connection with the bus bars **821** to **824**. This layout results in the connecting terminals **812** being located close to the stator winding **731** and also results in the input-output terminals **813** being located closer to the inverter, thereby enabling electrical paths connecting between the stator winding **731** and the connecting terminals **812** and between the inverter and the input-output terminals **813** to be shortened, which reduces losses of electrical current flowing through the electrical paths.

Sixteenth Modification

The fifteenth modification may be designed to have the structure illustrated in FIG. **100**. FIG. **100** is a longitudinal sectional view of an inner unit and a bus bar module. In FIG. **100**, the same or corresponding structural elements as those in FIG. **99** will be indicated by the same reference symbols for the sake of convenience. FIG. **100** omits the stator winding **731**, the connecting terminals **812**, and the electrical device **840**.

The annular portion **811** of the bus bar module **810** is secured to one of axially opposed ends of the outer cylinder **772**. The annular portion **811** has an outer diameter identical with that of the outer cylinder **772**.

The above structure achieves a firm joint of the bus bar module **810** to the inner housing **771**.

Seventeenth Modification

The fifteenth modification may be designed to have the structure illustrated in FIG. **101**. FIG. **101** is a longitudinal sectional view of an inner unit and a bus bar module. In FIG. **101**, the same or corresponding structural elements as those in FIG. **100** will be indicated by the same reference symbols for the sake of convenience.

The stator core **734** extends in the axial direction to reach an end of the outer cylinder **772**. The annular portion **811** of the bus bar module **810** is attached to the axial end of the stator core **734**. The annular portion **811** may have an inner periphery thereof contacting an outer periphery of the end plate **774**.

The above structure achieves a firm joint of the bus bar module **810** to the stator core **734**.

Eighteenth Modification

The fifteenth modification may be designed to have the structure illustrated in FIG. **102**. FIG. **102** is a longitudinal sectional view of an inner unit and a bus bar module. In FIG. **102**, the same or corresponding structural elements as those in FIG. **101** will be indicated by the same reference symbols for the sake of convenience.

The stator winding **737** includes the straight portions **737***a* and the end portions **737***b* which are smaller in inner diameter than that of the straight portions **737***a*. The end portions **737***b* face the bus bar module **810** in the radial direction.

The end portions **737***b* have formed thereon the winding protrusions **737***c* which protrude radially inwardly. The winding protrusions **737***c* are provided on winding holders of the stator winding **737**. The annular portion **811** of the bus bar module **810** has the recesses **811***b* which are formed in a portion of the inner periphery thereof which is aligned with the winding protrusions **737***c* in the radial direction. The recesses **811***b* are hollowed inwardly in the radial direction of the annular portion **811**. The recesses **811***b* define the overhangs **811***a* on the outer periphery of the annular portion **811**. The overhangs **811***a* protrude radially outward and are located just above the recesses **811***b* in the axial direction. The overhangs **811***a* have outer peripheries placed in direct contact with the inner peripheries of the end portions **737***b*.

The annular portion **811** and the overhangs **811***a* have axial ends lying flush with an axial end of the stator winding **737**. In other words, the axial ends of the annular portion **811** and the overhangs **811***a* do not protrude outside the axial end of the stator winding **737**, thereby minimizing an axial dimension of the stator **730**.

Each of the overhangs **811***a* has the axial protrusion **850** which extends in the axial direction of the stator winding **737**. In this embodiment, each of the axial protrusions **850** is implemented by a pin. The axial protrusions **850** are provided one for each of the winding protrusions **737***c*. Each of the winding protrusions **737***c*, as clearly illustrated in FIG. **103**, has formed therein the fitting hole **737***d* which extends through the winding protrusion **737***c* in the axial direction of the stator **730**. The winding protrusions **737***c* are fit in the recesses **811***b*. The axial protrusions **850** are fit in the fitting hole **737***d*. FIG. **103** is a partial section view of each of the end portions **737***b*, as taken along a plane extending perpendicular to the axis of the rotor **710**.

For instance, a production method may be used which places the stator winding **737** in contact with the outer peripheral surface of the stator core **732** and then install the bus bar module **810** on the inner housing **771** from outside the inner housing **771** in the axial direction thereof. This achieves the fitting of the axial protrusions **850** in the fitting holes **737***d* of the winding protrusions **737***c* of the coil modules constituting the stator winding **737**.

This embodiment offers the following beneficial advantages.

The fitting of the winding protrusions **737***c* in the recesses **811***b* holds the coil modules of the stator winding **737** from being moved in the axial direction.

The fitting of the axial protrusions **850** in the fitting holes **737***d* provides the bus bar module **810** with a stopper feature which holds the coil modules of the stator winding **737** from being undesirably moved in the circumferential direction.

Other Modifications

In the eighteenth modification, each of the end portions **737***b* of the stator winding **737** may be designed to have a protrusion extending radially inwardly. The annular portion **811** may have recesses formed in the outer periphery thereof. The protrusions of the end portions **737***b* are fit in the recesses of the annular portion **811** to retain the stator winding **737** by the annular portion **811**.

In the fifteenth modification, the connecting terminals **812** and the input-output terminals **813** may be arranged on only a half of the circumference of the annular portion **811**.

The bus bar module is of an annular shape, but may alternatively be of a C-shape.

Each of the structures in the fifteenth to eighteenth modifications may be used with an inner-rotor rotating electrical machine instead of the outer-rotor rotating electrical machine.

For instance, the rotating electrical machine **500**, as illustrated in FIG. **50**, has the coolant path **545** equipped with the inlet path **571** and the outlet path **572** which are arranged close to each other, but however, the inlet path **571** and the outlet path **572** may alternatively be located away from each other in the circumferential direction of the rotating electrical machine **500**. For instance, the inlet path **571** and the outlet path **572** may be disposed at an interval of 180° away from each other in the circumferential direction.

In the tire wheel assembly **400** in the above embodiments, the rotating electrical machine **500** has the rotating shaft **501** which protrudes outside one of the axially opposed ends thereof, but may be designed to have the rotating shaft **501** which protrudes outside both the axially opposed ends thereof. This structure is useful for vehicles which is equipped with at least a front or a rear single wheel.

In the embodiments of the in-wheel motor for vehicles or the first to fourth modifications of the in-wheel motor, the rotating electrical machine **500** for use in the tire wheel assembly **400** may be of an inner-rotor type.

The rotating electrical machine is not limited to a star-connection type, but may be Δ-connection type.

This disclosure in this application is not limited to the above described embodiments. This disclosure includes the above embodiments and modifications which may be made by those of ordinary skill in the art. For instance, this disclosure is not limited to parts or combinations of the parts referred to in the embodiments, but may be realized using various combinations of the parts. This disclosure may include additional possible arrangements or omissions of the parts in the embodiments. This disclosure may include exchanges of the parts among the embodiments or combinations of the parts in the embodiments. Disclosed technical scopes are not limited to statements in the embodiments. It should be appreciated that the disclosed technical scopes include elements specified in the appended claims, equivalents of the elements, or all possible modifications of the elements without departing from the principle of this disclosure.

While the present disclosure has been described in terms of embodiments, it should be appreciated that the present disclosure is not limited to the embodiments or structures. Therefore, the disclosure should be understood to include all possible embodiments and modifications to the shown embodiments which can be embodied without departing from the principle of the disclosure.

What is claimed is:

1. An armature which radially faces a magnetic field-producing unit equipped with a magnet unit including a plurality of magnetic poles with polarities alternating in a circumferential direction of the magnet unit, the armature comprising:

a housing which includes a cylinder and an end plate which is of a disc shape and placed in contact with one of axially opposed ends of the cylinder;

an armature core which (i) is of a cylindrical shape, (ii) is disposed on a portion of the cylinder which radially faces the magnet unit, and (iii) has a curved peripheral surface which radially faces the magnet unit;

a multi-phase armature winding which is disposed on a portion of the armature core which radially faces the magnet unit; and

a bus bar module which (i) is equipped with bus bars electrically connecting phase windings of the armature winding together, (ii) is of an annular or a C-shape extending in a circumferential direction of the armature core, and (iii) has a retainer formed on an end portion thereof which radially faces the armature winding, the retainer serving to retain the armature winding, wherein:

the armature winding has an axial end which radially faces the bus bar module and has a winding protrusion formed on one of axially opposed ends thereof, the winding protrusion protruding radially toward the bus bar module;

the retainer includes a recess formed on a portion of the bus bar module which radially faces the winding protrusion, the recess being hollowed away from the armature winding in a radial direction of the bus bar module, and the winding protrusion being fit on the recess; and

the bus bar module is secured to the cylinder, the end plate, or one of axially opposed ends of the armature core.

2. The armature as set forth in claim **1**, wherein the retainer includes an axial protrusion which is formed in the recess and protrudes in an axial direction of the armature,

the winding protrusion has formed therein a fitting hole which extends in the axial direction, and

the axial protrusion is fit in the fitting hole.

3. The armature as set forth in claim **1**, wherein an annular portion of the bus bar module has an axial outer end which does not protrude outside an axial outer end of the armature winding in an axial direction of the armature.

4. The armature as set forth in claim **1**, further comprising:

a power converter which is disposed on a portion of the cylinder which is located away from the magnet unit in a radial direction of the armature and electrically connected to the armature winding; and

winding connecting terminals and device connecting terminals, the winding connecting terminals electrically connecting between the bus bars and the armature winding, and the device connecting terminals electrically connecting between the bus bars and the power converter.

5. The armature as set forth in claim **4**, wherein the bus bar module includes an annular portion which is of a circular shape and made from an electrically insulating material, and

the bus bars are embedded in the annular portion and located away from each other.

6. The armature as set forth in claim **5**, wherein the armature is arranged inside the magnetic field-producing unit in the radial direction of the armature, and an outer diameter of the annular portion is smaller than an inner diameter of the armature winding.

7. The armature as set forth in claim **6**, wherein the winding connecting terminals protrude radially outside the annular portion and connect with the bus bars, and the device connecting terminals protrude radially outside the annular portion and connect with the bus bars.

8. An armature which radially faces a magnetic field-producing unit equipped with a magnet unit including a plurality of magnetic poles with polarities alternating in a circumferential direction of the magnet unit, the armature comprising:

a housing which includes a cylinder and an end plate which is of a disc shape and placed in contact with one of axially opposed ends of the cylinder;

an armature core which is of a cylindrical shape and is disposed on a portion of the cylinder which radially faces the magnet unit;

a multi-phase armature winding which is disposed on a portion of the armature core which radially faces the magnet unit;

a bus bar module which is equipped with bus bars electrically connecting phase windings of the armature winding together and is of an annular or a C-shape extending in a circumferential direction of the armature core;

a power converter which is disposed on a portion of the cylinder which is located away from the magnet unit in a radial direction of the armature and electrically connected to the armature winding; and

winding connecting terminals and device connecting terminals, the winding connecting terminals electrically connecting between the bus bars and the armature winding, the device connecting terminals electrically connecting between the bus bars and the power converter,

wherein the bus bar module is secured to the cylinder, the end plate, or one of axially opposed ends of the armature core.

9. The armature as set forth in claim **8**, wherein the armature core has a curved peripheral surface which radially faces the magnet unit,

the armature winding has an axial end which radially faces the bus bar module, and

the bus bar module has a retainer formed on an end portion thereof which radially faces the armature winding, the retainer serving to retain the armature winding.

10. The armature as set forth in claim **9**, wherein the armature winding has a winding protrusion formed on one of axially opposed ends thereof, the winding protrusion protruding radially toward the bus bar module,

the retainer includes a recess formed on a portion of the bus bar module which radially faces the winding protrusion, the recess being hollowed away from the armature winding in a radial direction of the bus bar module,

the winding protrusion is fit on the recess,

the retainer includes an axial protrusion which is formed in the recess and protrudes in an axial direction of the armature,

the winding protrusion has formed therein a fitting hole which extends in the axial direction, and

the axial protrusion is fit in the fitting hole.

11. The armature as set forth in claim **9**, wherein an annular portion of the bus bar module has an axial outer end which does not protrude outside an axial outer end of the armature winding in an axial direction of the armature.

12. The armature as set forth in claim **8**, wherein the bus bar module includes an annular portion which is of a circular shape and made from an electrically insulating material, and

the bus bars are embedded in the annular portion and located away from each other.

13. The armature as set forth in claim **12**, wherein the armature is arranged inside the magnetic field-producing unit in the radial direction of the armature, and an outer diameter of the annular portion is smaller than an inner diameter of the armature winding.

14. The armature as set forth in claim **13**, wherein the winding connecting terminals protrude radially outside the annular portion and connect with the bus bars, and the device connecting terminals protrude radially outside the annular portion and connect with the bus bars.

* * * * *