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(54) **TANDEM ROTOR SERVO MOTOR**

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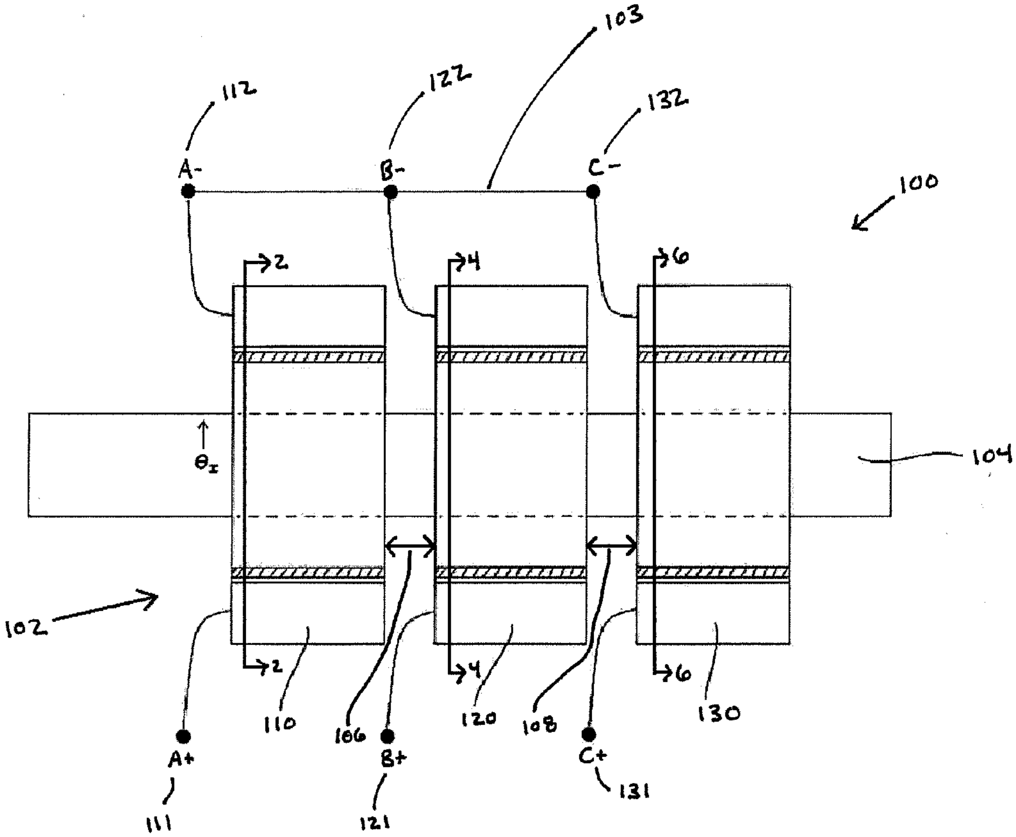
USPC **310/114**

(57) **ABSTRACT**

A tandem rotor servo motor assembly is provided comprising a first phase element positioned on a shaft, the first phase element having a first rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged. A second phase element is positioned on the shaft a first distance from the first phase element, the second phase element having a second rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged. A third phase element is positioned on the shaft a second distance from the second phase element, the third phase element having a third rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged. The second rotor is offset about the shaft from the first rotor by sixty degrees of rotation and the third rotor being offset about the shaft from the first rotor by one hundred and twenty degrees of rotation.



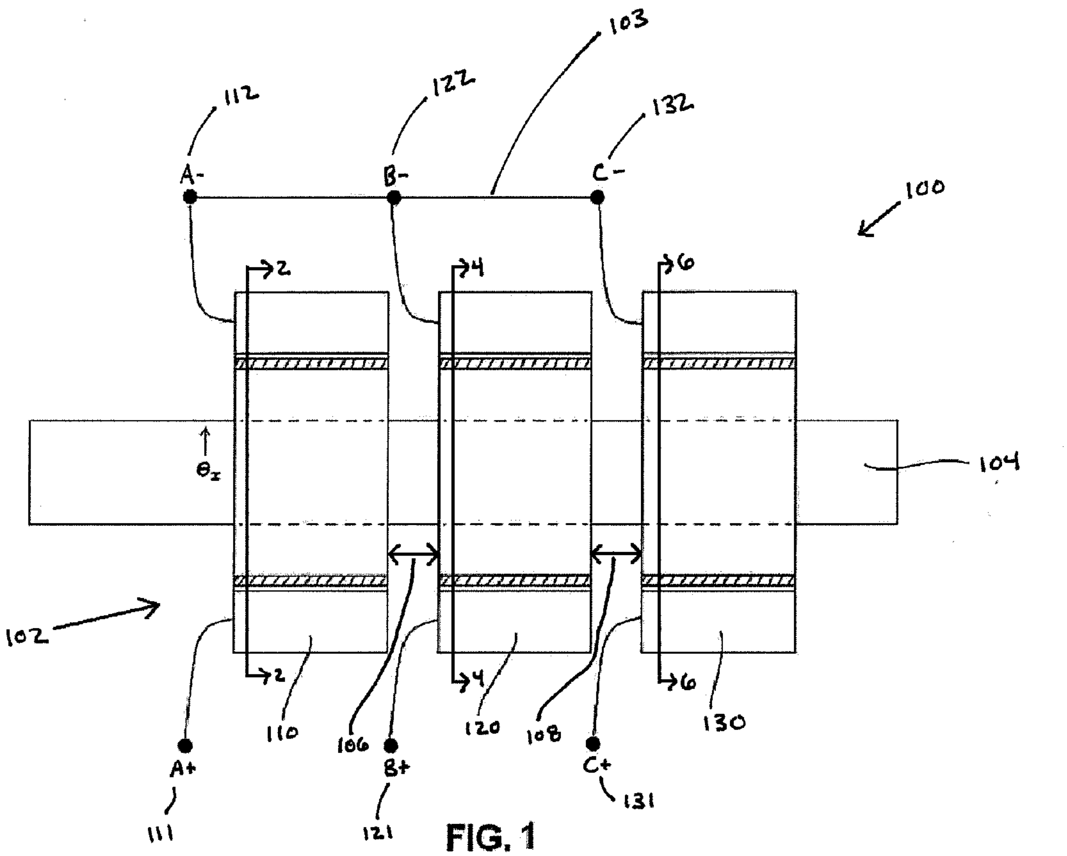

103
112
122
132
A-
B-
C-
100
2
4
6
104
θ_x
102
2
4
6
110
106
120
108
130
A+
B+
C+
111
121
131

FIG. 1

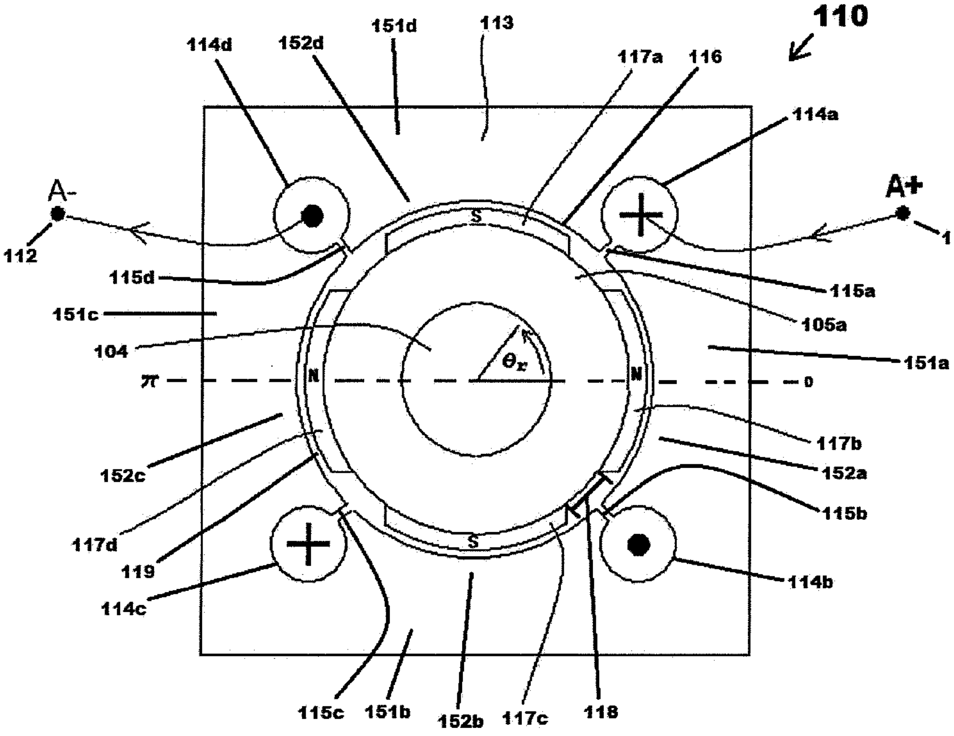

110
114d
152d
151d
113
117a
116
114a
A-
A+
112
111
115d
115a
151c
105a
104
θ_r
151a
π
N
N
0
S
S
117b
152c
152a
115b
117d
119
114b
114c
115c
151b
152b
117c
118

FIG. 2

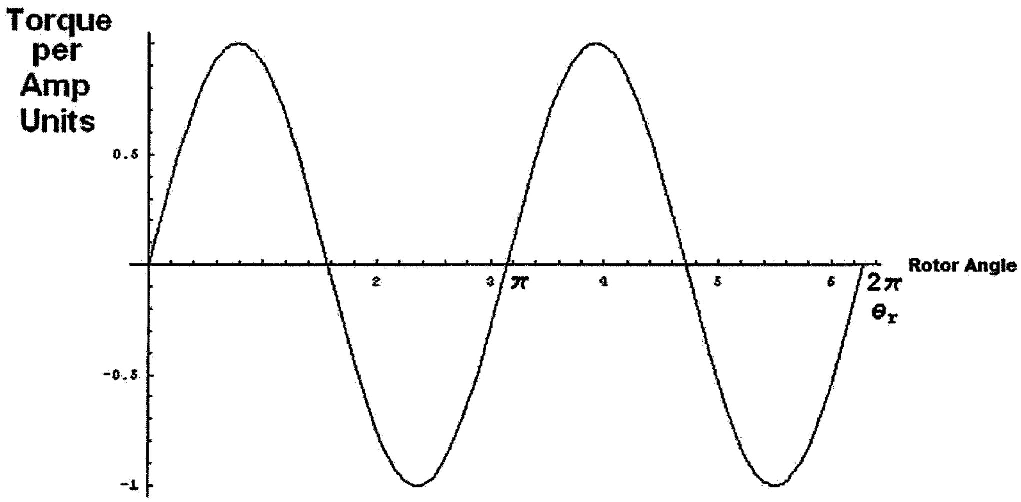

Torque per Amp Units
0.5
-0.5
-1
Rotor Angle
2
3
π
4
5
6
2π
θ_r

FIG. 3

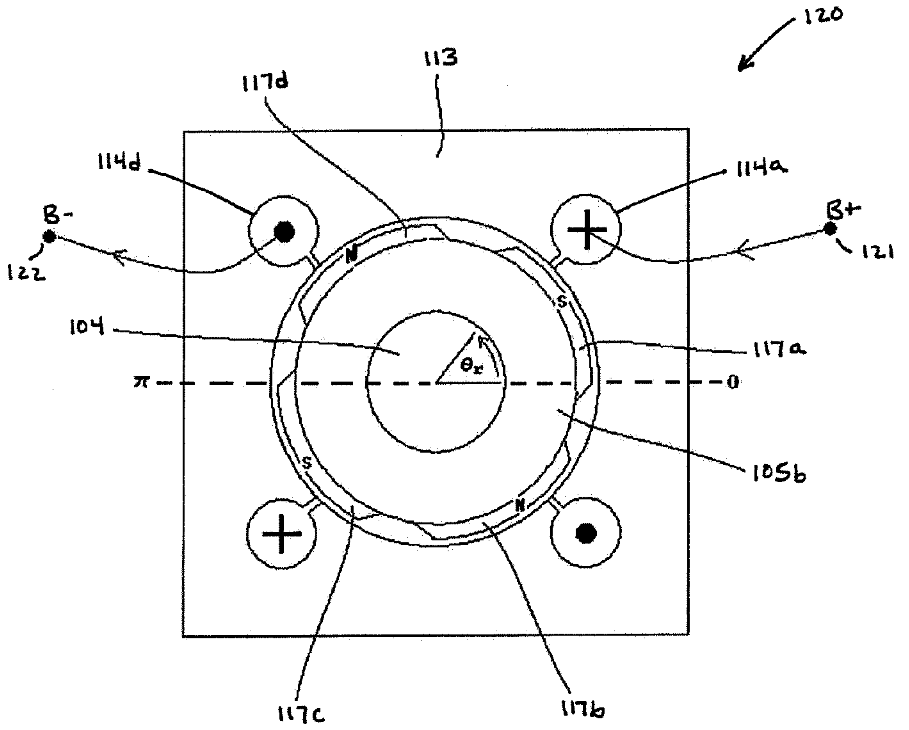

120
113
117d
114d
114a
B-
B+
122
121
N
S
104
θ_r
117a
π
0
105b
S
N
117c
117b

FIG. 4

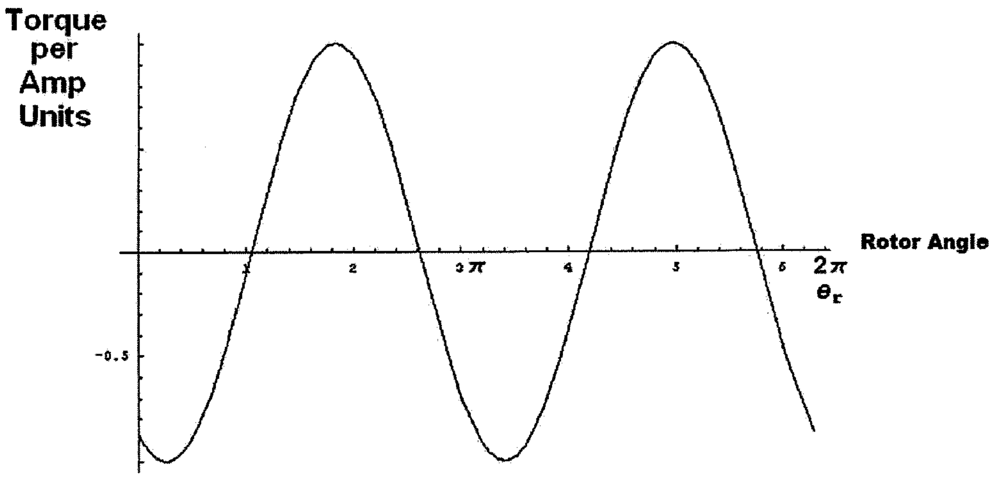

Torque per Amp Units
Rotor Angle
1
2
3 π
4
5
6
2π
θ_r
-0.5

FIG. 5

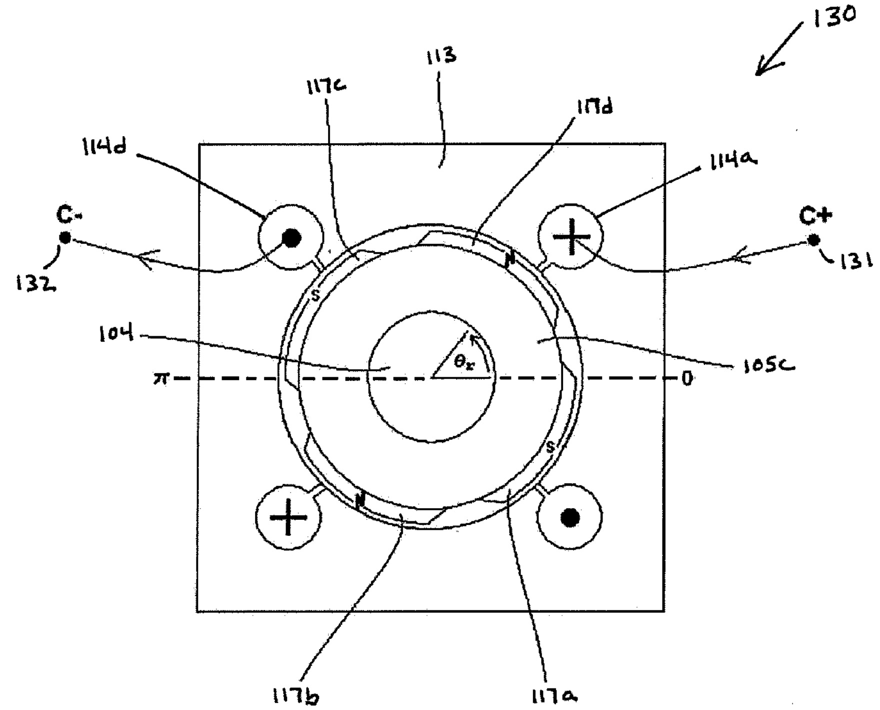

130
113
117c
117d
114d
114a
C-
C+
132
131
S
N
104
θ_r
105c
π
0
S
N
117b
117a

FIG. 6

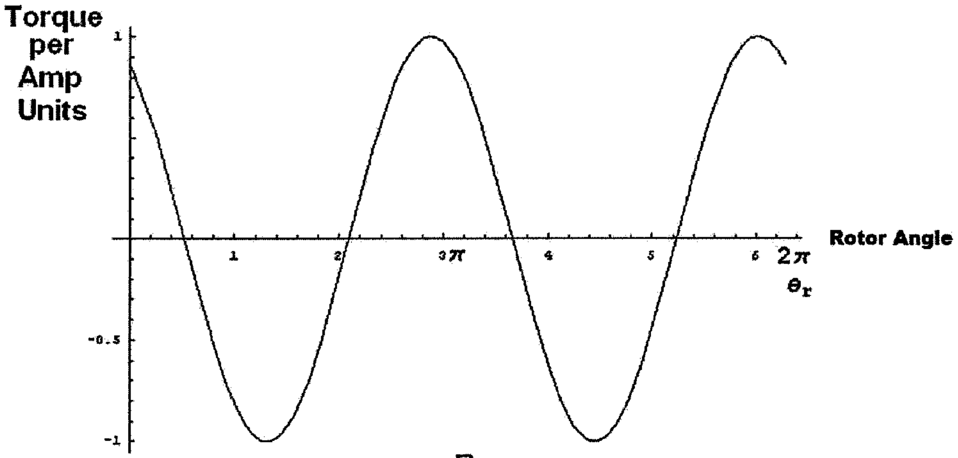

Torque per Amp Units
1
-0.5
-1
Rotor Angle
1
2
3π
4
5
6
2π
θ_r

FIG. 7

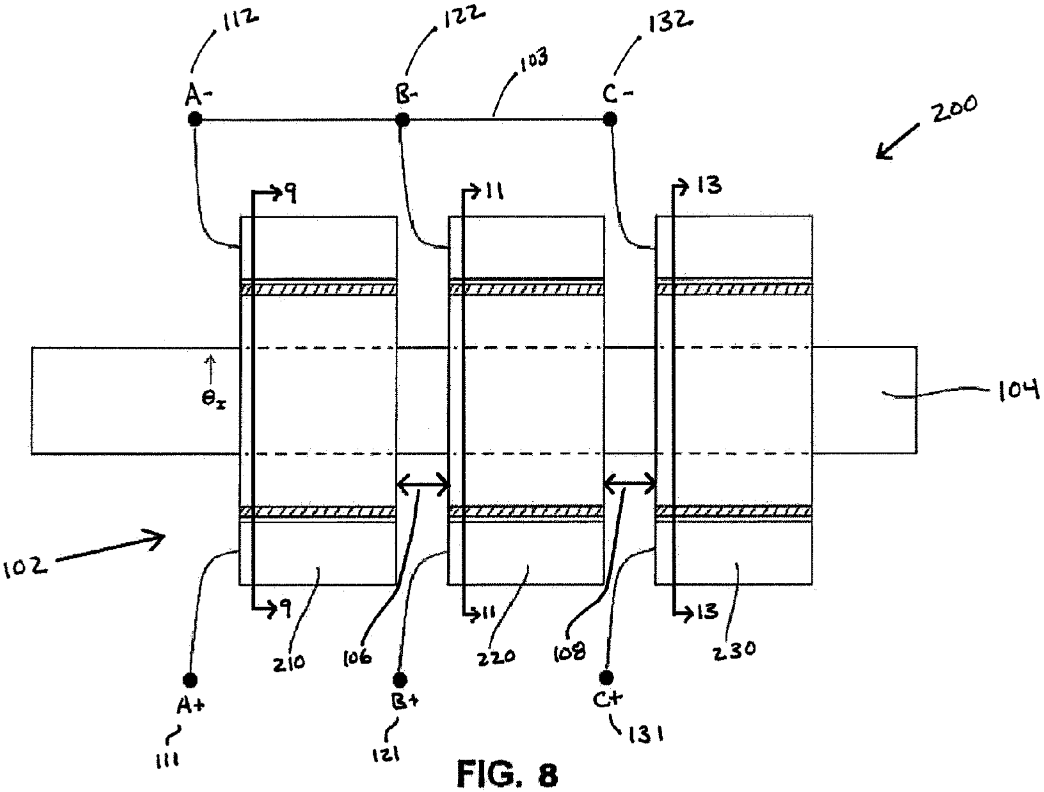

112
122
132
103
A-
B-
C-
200
9
11
13
θ_x
104
102
9
11
13
210
106
220
108
230
A+
B+
C+
111
121
131

FIG. 8

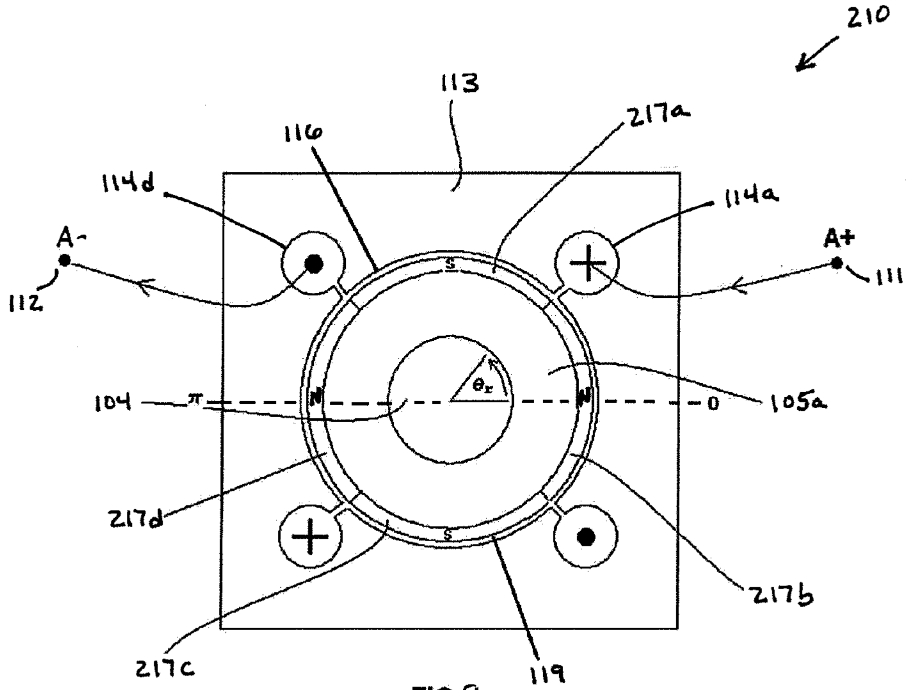

210
113
116
217a
114d
114a
A-
A+
112
111
S
N
N
θ_r
104
π
0
105a
217d
S
217b
217c
119

FIG. 9

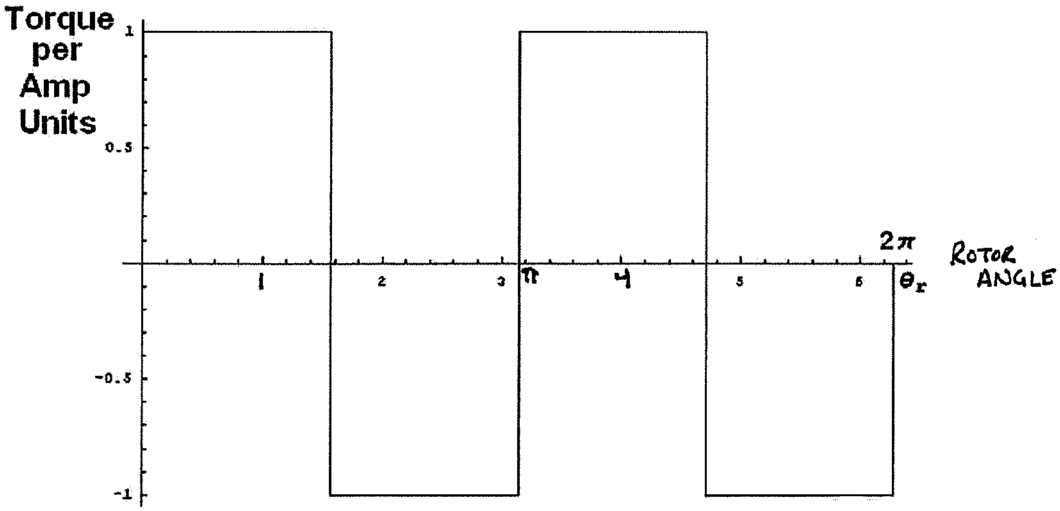

Torque per Amp Units
1
0.5
-0.5
-1
1
2
3
π
4
5
6
2π
θ_r
ROTOR ANGLE

FIG. 10

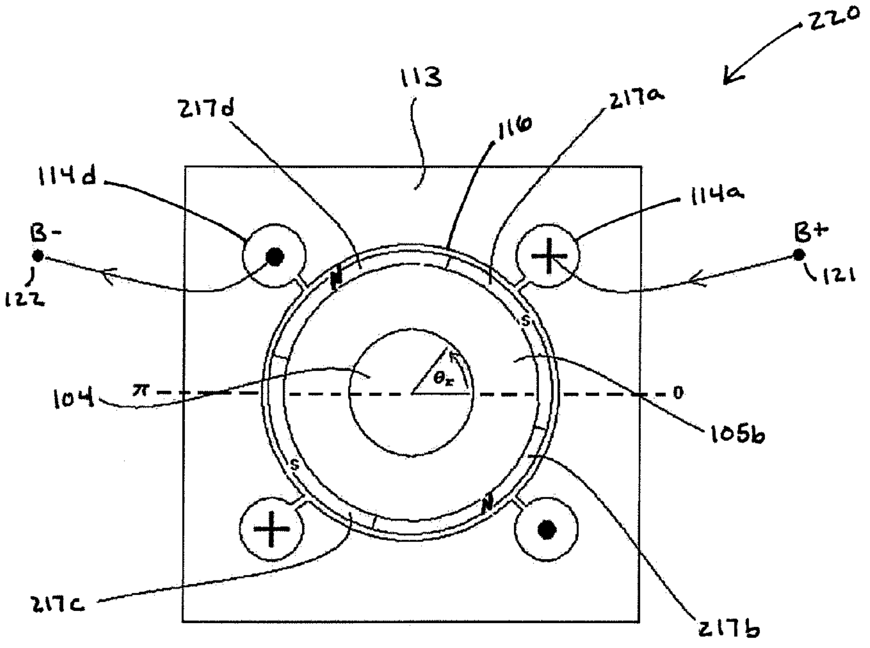

220
113
217d
116
217a
114d
114a
B-
B+
122
121
N
S
π
0
θr
104
105b
S
N
217c
217b

FIG. 11

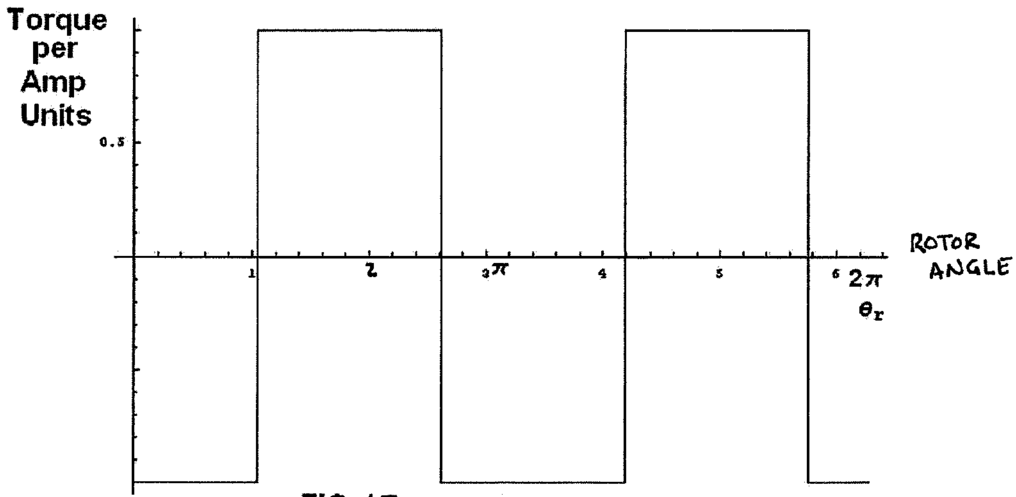

Torque per Amp Units
0.5
1
2
3π
4
5
6
2π
θr
ROTOR ANGLE

FIG. 12

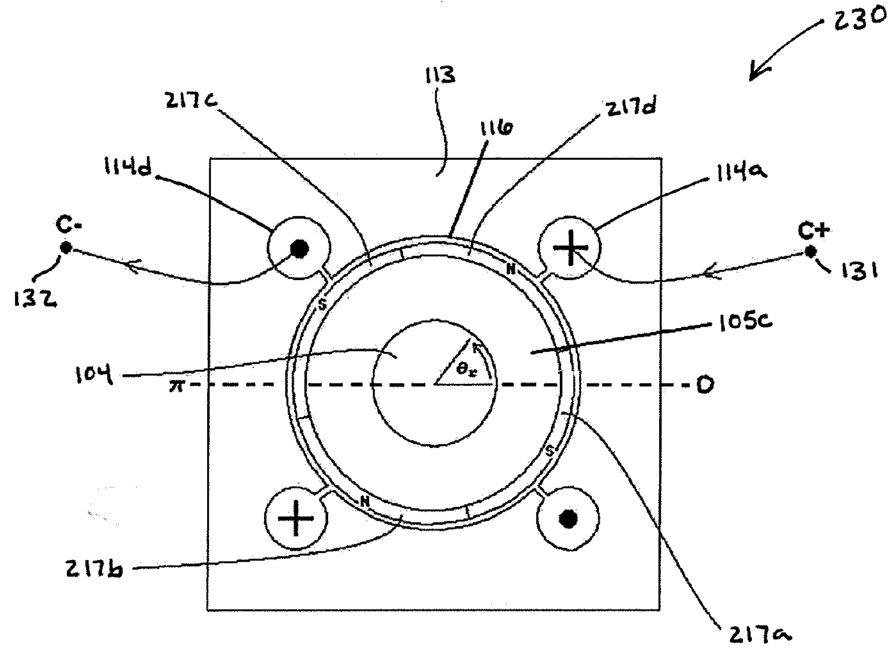

230
113
217c
116
217d
114d
114a
C-
C+
132
131
105c
104
θ_r
π
0
S
N
N
S
217b
217a

FIG. 13

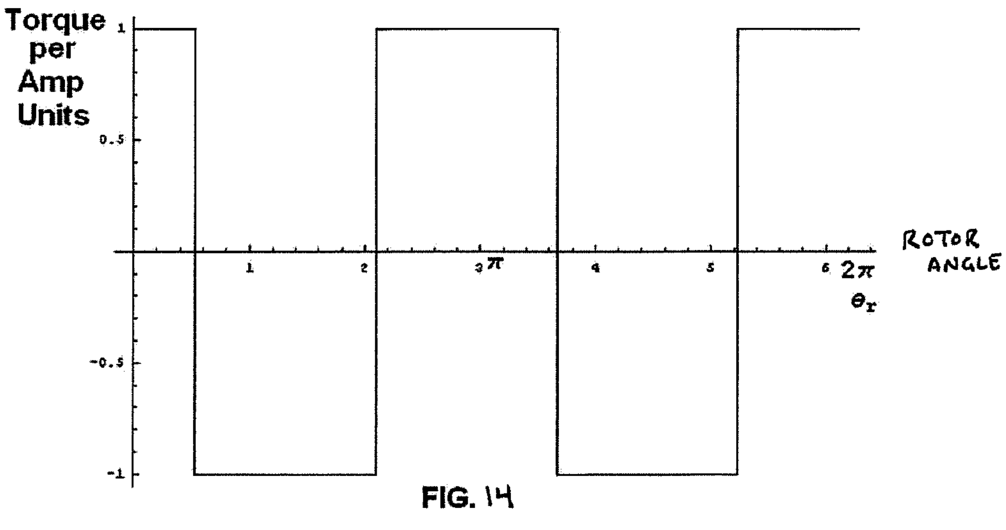

Torque per Amp Units
1
0.5
-0.5
-1
1
2
3 π
4
5
6 2π
ROTOR ANGLE
θ_r

FIG. 14

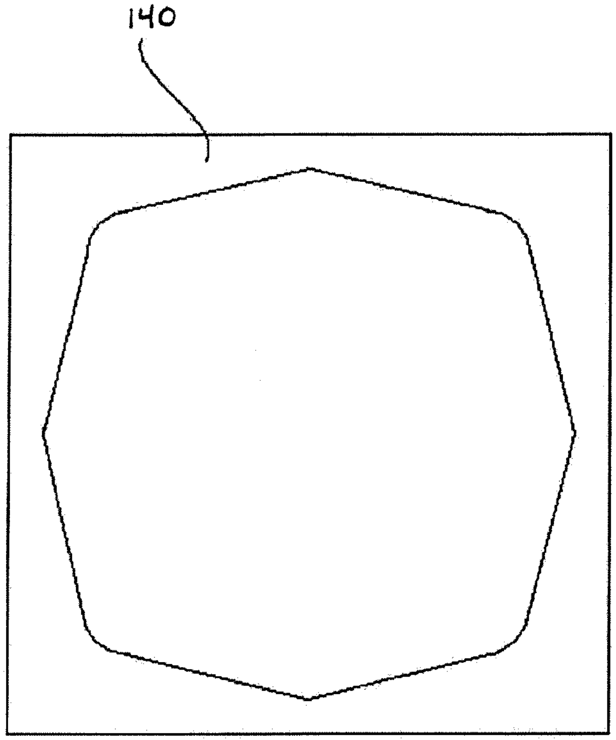

140

FIG. 15

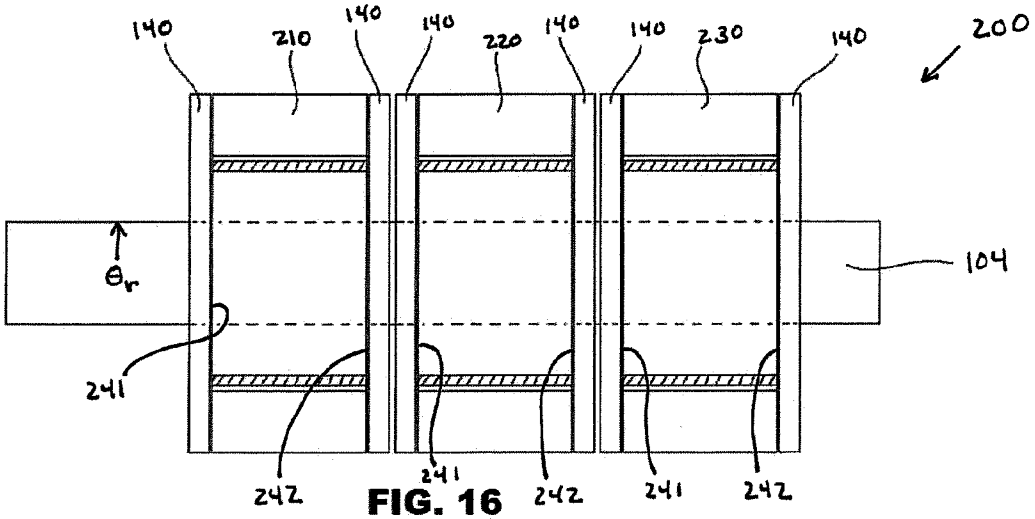

140
210
140
140
220
140
140
230
140
200
104
θ_r
241
242
241
242
241
242

FIG. 16

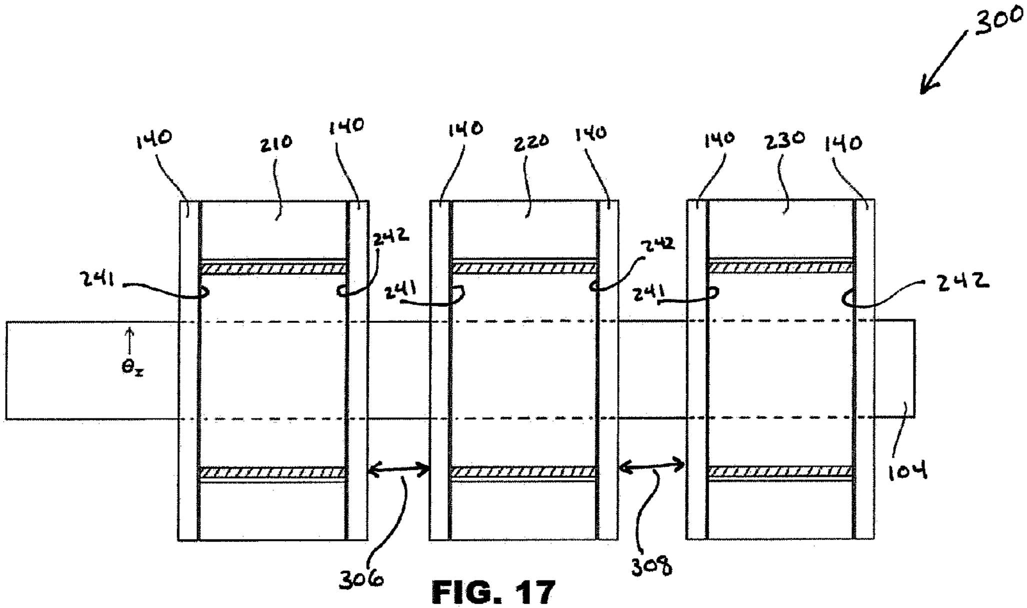

300
140
210
140
140
220
140
140
230
140
242
242
241
241
241
242
θ_z
104
306
308

FIG. 17

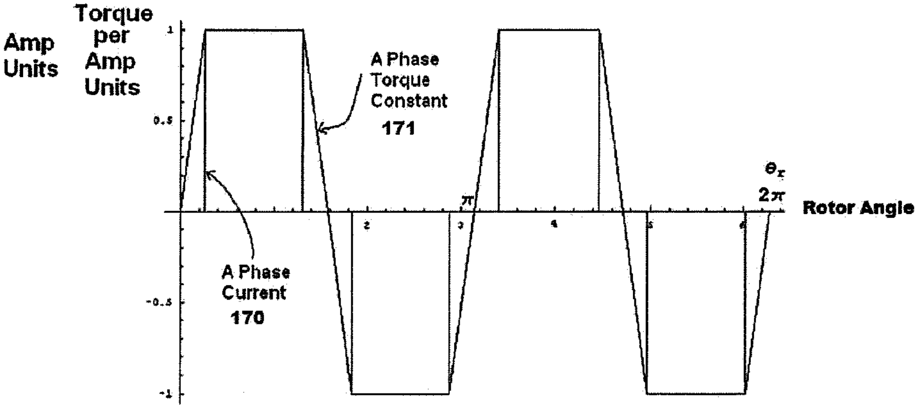


FIG. 18

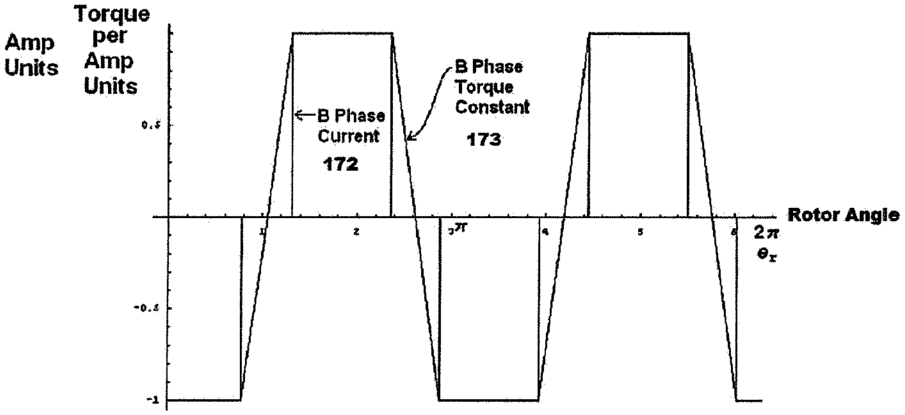


FIG. 19

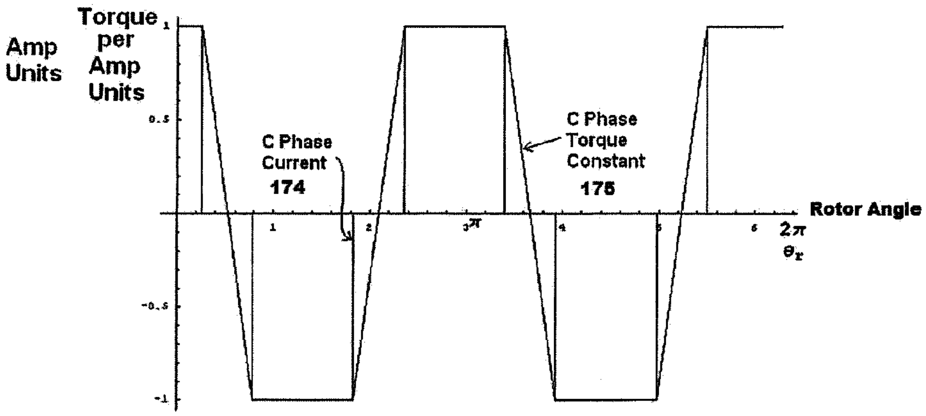


FIG. 20

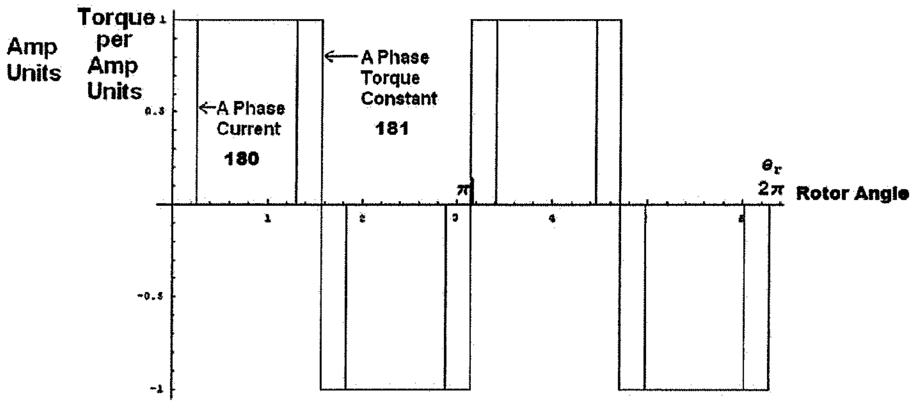


FIG. 21

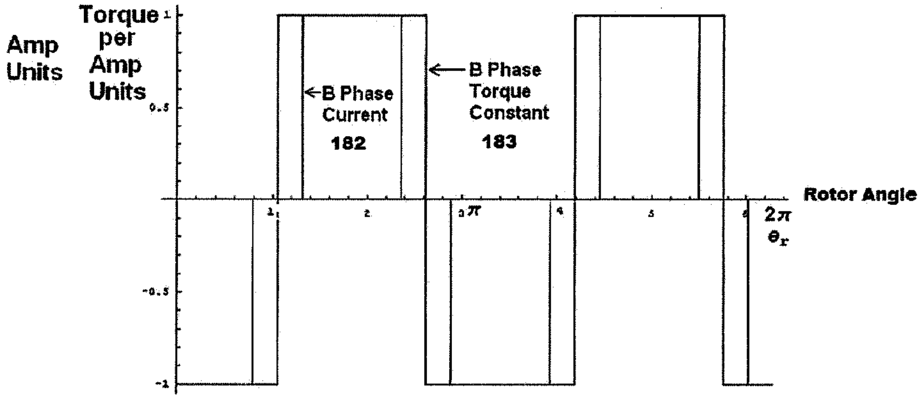


FIG. 22

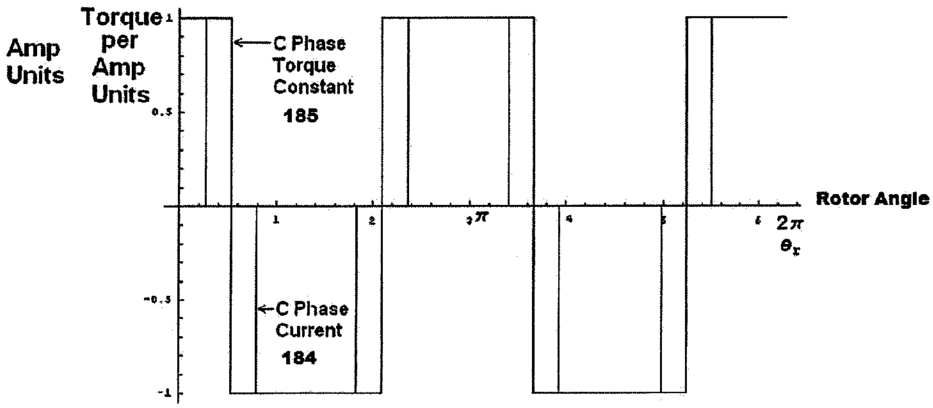


FIG. 23

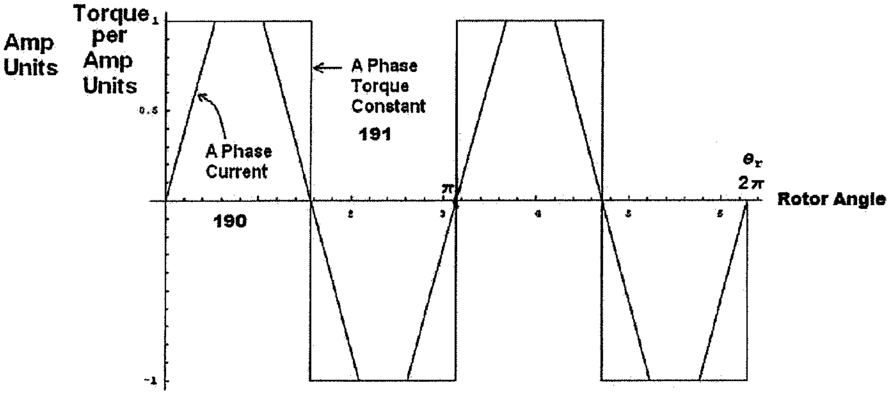


FIG. 24

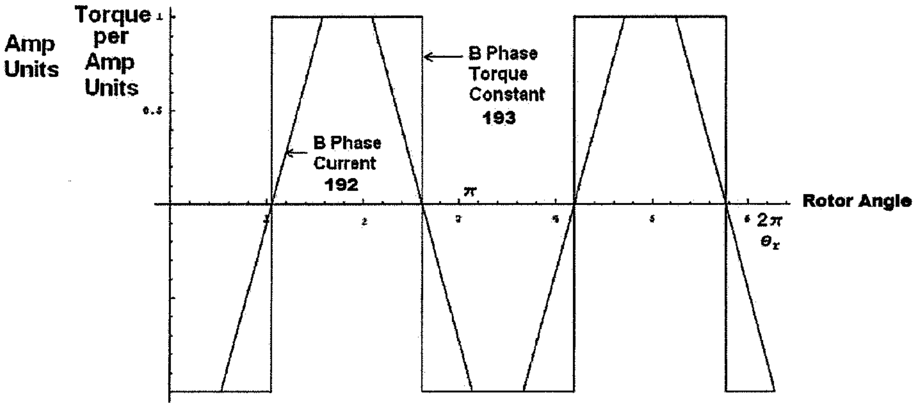


FIG. 25

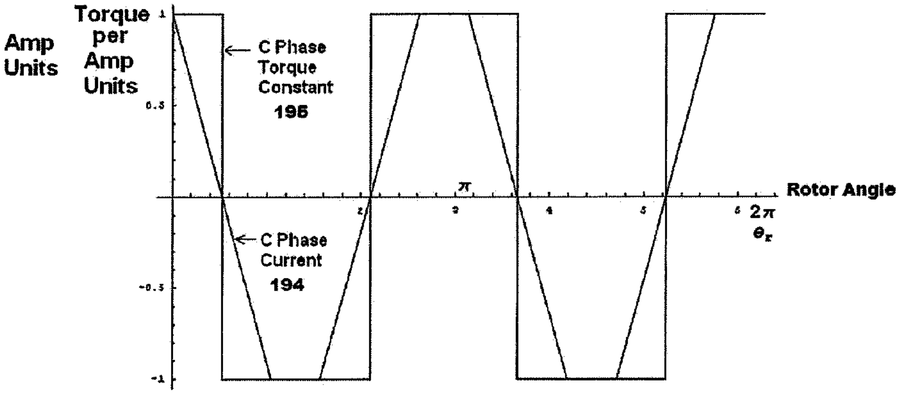


FIG. 26

TANDEM ROTOR SERVO MOTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from United States Nonprovisional application Ser. No. 12/944,834 filed Nov. 12, 2010, entitled TANDEM ROTOR SERVO MOTOR and U.S. Provisional Application Ser. No. 61/280,944, filed Nov. 12, 2009, entitled TANDEM ROTOR SERVO MOTOR AND ELECTRONIC DRIVE METHODS, the contents of which are incorporated herein by reference in their entirety.

FIELD OF THE INVENTION

[0002] The present invention relates to a tandem servo motor assembly. The present invention more specifically relates to a tandem servo motor assembly generating high torque at a reduced inertia and providing a smooth, ripple free torque operation.

BACKGROUND

[0003] Servo motors are generally known in the art. A servo motor is an electromechanical device in which an electrical input determines a mechanical output, for example the rotational velocity and torque of a corresponding motor shaft. A multi-phase servo motor generally includes a rotor surrounded by a nonmoving stator. Windings, or coils of wire, are positioned on the stator. Electrical currents of differing phase are provided to the windings, producing a rotating magnetic field. The rotating magnetic field interacts with the rotor, causing the rotor to turn. The electrical current is generally provided by a drive. The drive can control the amount of electrical current transmitted to the motor, correspondingly controlling the rotation of the motor shaft. Such drives may be referred to as variable-speed or variable-frequency drives.

[0004] It is desired for some end uses of a servo motor to have a high torque to low inertia ratio. A servo motor having a high torque to low inertia ratio provides a fast rate of acceleration of the motor rotor. However, multi-phase servo motors as described above have limitations on the torque to inertia ratio, especially in applications requiring a larger sized motor. This is due to the larger, higher weight motor and components necessary to rotate a rotor at higher speeds or revolutions per minute (RPM).

[0005] In addition, it is desired for servo motors to operate with a smooth torque output, minimizing the amount of ripple torque, also known as torque ripple. Torque ripple is a fluctuation in torque delivered by a motor due to electromechanical effects. Torque ripple results in unwanted pulsations which can increase in strength and frequency at higher motor and/or rotor speeds. A source of torque ripple in a multi-phase servo motor occurs when the torque per amp of a phase shifts, or moves out of phase in association with the other phases. In situations where a phase shifts, torque ripple can be reduced or minimized by improving the torque constant of a motor. Multi-phase servo motors as described above generally have a trapezoidal shaped torque constant. Accordingly, should a phase shift in a multi-phase servo motor as described above, torque ripple will occur.

[0006] Accordingly, an improved servo motor assembly and method of driving a servo motor is provided.

SUMMARY OF THE INVENTION

[0007] A tandem rotor servo motor assembly is provided comprising a first phase element positioned on a shaft, the first phase element having a first rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged. A second phase element is positioned on the shaft a first distance from the first phase element, the second phase element having a second rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged. A third phase element is positioned on the shaft a second distance from the second phase element, the third phase element having a third rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged. The second rotor is offset about the shaft from the first rotor by sixty degrees of rotation and the third rotor being offset about the shaft from the first rotor by one hundred and twenty degrees of rotation.

[0008] In another embodiment of a tandem rotor servo motor assembly, the assembly comprises a multi-phase servo motor having a first phase element, a second phase element, and a third phase element, the first, second and third phase elements including a rotor and a stator carrying four magnetically charged poles, each pole exerting a magnetic force when said poles are electrically charged. A shaft is connected to the rotors of the first, second and third phase elements, the second rotor is provided on the shaft $\pi/3$ radians offset from the first rotor, and the third rotor is provided on the shaft $2\pi/3$ radians offset from the first rotor.

[0009] In another embodiment of a tandem servo motor, the motor comprises a first phase element in communication with a shaft, the first phase element having a first rotor connected to the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged by a first phase of a three-phase current, said first phase element producing a square waveform torque constant. A second phase element is in communication with the shaft a first distance from the first phase element, the second phase element having a second rotor connected to the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged by a second phase of a three-phase current, said second phase element producing a square waveform torque constant. A third phase element in communication with the shaft a second distance from the second phase element and a third distance from the first phase element, the third phase element having a third rotor connected to the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged by a third phase of a three-phase current, said third phase element producing a square waveform torque constant. The second rotor is offset about the shaft from the first rotor by approximately sixty degrees of rotation and the third rotor is offset about the shaft from the first rotor by approximately one hundred and twenty degrees of rotation and from the second rotor by approximately sixty degrees of rotation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1** is a plan view according to one or more examples of embodiments of a tandem rotor servo motor assembly, showing the rotor and stator assemblies.

[0011] FIG. **2** is a cross-sectional view of a section of the tandem rotor servo motor assembly of FIG. **1**, showing a first phase tandem motor element taken along line **2-2** of FIG. **1**.

[0012] FIG. **3** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the first phase tandem motor element of FIG. **2**.

[0013] FIG. **4** is a cross-sectional view of a section of the tandem rotor servo motor assembly of FIG. **1**, showing a second phase tandem motor element taken along line **4-4** of FIG. **1**.

[0014] FIG. **5** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the second phase tandem motor element of FIG. **4**.

[0015] FIG. **6** is a cross-sectional view of a section of the tandem rotor servo motor assembly of FIG. **1**, showing a third phase tandem motor element taken along line **6-6** of FIG. **1**.

[0016] FIG. **7** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the third phase tandem motor element of FIG. **6**.

[0017] FIG. **8** is a plan view according to one or more examples of embodiments of the tandem rotor servo motor assembly of FIG. **1**, showing the rotor and stator assemblies.

[0018] FIG. **9** is a cross-sectional view of a section of the tandem rotor servo motor assembly of FIG. **8**, showing a first phase tandem motor element taken along line **9-9** of FIG. **8**.

[0019] FIG. **10** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the first phase tandem motor element of FIG. **9**.

[0020] FIG. **11** is a cross-sectional view of a section of the tandem rotor servo motor assembly of FIG. **8**, showing a second phase tandem motor element taken along line **11-11** of FIG. **8**.

[0021] FIG. **12** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the second phase tandem motor element of FIG. **11**.

[0022] FIG. **13** is a cross-sectional view of a section of the tandem rotor servo motor assembly of FIG. **8**, showing a third phase tandem motor element taken along line **13-13** of FIG. **8**.

[0023] FIG. **14** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the third phase tandem motor element of FIG. **13**.

[0024] FIG. **15** is a cross-sectional view according to one or more examples of embodiments of a tandem rotor servo motor assembly lamination.

[0025] FIG. **16** is a plan view of the tandem rotor servo motor assembly of FIG. **8**, illustrating placement of one or more laminations.

[0026] FIG. **17** is a plan view of one or more examples of embodiments of a tandem rotor servo motor assembly of FIG. **1**, illustrating placement of one or more laminations.

[0027] FIG. **18** is a graph showing the torque per amp versus rotor angle for one revolution of a rotor of a first phase or A phase of a conventional single rotor, single stator three-phase motor.

[0028] FIG. **19** is a graph showing the torque per amp versus rotor angle for one revolution of a rotor of a second phase or B phase of a conventional single rotor, single stator three-phase motor.

[0029] FIG. **20** is a graph showing the torque per amp versus rotor angle for one revolution of a rotor of a third phase or C phase of a conventional single rotor, single stator three-phase motor.

[0030] FIG. **21** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the first phase or A phase tandem motor element of FIG. **9** driven by a square wave current provided from a drive.

[0031] FIG. **22** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the second phase or B phase tandem motor element of FIG. **11** driven by a square wave current provided from a drive.

[0032] FIG. **23** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the third phase or C phase tandem motor element of FIG. **13** driven by a square wave current provided from a drive.

[0033] FIG. **24** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the first phase or A phase tandem motor element of FIG. **9** driven by a trapezoidal wave current provided from a drive.

[0034] FIG. **25** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the second phase or B phase tandem motor element of FIG. **11** driven by a trapezoidal wave current provided from a drive.

[0035] FIG. **26** is a graph showing the torque per amp versus rotor angle for one revolution of the rotor of the third phase or C phase tandem motor element of FIG. **13** driven by a trapezoidal wave current provided from a drive.

DETAILED DESCRIPTION

[0036] The invention shown in the Figures is generally directed to a tandem rotor servo motor assembly **100**, and in particular a multi-phase servo motor **102** having a plurality of phase elements **110**, **120**, **130** mounted upon a common shaft **104**. For ease of discussion and understanding, the following detailed description and illustrations refer to each phase element **110**, **120**, **130** of the multi-phase servo motor **102** as a permanent magnet motor. It should be appreciated that a permanent magnet motor is provided for purposes of illustration, and that the multi-phase servo motor **102** and associated phase elements **110**, **120**, **130** disclosed herein may be employed as a different type of motor, including, but not limited to, a reluctance motor or induction motor.

[0037] FIG. **1** is a plan view of an embodiment of a tandem rotor servo motor assembly **100**. The tandem rotor servo motor assembly **100** generally includes a multi-phase servo motor **102**. The multi-phase servo motor **102** includes three phases which are separated into three phase elements, a first or A phase element **110**, a second or B phase element **120**, and a third or C phase element **130**. Each phase element **110**, **120**, **130** includes a respective input terminal connection or input lead **111**, **121**, **131**, each of which corresponds to a phase of a three phase drive (not shown). An example of a three phase drive may include a DIGIFLEX® PERFORMANCE™ Series servo drive, Product Number DPRAHIE-030A800 available from ADVANCED MOTION CONTROLS® (located in Camarillo, Calif.). Each phase element **110**, **120**, **130** additionally includes a respective output terminal connection or output lead **112**, **122**, **132**. Output terminal connections **112**, **122**, **132** are electrically connected by connector **103**.

[0038] The multi-phase servo motor **102** also includes a common shaft **104**. Each phase element **110**, **120**, **130** is mounted on or connected to shaft **104**. As shown in FIG. **1**, when connected to shaft **104**, each phase element **110**, **120**,

130 is spaced or separated from one another by a distance **106**, **108**. For example, the first phase element **110** is separated from the second phase element **120** by a first distance or gap or spacing **106**. Similarly, the second phase element **120** is separated from the third phase element **130** by a second distance or gap or spacing **108**.

[0039] The tandem rotor servo motor assembly **100** may also include a casing or heat shrink tube (not shown) which encases or surrounds the multi-phase servo motor **102**, end-bells (not shown), and bearings, bearing supports and/or associated bearing assemblies (not shown).

[0040] FIG. **2** illustrates a cross-sectional view of the first phase element **110**. The first phase element **110** includes a stator or stator lamination **113**. While one stator lamination **113** is shown, the first phase element **110** may include a stack or series or plurality of stator laminations **113**. Stator lamination **113** includes back iron **151**. As illustrated in FIG. **2**, stator lamination **113** may include a plurality of back iron segments **151**. Back iron segment or first back iron **151***a* is provided in a region between corner slots **114***a* and **114***b*. Back iron segment or second back iron **151***b* is provided in a region between corner slots **114***b* and **114***c*. Back iron segment or third back iron **151***c* is provided in a region between corner slots **114***c* and **114***d*. Back iron segment or fourth back iron **151***d* is provided in a region between corner slots **114***d* and **114***a*. The stator lamination **113** and associated back iron segments **151** are illustrated in FIG. **2** as arranged in an approximate square shaped configuration. An approximate square shaped configuration provides advantages over standard circular stator lamination and back iron arrangements. An approximate square shaped configuration provides a greater or increased amount of back iron **151** in the stator lamination **113** than a standard circular stator lamination. This allows for an increased amount of conductive material to be placed in or about corner slots **114** than a standard circular stator lamination. In addition, the greater amount of back iron **151** provides for corner slots **114** to be larger in size, also allowing for an increased amount of conductive material to be placed in or about corner slots **114**. Further, the greater amount of back iron **151** allows for corner slots **114** to be provided toward the corners of stator lamination **113**, allowing for less heat build-up in the stator lamination **113** due to improved heat transfer or heat dissipation or cooling. In one or more examples of embodiments, the stator lamination **113** may be rectangular or any other polygonal arrangement which provides for an increased amount of back iron in the stator lamination **113** than a standard circular stator lamination. Stator lamination **113** may be formed from iron, a combination of iron and silicon, silicon steel, metallic alloys or by any other known and suitable materials, processes or methods.

[0041] The stator lamination **113** includes or defines a plurality of corner slots **114**. The illustrated stator lamination **113** defines four corner slots **114***a*, **114***b*, **114***c*, **114***d*. Each corner slot **114** corresponds with one of four poles of the servo motor **102**. Accordingly, the four corner slots **114***a*, **114***b*, **114***c*, **114***d* define a four pole concentrated winding. The four corner slots **114***a*, **114***b*, **114***c*, **114***d* are provided in an arrangement approximately orthogonal or perpendicular to one another. For example, as shown in FIG. **2**, corner slot **114***a* is neighbored by corner slots **114***b* and **114***d*. Corner slots **114***b* and **114***d* are provided approximately orthogonal to corner slot **114***a*. To this end, the four corner slots **114***a*, **114***b*, **114***c*, **114***d* are provided in relation to one another to approximately form the corners of a square. Each corner slot **114***a*, **114***b*, **114***c*, **114***d* alternates with its neighboring corner slot between carrying an electrical current into the corner slot or carrying an electrical current out of the corner slot. As shown in FIG. **2**, corner slots **114***a* and **114***c* carry an electrical current into the respective slots, which is illustrated by a "+" or plus, while corner slots **114***b* and **114***d* carry an electrical current out of the respective slots, which is illustrated by a "•" or dot. In addition, corner slot **114***a* receives the first input terminal connection **111**, while the first output terminal connection **112** exits from corner slot **114***d*. In one or more examples of embodiments, corner slots **114** may be circular, square, rectangular, or any other polygonal arrangement or appropriate size to maximize conductive material or windings in accordance with the present invention.

[0042] The stator lamination **113** may include or define a slot opening or neck or passage **115**. The illustrated stator lamination **113** defines four slot openings **115***a*, **115***b*, **115***c*, **115***d*. Each slot opening **115***a*, **115***b*, **115***c*, **115***d* is in communication with a respective corner slot **114***a*, **114***b*, **114***c*, **114***d*. The width of slot opening **115***a*, **115***b*, **115***c*, **115***d* is preferably narrower than the width of the respective corner slot **114***a*, **114***b*, **114***c*, **114***d*.

[0043] The stator lamination **113** may also include stator tooth or teeth **152**. Stator teeth **152** may generally be provided between the respective slot openings **115**. As illustrated in FIG. **2**, stator tooth or first stator tooth **152***a* is provided in a region between slot openings **115***a* and **115***b*. Stator tooth or second stator tooth **152***b* is provided in a region between slot openings **115***b* and **115***c*. Stator tooth or third stator tooth **152***c* is provided in a region between slot openings **115***c* and **115***d*. Stator tooth or fourth stator tooth **152***d* is provided in a region between slot openings **115***d* and **115***a*.

[0044] The stator lamination **113** includes or defines a rotor aperture **116**. The rotor aperture **116** is in communication with corner slots **114***a*, **114***b*, **114***c*, **114***d*, for example, as illustrated in FIG. **2**, through slot openings **115***a*, **115***b*, **115***c*, **115***d*. In addition, rotor aperture **116** receives or surrounds shaft **104**.

[0045] Within rotor aperture **116**, shaft **104** carries rotor **105***a*. Mounted upon or connected to rotor **105***a* is a plurality of magnets **117**. As illustrated in FIG. **2**, rotor **105***a* carries four magnets **117***a*, **117***b*, **117***c*, **117***d*. Magnets **117***a*, **117***b*, **117***c*, **117***d* are respectively provided about a portion of the circumference of rotor **105***a*. Further, each neighboring magnet **117***a*, **117***b*, **117***c*, **117***d* alternates its exposed pole about the circumference of rotor **105***a*. For example, magnets **117***a* and **117***c* may expose a south pole, which is illustrated by an "S", while magnets **117***b* and **117***d* may expose a north pole, which is illustrated by an "N". Magnets **117***a*, **117***b*, **117***c*, **117***d* are spaced apart from each respective neighboring magnet by a distance **118**. The shaft **104** and associated rotor **105***a* and magnets **117***a*, **117***b*, **117***c*, **117***d* are spaced a distance from rotor aperture **116** by an air gap **119**. The air gap **119** enables the shaft **104**, rotor **105***a* and magnets **117***a*, **117***b*, **117***c*, **117***d* to rotate unobstructed within rotor aperture **116**. As observed from the cross-sectional view of FIG. **2**, the shaft **104**, rotor **105***a* and magnets **117***a*, **117***b*, **117***c*, **117***d* rotate counter-clockwise within rotor aperture **116**. In one or more examples of embodiments, magnets **117** may include straight cut edges, as illustrated in FIGS. **2**, **4** and **6**. In one or more examples of embodiments, magnets **117** may include angled edges, tapered edges, or any suitable edge for operation of the motor assembly **100** in accordance with the present invention.

Further, in one or more examples of embodiments, distance **118** may be any suitable distance appropriate for the end use of the motor assembly **100** in accordance with the present invention.

[0046] FIG. **3** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of the rotor, θ_r (Y-axis) for one revolution of rotor **105***a* about the periphery of the air gap **119** of the first phase element **110**. The torque per amp versus rotor angle of the first phase element **110** is in the shape of a sinusoidal curve. Based upon the four magnetic poles of the first phase element **110**, the torque per amp versus rotor angle completes two electrical cycles for every one revolution of rotor **105***a*. The first electrical cycle is completed at 180° (one-hundred and eighty degrees) or π (*pie*) radians of rotation of rotor **105***a*, while the second electrical cycle is completed at 360° (three-hundred and sixty degrees) or 2π (two pie) radians of rotation of rotor **105***a*.

[0047] FIG. **4** illustrates a cross-sectional view of a cross section of the second phase element **120** of tandem rotor servo motor assembly **100**. The second phase element **120** includes a stator lamination **113**, corner slots **114**, slot openings **115**, rotor aperture **116**, magnets **117**, distance between magnets **118**, air gap **119**, back iron **151** and stator teeth **152** which are substantially as described herein in association with the first phase element **110**. Operation and particular components described herein are substantially the same and like numbers have been used to illustrate the like components. Corner slot **114***a* of the second phase element **120** receives the second input terminal connection **121**, while the second output terminal connection **122** exits from corner slot **114***d*. Within the rotor aperture **116** of the second phase element **120**, common shaft **104** carries rotor **105***b*. Mounted upon or connected to rotor **105***b* is a plurality of magnets **117**. As illustrated in FIG. **4**, rotor **105***b* carries four magnets **117***a*, **117***b*, **117***c*, **117***d*. Rotor **105***b* is substantially the same as rotor **105***a*, but for the positioning of rotor **105***b* in relation to rotor **105***a* on shaft **104**. Rotor **105***b* is provided on shaft **104** approximately 60° (sixty degrees) mechanically lagging from rotor **105***a*. In other words, comparing the cross-sectional view of the first phase element **110** of FIG. **2** to the cross-sectional view of the second phase element **120** of FIG. **4**, rotor **105***b* (and the associated magnets **117**) is illustrated as offset from rotor **105***a* (and the associated magnets **117**) by approximately 60° (sixty degrees) lagging. Put differently, according to the illustrated view of FIG. **4**, rotor **105***b* (and the associated magnets **117**) is disposed about shaft **104** approximately 60° (sixty degrees) in the clockwise direction as compared to rotor **105***a* (of FIG. **2**), as FIGS. **2** and **4** illustrate the rotation of shaft **104** as in the counter-clockwise direction. In addition to rotor **105***b* mechanically lagging rotor **105***a* by approximately 60° (sixty degrees), rotor **105***b* has an electrical angle which is lagging rotor **105***a* by approximately 120° (one hundred and twenty degrees). The associated electrical angle of rotor **105***b* can be calculated by multiplying the mechanical angle by N, where N equals the number of pole pairs (or one-half the total number of poles).

[0048] FIG. **5** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of the rotor, θ_r (Y-axis) for one revolution of rotor **105***b* about the periphery of the air gap **119** of the second phase element **120**. The torque per amp versus rotor angle of the second phase element **120** is in the shape of a sinusoidal curve. Based upon the four magnetic poles of the second phase element **120**, the torque per amp versus rotor angle completes two electrical cycles for every one revolution of rotor **105***b*. The first electrical cycle is completed at 180° (one-hundred and eighty degrees) or π (*pie*) radians of rotation of rotor **105***b*, while the second electrical cycle is completed at 360° (three-hundred and sixty degrees) or 2π (two pie) radians of rotation of rotor **105***b*. Comparing torque per amp versus rotor angle of FIG. **5** to FIG. **3**, the torque per amp of FIG. **5** is shifted 60° (sixty degrees) mechanically lagging to the torque per amp of FIG. **3**. In other words, the torque per amp curve of FIG. **5** is shifted $\lambda/3$ radians to the right as compared to the torque per amp curve of FIG. **3**. This is due to rotor **105***b* being rotated about shaft **104** 60° (sixty degrees) behind, or lagging, rotor **105***a*.

[0049] FIG. **6** illustrates a cross-sectional view of a cross section of the third phase element **130** of tandem rotor servo motor assembly **100**. The third phase element **130** includes a stator lamination **113**, corner slots **114**, slot openings **115**, rotor aperture **116**, magnets **117**, distance between magnets **118**, air gap **119**, back iron **151** and stator teeth **152**, which are substantially as described herein in association with the first phase element **110**. Operation and particular components described herein are substantially the same and like numbers have been used to illustrate the like components. Corner slot **114***a* of the third phase element **130** receives the third input terminal connection **131**, while the third output terminal connection **132** exits from corner slot **114***d*. Within the rotor aperture **116** of the third phase element **130**, common shaft **104** carries rotor **105***c*. Mounted upon or connected to rotor **105***c* is a plurality of magnets **117**. As illustrated in FIG. **6**, rotor **105***c* carries four magnets **117***a*, **117***b*, **117***c*, **117***d*. Rotor **105***c* is substantially the same as rotor **105***a*, but for the positioning of rotor **105***c* in relation to rotor **105***a* on shaft **104**. Rotor **105***c* is provided on shaft **104** approximately 120° (one hundred and twenty degrees) mechanically lagging from rotor **105***a*. In other words, comparing the cross-sectional view of the first phase element **110** of FIG. **2** to the cross-sectional view of the third phase element **130** of FIG. **6**, rotor **105***c* (and the associated magnets **117**) is illustrated as offset from rotor **105***a* (and the associated magnets **117**) by approximately 120° (one hundred and twenty degrees) lagging. Put differently, according to the illustrated view of FIG. **6**, rotor **105***c* (and the associated magnets **117**) is disposed about shaft **104** approximately 120° (one hundred and twenty degrees) in the clockwise direction as compared to rotor **105***a* (of FIG. **2**), as FIGS. **2** and **6** illustrate the rotation of shaft **104** as in the counter-clockwise direction. In addition to rotor **105***c* mechanically lagging rotor **105***a* by approximately 120° (one hundred and twenty degrees), rotor **105***c* has an electrical angle which is lagging rotor **105***a* by approximately 240° (two hundred and forty degrees).

[0050] FIG. **7** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of the rotor, θ_r (Y-axis) for one revolution of rotor **105***c* about the periphery of the air gap **119** of the third phase element **130**. The torque per amp versus rotor angle of the third phase element **130** is in the shape of a sinusoidal curve. Based upon the four magnetic poles of the third phase element **130**, the torque per amp versus rotor angle completes two electrical cycles for every one revolution of rotor **105***c*. The first electrical cycle is completed at 180° (one-hundred and eighty degrees) or π (*pie*) radians of rotation of rotor **105***c*, while the second electrical cycle is completed at 360° (three-hundred and sixty degrees) or 2π (two pie) radians of rotation of rotor **105***c*. Comparing torque per amp versus rotor angle of FIG. **7**

to FIG. **3**, the torque per amp of FIG. **7** is shifted 120° (one hundred and twenty degrees) mechanically lagging to the torque per amp of FIG. **3**. In other words, the torque per amp curve of FIG. **7** is shifted 2π/3 radians to the right as compared to the torque per amp curve of FIG. **3**. This is due to rotor **105***c* being rotated about shaft **104** 120° (one hundred and twenty degrees) behind, or lagging, rotor **105***a*.

[0051] An alternative embodiment of the tandem rotor servo motor assembly **200** is shown in FIGS. **8-14**. The tandem rotor servo motor assembly **200** includes features which are substantially as described herein in association with the tandem rotor servo motor assembly **100**. Operation and particular components described herein are substantially the same and like numbers have been used to illustrate the like components. Referring to FIG. **8**, in this embodiment, the multi-phase servo motor **102** includes three phases which are separated into three phase elements, a first or A phase element **210**, a second or B phase element **220**, and a third or C phase element **230**.

[0052] FIG. **9** illustrates a cross-sectional view of a cross section of the first phase element **210** of tandem rotor servo motor assembly **200**. The first phase element **210** includes a stator lamination **113**, corner slots **114**, slot openings **115**, rotor aperture **116**, air gap **119**, back iron **151** and stator teeth **152**, which are substantially as described herein in association with the first phase element **110**. Operation and particular components described herein are substantially the same and like numbers have been used to illustrate the like components. Within the rotor aperture **116** of the first phase element **210**, common shaft **104** carries rotor **105***a*. Mounted upon or connected to rotor **105***a* is a plurality of magnets **217**. As illustrated in FIG. **9**, rotor **105***a* carries four magnets **217***a*, **217***b*, **217***c*, **217***d*. Magnets **217** are substantially as described herein in association with magnets **117**, but for how magnets **217** are provided about a portion of the circumference of rotor **105***a*. As illustrated in FIG. **9**, magnets **217***a*, **217***b*, **217***c*, **217***d* are provided about the circumference of rotor **105***a* such that each neighboring magnet **217***a*, **217***b*, **217***c*, **217***d* alternates its exposed pole. For example, magnets **217***a* and **217***c* may expose a south pole, which is illustrated by an "S", while magnets **217***b* and **217***d* may expose a north pole, which is illustrated by an "N". Further, magnets **217***a*, **217***b*, **217***c*, **217***d* abut or border or communicate with each respective neighboring magnet **217**. To this end, magnets **217***a*, **217***b*, **217***c*, **217***d* are the same thickness radially outward from shaft **104**. In other words, magnets **217***a*, **217***b*, **217***c*, **217***d* have the same or a uniform or a continuous thickness about the circumference of rotor **105***a* within air gap **119**. As observed from the cross-sectional view of FIG. **9**, the shaft **104**, rotor **105***a* and magnets **217***a*, **217***b*, **217***c*, **217***d* rotate counter-clockwise within rotor aperture **116**.

[0053] FIG. **10** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of the rotor, θ_r (Y-axis) for one revolution of rotor **105***a* about the periphery of the air gap **119** of the first phase element **210**. The torque per amp versus rotor angle of the first phase element **210** is in the shape of a square wave. The square wave is generated by the continuous uniform thickness of magnets **217** about rotor **105***a* in air gap **119**. Based upon the four magnetic poles of the first phase element **210**, the torque per amp versus rotor angle completes two electrical cycles for every one revolution of rotor **105***a*. The first electrical cycle is completed at 180° (one-hundred and eighty degrees) or π (*pie*) radians of rotation of rotor **105***a*, while the second electrical cycle is completed at 360° (three-hundred and sixty degrees) or 2π (two pie) radians of rotation of rotor **105***a*.

[0054] FIG. **11** illustrates a cross-sectional view of a cross section of the second phase element **220** of tandem rotor servo motor assembly **200**. The second phase element **220** includes substantially the same features which are substantially as described herein in association with the first phase element **210**. Operation and particular components described herein are substantially the same and like numbers have been used to illustrate the like components. Corner slot **114***a* of the second phase element **220** receives the second input terminal connection **121**, while the second output terminal connection **122** exits from corner slot **114***d*. Within the rotor aperture **116** of the second phase element **220**, common shaft **104** carries rotor **105***b*. Mounted upon or connected to rotor **105***b* is a plurality of magnets **217**. As illustrated in FIG. **11**, rotor **105***b* carries four magnets **217***a*, **217***b*, **217***c*, **217***d*. Rotor **105***b* is substantially the same as rotor **105***a*, but for the positioning of rotor **105***b* in relation to rotor **105***a* on shaft **104**. Rotor **105***b* is provided on shaft **104** approximately 60° (sixty degrees) mechanically lagging from rotor **105***a*. In other words, comparing the cross-sectional view of the first phase element **210** of FIG. **9** to the cross-sectional view of the second phase element **220** of FIG. **11**, rotor **105***b* (and the associated magnets **217**) is illustrated as offset from rotor **105***a* (and the associated magnets **217**) by approximately 60° (sixty degrees) lagging. Put differently, according to the illustrated view of FIG. **11**, rotor **105***b* (and the associated magnets **217**) is disposed about shaft **104** approximately 60° (sixty degrees) in the clockwise direction as compared to rotor **105***a* (of FIG. **9**), as FIGS. **9** and **11** illustrate the rotation of shaft **104** as in the counter-clockwise direction. In addition to rotor **105***b* mechanically lagging rotor **105***a* by approximately 60° (sixty degrees), rotor **105***b* has an electrical angle which is lagging rotor **105***a* by approximately 120° (one hundred and twenty degrees).

[0055] FIG. **12** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of the rotor, $_{\theta r}$ (Y-axis) for one revolution of rotor **105***b* about the periphery of the air gap **119** of the second phase element **220**. The torque per amp versus rotor angle of the second phase element **220** is in the shape of a square wave. Based upon the four magnetic poles of the second phase element **220**, the torque per amp versus rotor angle completes two electrical cycles for every one revolution of rotor **105***b*. The first electrical cycle is completed at 180° (one-hundred and eighty degrees) or π (*pie*) radians of rotation of rotor **105***b*, while the second electrical cycle is completed at 360° (three-hundred and sixty degrees) or 2π (two pie) radians of rotation of rotor **105***b*. Comparing torque per amp versus rotor angle of FIG. **12** to FIG. **10**, the torque per amp of FIG. **12** is shifted 60° (sixty degrees) mechanically lagging to the torque per amp of FIG. **10**. In other words, the torque per amp curve of FIG. **12** is shifted π/3 radians to the right as compared to the torque per amp curve of FIG. **10**. This is due to rotor **105***b* being rotated about shaft **104** 60° (sixty degrees) behind, or lagging, rotor **105***a*.

[0056] FIG. **13** illustrates a cross-sectional view of a cross section of the third phase element **230** of tandem rotor servo motor assembly **200**. The third phase element **230** includes substantially the same features which are substantially as described herein in association with the first phase element **210**. Operation and particular components described herein are substantially the same and like numbers have been used to illustrate the like components. Corner slot **114***a* of the third phase element **230** receives the third input terminal connection **131**, while the third output terminal connection **132** exits from corner slot **114***d*. Within the rotor aperture **116** of the third phase element **230**, common shaft **104** carries rotor **105***c*. Mounted upon or connected to rotor **105***c* is a plurality of magnets **217**. As illustrated in FIG. **13**, rotor **105***c* carries four magnets **217***a*, **217***b*, **217***c*, **217***d*. Rotor **105***c* is substantially the same as rotor **105***a*, but for the positioning of rotor **105***c* in relation to rotor **105***a* on shaft **104**. Rotor **105***c* is provided on shaft **104** approximately 120° (one hundred and twenty degrees) mechanically lagging from rotor **105***a*. In other words, comparing the cross-sectional view of the first phase element **210** of FIG. **9** to the cross-sectional view of the third phase element **230** of FIG. **13**, rotor **105***c* (and the associated magnets **217**) is illustrated as offset from rotor **105***a* (and the associated magnets **217**) by approximately 120° (one hundred and twenty degrees) lagging. Put differently, according to the illustrated view of FIG. **13**, rotor **105***c* (and the associated magnets **217**) is disposed about shaft **104** approximately 120° (one hundred and twenty degrees) in the clockwise direction as compared to rotor **105***a* (of FIG. **9**), as FIGS. **9** and **13** illustrate the rotation of shaft **104** as in the counter-clockwise direction. In addition, to rotor **105***c* mechanically lagging rotor **105***a* by approximately 120° (one hundred and twenty degrees), rotor **105***c* has an electrical angle which is lagging rotor **105***a* by approximately 240° (two hundred and forty degrees).

[0057] FIG. **14** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of the rotor, θ_r (Y-axis) for one revolution of rotor **105***c* about the periphery of the air gap **119** of the third phase element **230**. The torque per amp versus rotor angle of the third phase element **230** is in the shape of a square wave. Based upon the four magnetic poles of the third phase element **230**, the torque per amp versus rotor angle completes two electrical cycles for every one revolution of rotor **105***c*. The first electrical cycle is completed at 180° (one-hundred and eighty degrees) or π (*pie*) radians of rotation of rotor **105***c*, while the second electrical cycle is completed at 360° (three-hundred and sixty degrees) or 2π (two pie) radians of rotation of rotor **105***c*. Comparing torque per amp versus rotor angle of FIG. **14** to FIG. **10**, the torque per amp of FIG. **14** is shifted 120° (one hundred and twenty degrees) mechanically lagging to the torque per amp of FIG. **10**. In other words, the torque per amp curve of FIG. **14** is shifted $2\pi/3$ radians to the right as compared to the torque per amp curve of FIG. **10**. This is due to rotor **105***c* being rotated about shaft **104** 120° (one hundred and twenty degrees) behind, or lagging, rotor **105***a*.

[0058] FIG. **15** illustrates an embodiment of a back iron lamination ring **140**. The ring **140** advantageously provides greater surface area for conduction of the magnetic field in the stator. By providing greater surface area for conduction, the ring **140** prevents the stator back iron from magnetically saturating. Saturation of the stator back iron decreases the magnetic field and reduces torque. In one or more examples of embodiments, the ring **140** may be provided with a geometry or associated shape to maximize surface area of a motor assembly **100** stator in accordance with the present invention.

[0059] FIG. **16** illustrates an example of placement of a plurality of lamination rings **140** in association with an embodiment of a tandem rotor servo motor assembly **200**. Each phase element **210**, **220**, **230** may respectively include a pair of lamination rings **140**. As illustrated, lamination rings **140** may be connected to or attached to or affixed on faces **240** of each phase element **210**, **220**, **230**, for example by, but not limited to, bolt or adhesive. Faces **240** may include a first edge face **241** and a second edge face **242**. Edge faces **241**, **242** and the associated lamination rings **140** are provided approximately perpendicular to common shaft **104**.

[0060] FIG. **17** illustrates an alternative embodiment of a tandem rotor servo motor assembly **300**. The tandem rotor servo motor assembly **300** includes features which are substantially as described herein in association with the tandem rotor servo motor assembly **200**. Operation and particular components described herein are substantially the same and like numbers have been used to illustrate the like components. Referring to FIG. **17**, in this embodiment, the first, second, and third phase elements **210**, **220**, **230** include lamination rings **140** provided perpendicular to common shaft **104** and attached to edge faces **241**, **242** of each phase element **210**, **220**, **230**. In addition, when connected to shaft **104**, each phase element **210**, **220**, **230** is spaced or separated from one another by a distance **306**, **308**. For example, the first phase element **210** is separated from the second phase element **220** by a first distance or gap or spacing **306**. Similarly, the second phase element **220** is separated from the third phase element **230** by a second distance or gap or spacing **308**. Distances **306**, **308** may be greater than distances **106**, **108** of FIG. **1**. Phase elements **210**, **220**, **230** may be spaced a distance **306**, **308** apart on shaft **104**, advantageously providing more surface area for the cooling of each phase element **210**, **220**, **230**. Further, spacing phase elements **210**, **220**, **230** a distance **306**, **308** apart on shaft **104** does not substantially increase the inertia of the tandem rotor servo motor assembly **300**. Accordingly, in one or more examples of embodiments, spacing phase elements **210**, **220**, **230** a distance **306**, **308** from one another may lead to an increase in torque to inertia ratio. Electrical current transmitted through windings generates heat. Providing more surface area for the cooling of each phase element **210**, **220**, **230** dissipates heat generated by the windings. Consequently, more electrical current can be transmitted through the windings, increasing the torque output, without burning out the windings of the motor.

[0061] FIG. **18** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of a rotor in the A phase or first phase of a conventional single stator, single rotor multi-phase motor. The A phase current **170** is illustrated as a conventional square wave current provided from a drive. The A phase torque constant **171** is a trapezoidal wave form. FIG. **19** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of a rotor in the B phase or second phase of a conventional single stator, single rotor multi-phase motor. The B phase current **172** is illustrated as a conventional square wave current provided from a drive, while the B phase torque constant **173** is a trapezoidal wave form. FIG. **20** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of a rotor in the C phase or third phase of a conventional single stator, single rotor multi-phase motor. The C phase current **174** is illustrated as a conventional square wave current provided from a drive, while the C phase torque constant **175** is a trapezoidal wave form. The trapezoidal wave forms of the A, B and C phase torque constants **171**, **173**, **175** is generated from the configuration of the stator windings of a conventional multi-phase motor. The stator windings of each phase are wound about a single stator. Accordingly, the winding phases generate interference with one another. The interference leads to the trapezoidal shaped torque constant. The trapezoidal wave forms of the A, B and C torque constants **171**, **173**, **175** leads to undesired torque ripple. Should any of the A, B, or C phases **170**, **172**, **174** shift out of phase with one another, torque ripple will occur.

[0062] FIG. **21** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of rotor **105***a* in the A phase or first phase element **210** of the tandem rotor servo motor assembly **200**. The A phase current **180** is illustrated as a conventional square wave current provided from a drive. The A phase torque constant **181** is a square wave form. FIG. **22** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of rotor **105***b* in the B phase or second phase element **220** of the tandem rotor servo motor assembly **200**. The B phase current **182** is illustrated as a conventional square wave current provided from a drive, while the B phase torque constant **183** is a square wave form. FIG. **23** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of rotor **105***c* in the C phase or third phase element **230** of the tandem rotor servo motor assembly **200**. The C phase current **184** is illustrated as a conventional square wave current provided from a drive, while the C phase torque constant **185** is a square wave form. The square wave form of the A, B and C phase torque constants **181**, **183**, **185** is generated from the separated phase elements **210**, **220**, **230** of the tandem rotor servo motor assembly **200** as described herein. Separation of the phase elements **210**, **220**, **230** eliminates interference by other phases, allowing for the generation of a square wave form torque constant. The square wave form torque constants **181**, **183**, **185** are desired and advantageous, as should any of the A, B, or C phases **180**, **182**, **184** shift out of phase with one another, torque ripple will be minimized or not occur. For example, if any of the A, B, or C phases **180**, **182**, **184** shift out of phase by an electrical angle θ (theta), the torque output will not be reduced and no torque ripple will occur, as long as the electrical angle θ (theta) is less than 15° (fifteen degrees).

[0063] FIG. **24** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of rotor **105***a* in the A phase or first phase element **210** of the tandem rotor servo motor assembly **200**. The A phase current **190** is illustrated as a conventional trapezoidal wave current provided from a drive. A trapezoidal wave current is preferred at higher motor or rotor speeds. The A phase torque constant **191** is a square wave form. FIG. **25** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of rotor **105***b* in the B phase or second phase element **220** of the tandem rotor servo motor assembly **200**. The B phase current **192** is illustrated as a conventional trapezoidal current provided from a drive, while the B phase torque constant **193** is a square wave form. FIG. **23** illustrates a graphical representation of the torque per amp (X-axis) versus the angle of rotation of a rotor, θ_r (Y-axis) for one revolution of rotor **105***c* in the C phase or third phase element **230** of the tandem rotor servo motor assembly **200**. The C phase current **194** is illustrated as a conventional trapezoidal current provided from a drive, while the C phase torque constant **195** is a square wave form. The square wave form of the A, B and C phase torque constants **191**, **193**, **195** is generated from the separated phase elements **210**, **220**, **230** of the tandem rotor servo motor assembly **200** as described herein. Separation of the phase elements **210**, **220**, **230** eliminates interference by other phases, allowing for the generation of a square wave form torque constant. The square wave form torque constants **191**, **193**, **195** are desired and advantageous, as should any of the A, B, or C phases **190**, **192**, **194** shift out of phase with one another, torque ripple will be minimized over a conventional single stator, single rotor multi-phase motor. For example, if any of the A, B, or C phases **180**, **182**, **184** shift out of phase by an electrical angle θ (theta), a torque ripple will occur, however, will not be as severe as a conventional single stator, single rotor multi-phase motor for the same angle θ. In addition, the tandem rotor servo motor assembly **200** and associated A, B and C phase current waveforms **190**, **192**, **194** and torque constants **191**, **193**, **195** illustrated in FIGS. **24-26** eliminate a source of torque ripple present in conventional single stator, single rotor multi-phase motors. As illustrated in FIGS. **18-20**, the drive of a conventional single stator, single rotor multi-phase motor is required to quickly produce the exact step current functions for the current waveforms **170**, **172**, **174**. However, drives are unable to provide the exact step current functions fast enough, which causes torque ripple. The current waveforms **190**, **192**, **194** illustrated in FIGS. **24-26** do not change or transition quickly, eliminating the potential source of torque ripple.

[0064] There are several advantages to the tandem rotor servo motor assembly. The four pole square of each phase element allows for the fitting of more conductor material into the corner slots. This advantageously reduces the winding resistance and thus reduces the heat generated in the motor winding. Further, the amount of slot liner insulation will be significantly less than conventional single stator, single rotor multi-phase servo motors. Slot liner insulation is placed inside of a slot to separate conductor wires and avoid a short. By increasing the size of corner slots, more conductor wires may be placed in each slot. By providing more room for conductor material in the slots of each of the four poles, and accordingly more conductor wires than insulation in a slot, heat is reduced. In addition, the four pole arrangement lowers the electrical frequency at high shaft and rotor speeds than conventional servo motor designs incorporating six or more poles. Conventional servo motors typically utilize six or more poles to reduce the back iron and thus reduce the size of the motor. This results in reducing the rated continuous torque at higher speeds because of higher iron losses due to higher electrical frequencies by the increased poles/pole pairs. The four pole square tandem rotor servo motor assembly does not reduce the rating of continuous torque at high speeds as much as conventional motor designs because of the lower frequency iron losses. Further, the tandem rotor servo motor assembly has a better speed range than conventional servo motors. At high speeds, conventional servo motor drives will have to drive the inductance. This requires extra voltage to drive the inductance proportional to the electrical frequency. The four pole square tandem servo motor assembly has a lower electrical frequency at higher speeds than conventional servo motors incorporating six poles or more. This advantageously enables the tandem rotor servo motor assembly to reach a greater maximum speed than conventional servo motors and accordingly a greater speed range.

[0065] Although various representative embodiments of this invention have been described above with a certain degree of particularity, those skilled in the art could make numerous alterations to the disclosed embodiments without departing from the spirit or scope of the inventive subject matter set forth in the specification and claims. Joinder references (e.g., attached, coupled, connected) are to be construed broadly and may include intermediate members between a connection of elements and relative movement between elements. As such, joinder references do not necessarily infer that two elements are directly connected and in fixed relation to each other. In some instances, in methodologies directly or indirectly set forth herein, various steps and operations are described in one possible order of operation, but those skilled in the art will recognize that steps and operations may be rearranged, replaced, or eliminated without necessarily departing from the spirit and scope of the present invention. It is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative only and not limiting. Changes in detail or structure may be made without departing from the spirit of the invention as defined in the appended claims.

[0066] Although the present invention has been described with reference to preferred embodiments, persons skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

What is claimed is:

1. A tandem rotor servo motor assembly comprising:

a first phase element positioned on a shaft, the first phase element having a first rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged;

a second phase element positioned on the shaft a first distance from the first phase element, the second phase element having a second rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged;

a third phase element positioned on the shaft a second distance from the second phase element, the third phase element having a third rotor in communication with the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged;

the second rotor being offset about the shaft from the first rotor by sixty degrees of rotation; and

the third rotor being offset about the shaft from the first rotor by one hundred and twenty degrees of rotation.

2. The tandem rotor servo motor assembly of claim **1**, wherein the first, second and third rotors each include permanent magnets.

3. The tandem rotor servo motor assembly of claim **2**, wherein the first, second and third rotors each include four permanent magnets.

4. The tandem rotor servo motor assembly of claim **3**, wherein the permanent magnets of the second rotor are offset about the shaft from the permanent magnets of the first rotor by sixty degrees of rotation and the permanent magnets of the third rotor are offset about the shaft from the permanent magnets of the first rotor by one hundred and twenty degrees of rotation.

5. The tandem rotor servo motor assembly of claim **1**, wherein the cross-section of the stator of the first, second and third phase elements is square in shape.

6. The tandem rotor servo motor assembly of claim **1** wherein the first, second and third phase elements each produce a square waveform torque constant.

7. The tandem rotor servo motor assembly of claim **1** further comprising at least one back iron lamination ring connected to a portion of at least one of the first phase element stator, the second phase element stator or the third phase element stator.

8. The tandem rotor servo motor assembly of claim **1**, wherein the first phase element receives a first phase of three-phase electric current, the second phase element receives a second phase of three-phase electric current, and the third phase element receives a third phase of three-phase electric current.

9. A tandem rotor servo motor assembly comprising:

a multi-phase servo motor having a first phase element, a second phase element, and a third phase element, the first, second and third phase elements including a rotor and a stator carrying four magnetically charged poles, each pole exerting a magnetic force when said poles are electrically charged; and

a shaft connected to the rotors of the first, second and third phase elements, the second rotor is provided on the shaft $\pi/3$ radians offset from the first rotor, and the third rotor is provided on the shaft $2\pi/3$ radians offset from the first rotor.

10. The tandem rotor servo motor assembly of claim **9**, wherein the stators of the first, second and third phase elements have a square cross-sectional profile taken parallel to the axis of rotation of the shaft.

11. The tandem rotor servo motor assembly of claim **9**, wherein the first, second and third phase elements respectively receive a separate phase of a three-phase electric current.

12. The tandem rotor servo motor assembly of claim **9**, wherein the first phase element is spaced along the shaft a first distance from the second phase element, the second phase element is spaced along the shaft a second distance from the third phase element, and the first phase element is spaced along the shaft a third distance from the third phase element.

13. The tandem rotor servo motor assembly of claim **9**, wherein the rotors of the first, second and third phase elements each include four permanent magnets, the four permanent magnets are provided about the rotor such that each magnet has an opposing pole as the neighboring magnet.

14. The tandem rotor servo motor assembly of claim **13**, wherein the four permanent magnets of at least one of the first, second and third phase elements are provided about the rotor such that each magnet has a distance between the neighboring magnet.

15. The tandem rotor servo motor assembly of claim **9** wherein the first, second and third phase elements each produce a square waveform torque constant.

16. A tandem servo motor comprising:

a first phase element in communication with a shaft, the first phase element having a first rotor connected to the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged by a first phase of a three-phase current, said first phase element producing a square waveform torque constant;

a second phase element in communication with the shaft a first distance from the first phase element, the second phase element having a second rotor connected to the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged by a second phase of a three-phase current, said second phase element producing a square waveform torque constant;

a third phase element in communication with the shaft a second distance from the second phase element and a third distance from the first phase element, the third phase element having a third rotor connected to the shaft and surrounded by a stator carrying four magnetic poles, each of said poles exerting a magnetic force when said poles are electrically charged by a third phase of a three-phase current, said third phase element producing a square waveform torque constant;

the second rotor being offset about the shaft from the first rotor by approximately sixty degrees of rotation; and

the third rotor being offset about the shaft from the first rotor by approximately one hundred and twenty degrees of rotation and from the second rotor by approximately sixty degrees of rotation.

17. The tandem servo motor of claim **16**, wherein the stators of the first, second and third phase elements have a square cross-sectional profile taken parallel to the axis of rotation of the shaft.

18. The tandem servo motor of claim **16**, wherein the first, second and third rotors each include four permanent magnets provided about the circumference of the rotor.

19. The tandem servo motor of claim **18**, wherein the permanent magnets of the second rotor are offset about the shaft from the permanent magnets of the first rotor by approximately sixty degrees of rotation and the permanent magnets of the third rotor are offset about the shaft from the permanent magnets of the first rotor by approximately one hundred and twenty degrees of rotation and from the second rotor by approximately sixty degrees of rotation.

20. The tandem servo motor of claim **16** further comprising at least one back iron lamination ring connected to a portion of at least one of a back iron of the first phase element stator, the second phase element stator or the third phase element stator.

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