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Liao et al.

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(54) **OFF-GRID POWER GENERATING APPARATUS AND VECTOR CONTROL METHOD THEREOF**

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H02P 21/22 (2016.01)
F02B 63/04 (2006.01)
H02P 101/25 (2016.01)

(52) **U.S. Cl.**
CPC **H02P 21/09** (2016.02); **F02B 63/042** (2013.01); **F02B 63/048** (2013.01); **H02P 21/22** (2016.02); **H02P 2101/25** (2015.01)

(58) **Field of Classification Search**
USPC 322/20; 290/40 A
See application file for complete search history.

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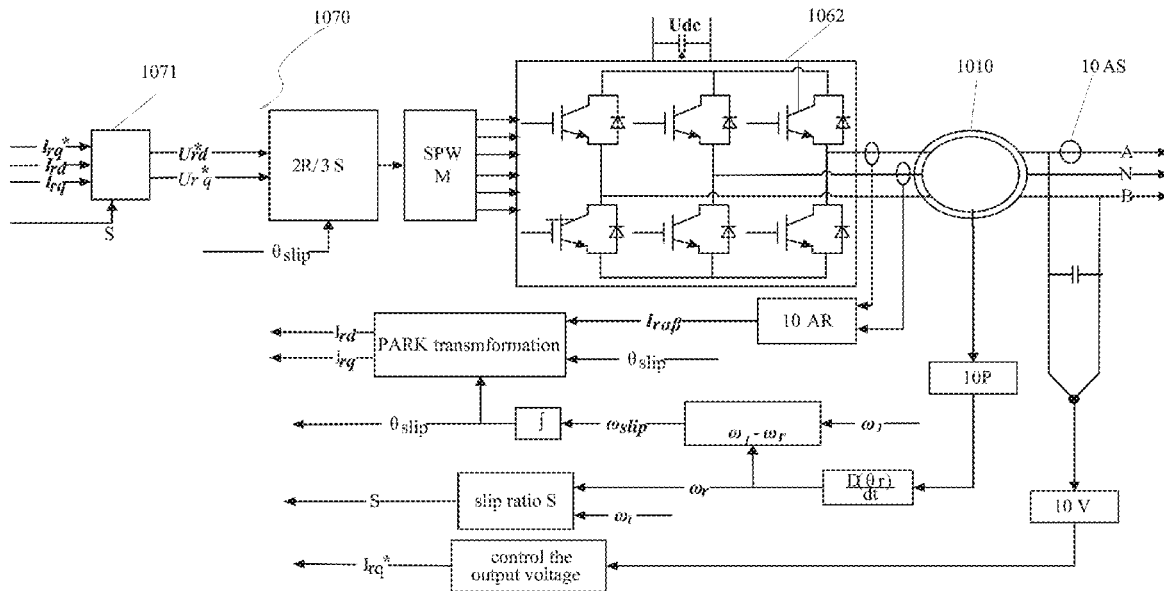
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(57) **ABSTRACT**

A power generating apparatus and vector control method thereof are provided. The apparatus includes a rotor with plurality of symmetric phase windings, a stator with a single phase winding, sensors and an excitation control device. Current sensors on the stator side and on the rotor side are configured to measure the amplitudes of the load current and the phase current of the rotor respectively. A position sensor is configured to measure the angle of the rotor. The excitation control device is configured to regulate the engine speed responsive to load power. The excitation control device also generates a modulating signal in accordance with the target voltage vector of the rotor and the slip angle and regulates the excitation current in the phase windings of the stator with the modulating signal.

20 Claims, 24 Drawing Sheets



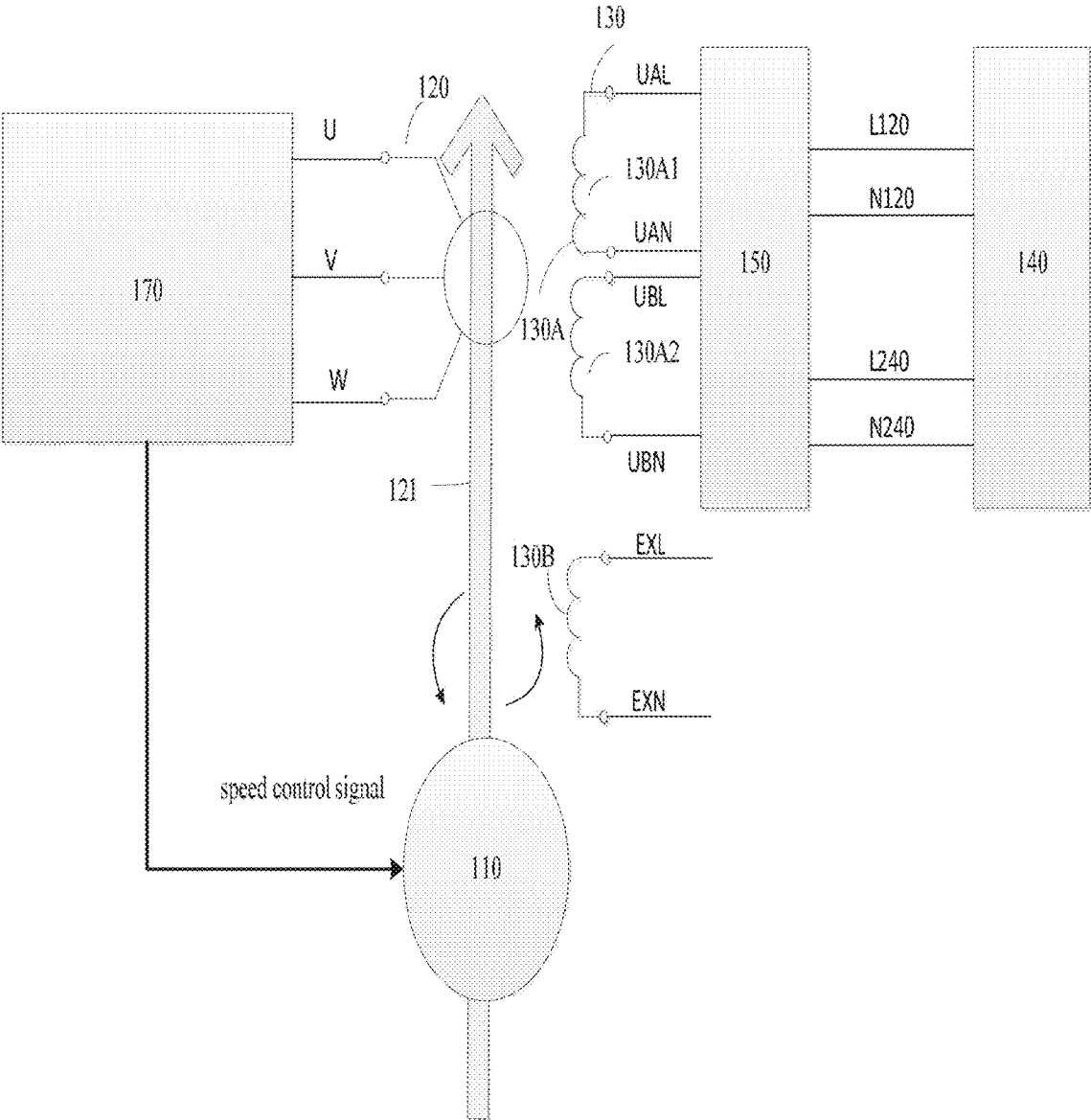


FIG. 1

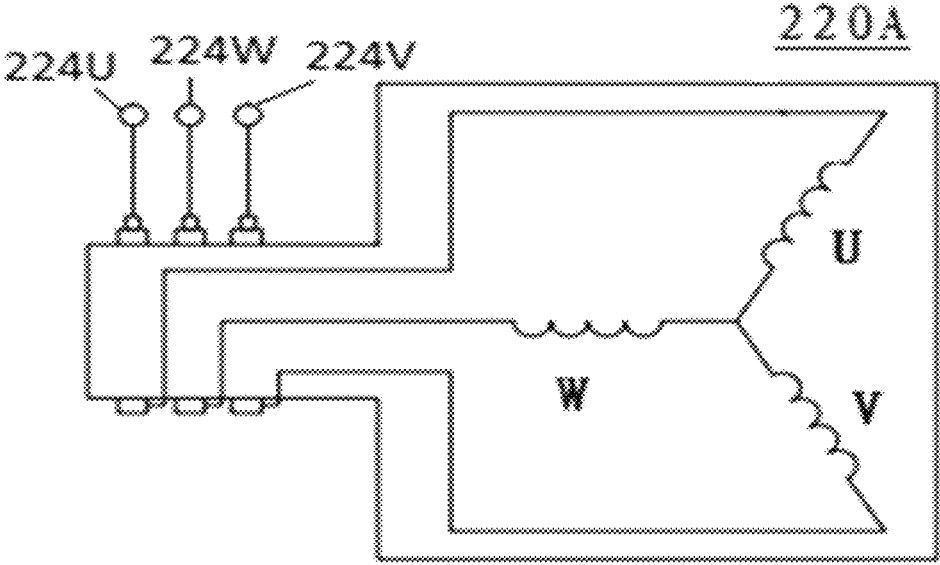


FIG. 2A

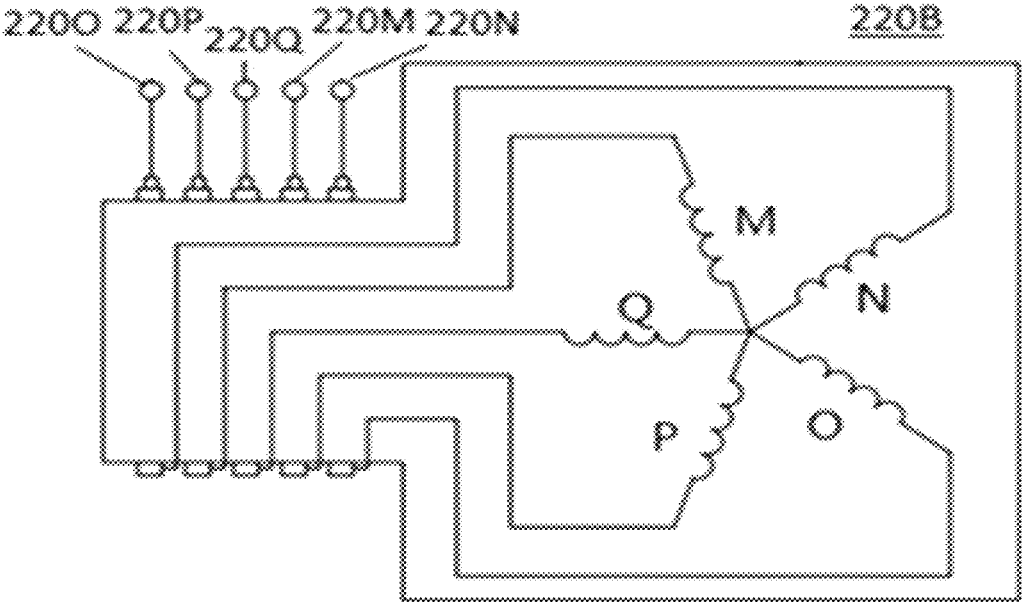


FIG. 2B

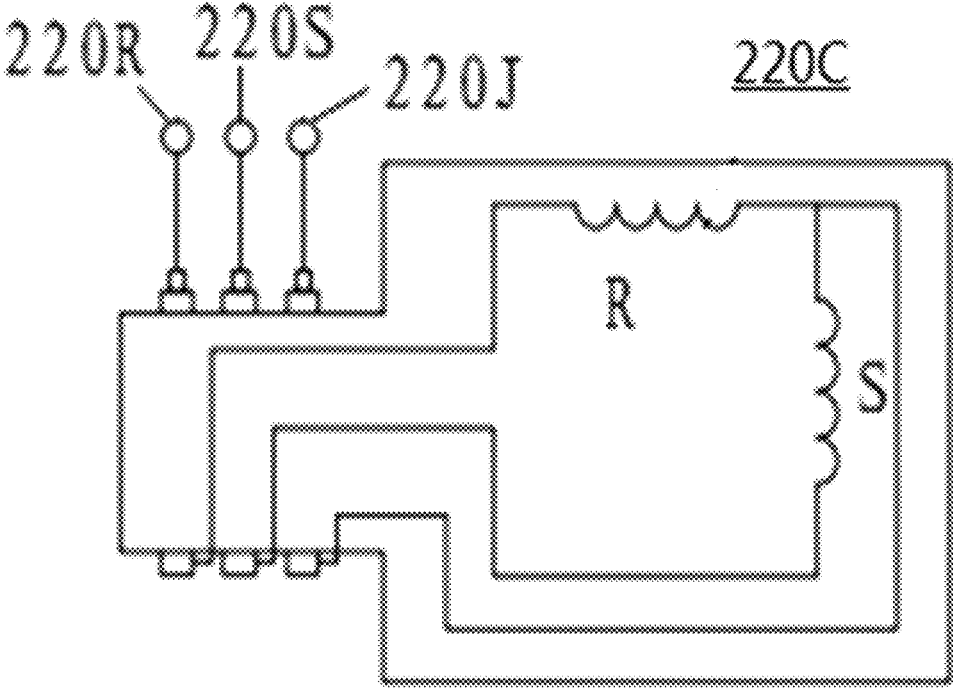


FIG. 2C

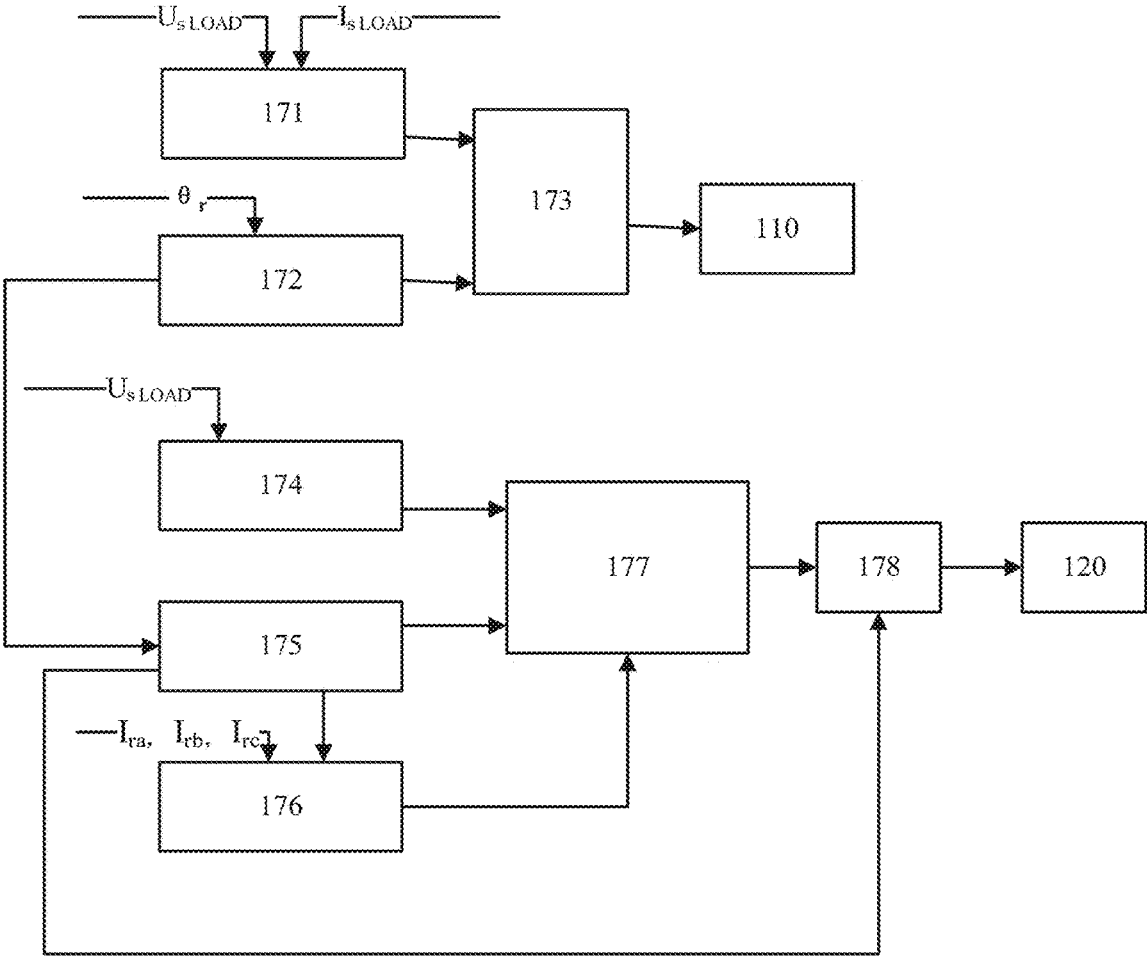


FIG. 3

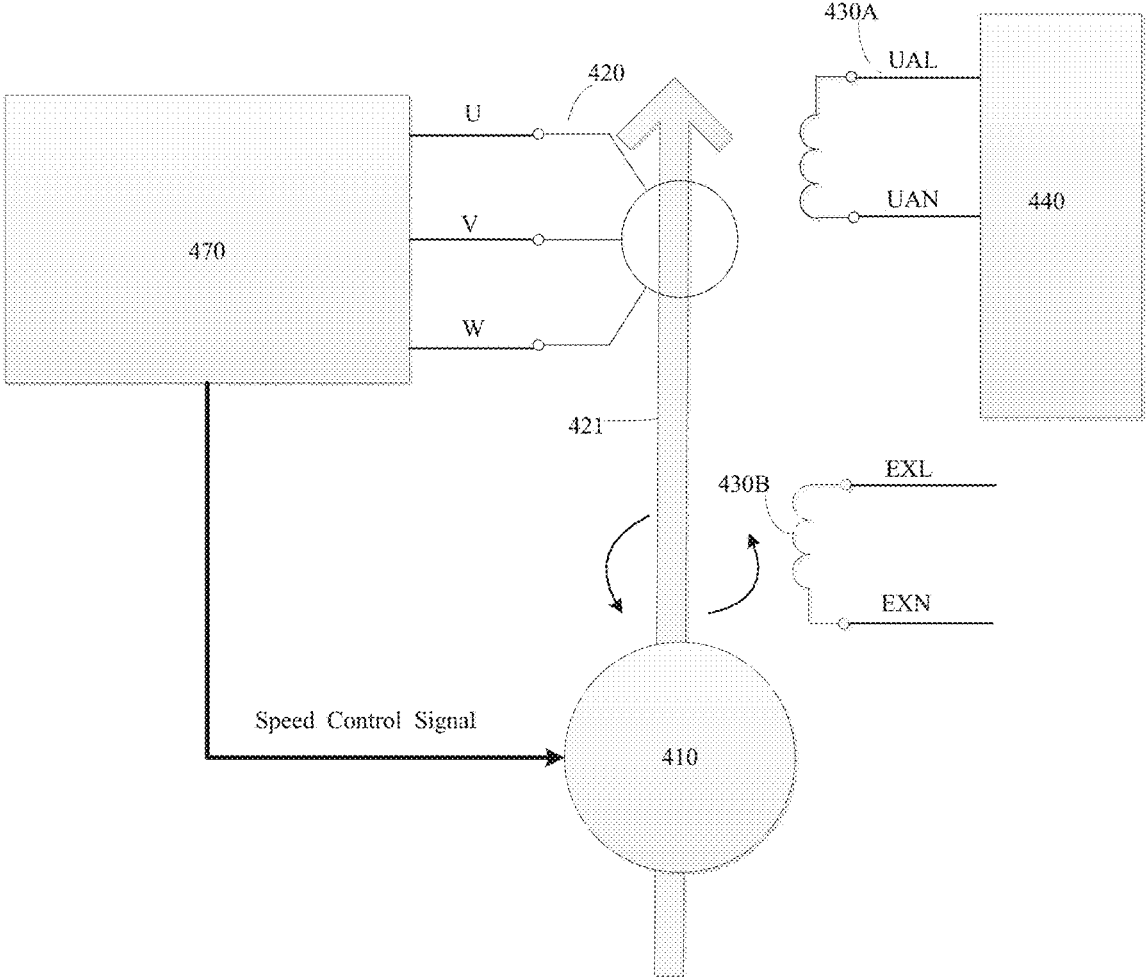


FIG. 4

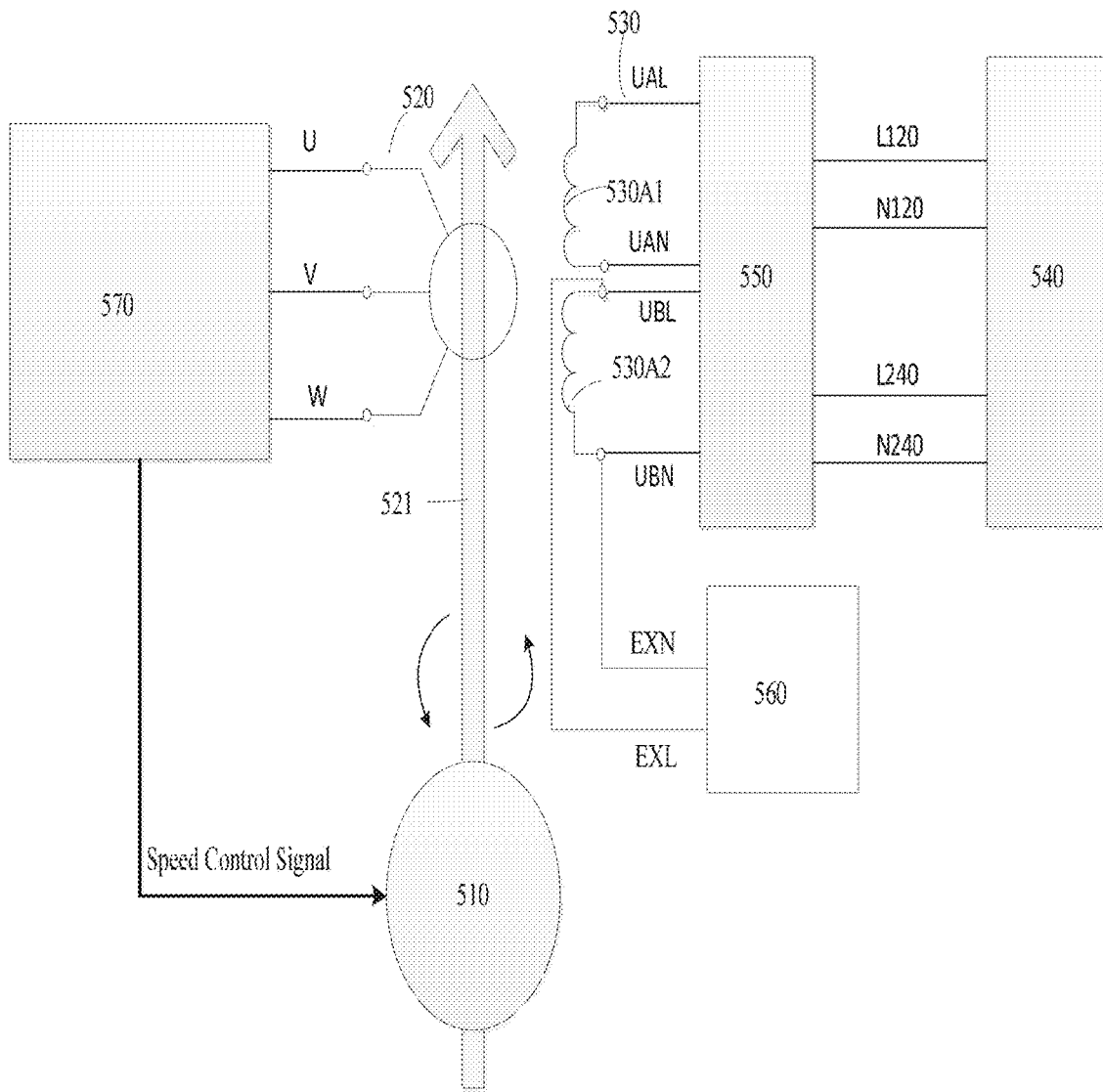


FIG. 5

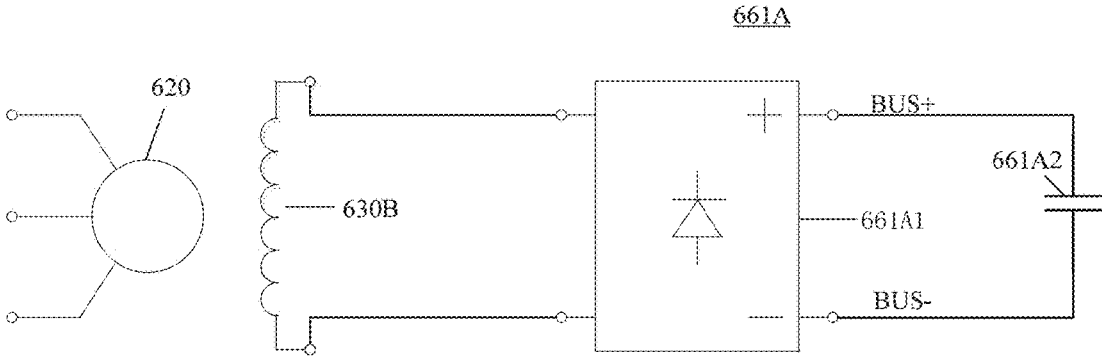


FIG. 6A

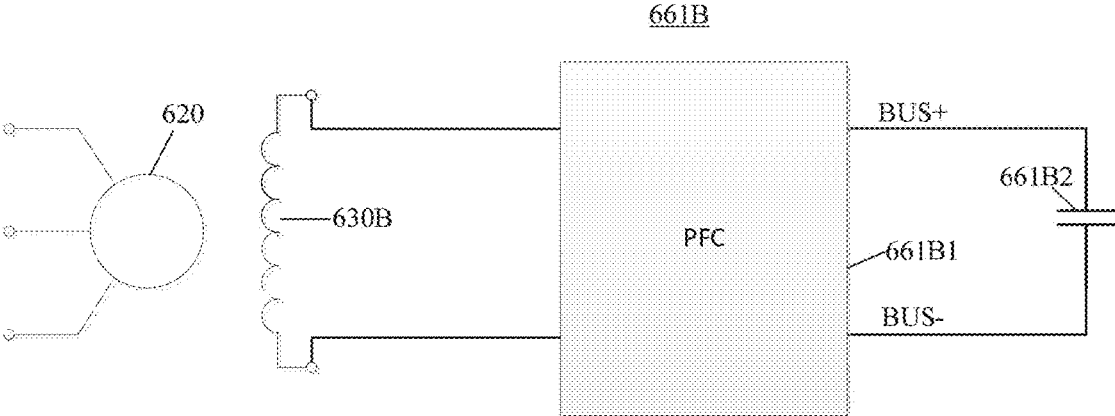


FIG. 6B

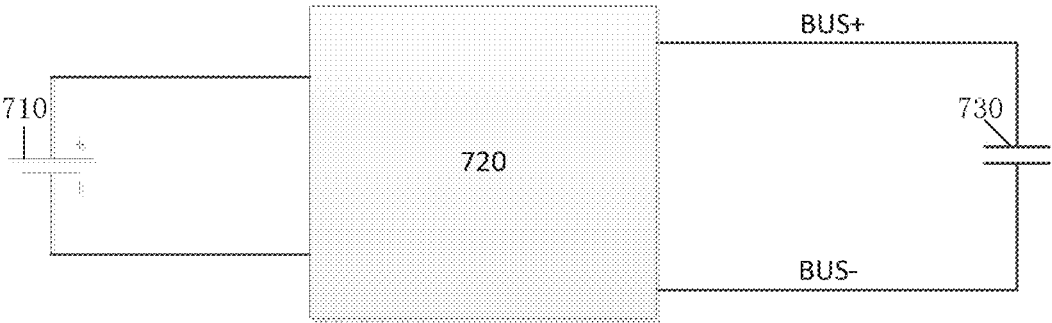


FIG. 7

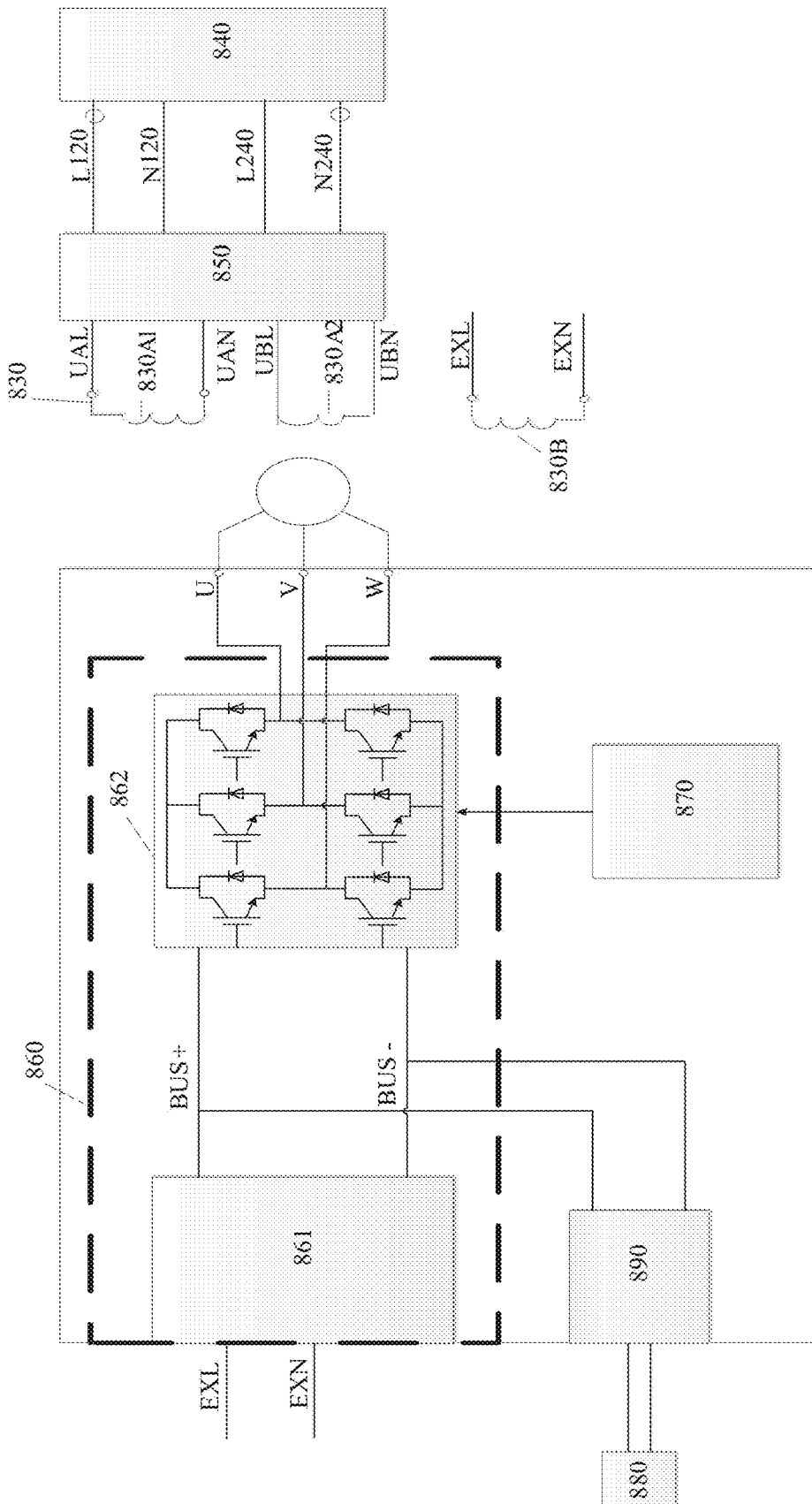


FIG. 8

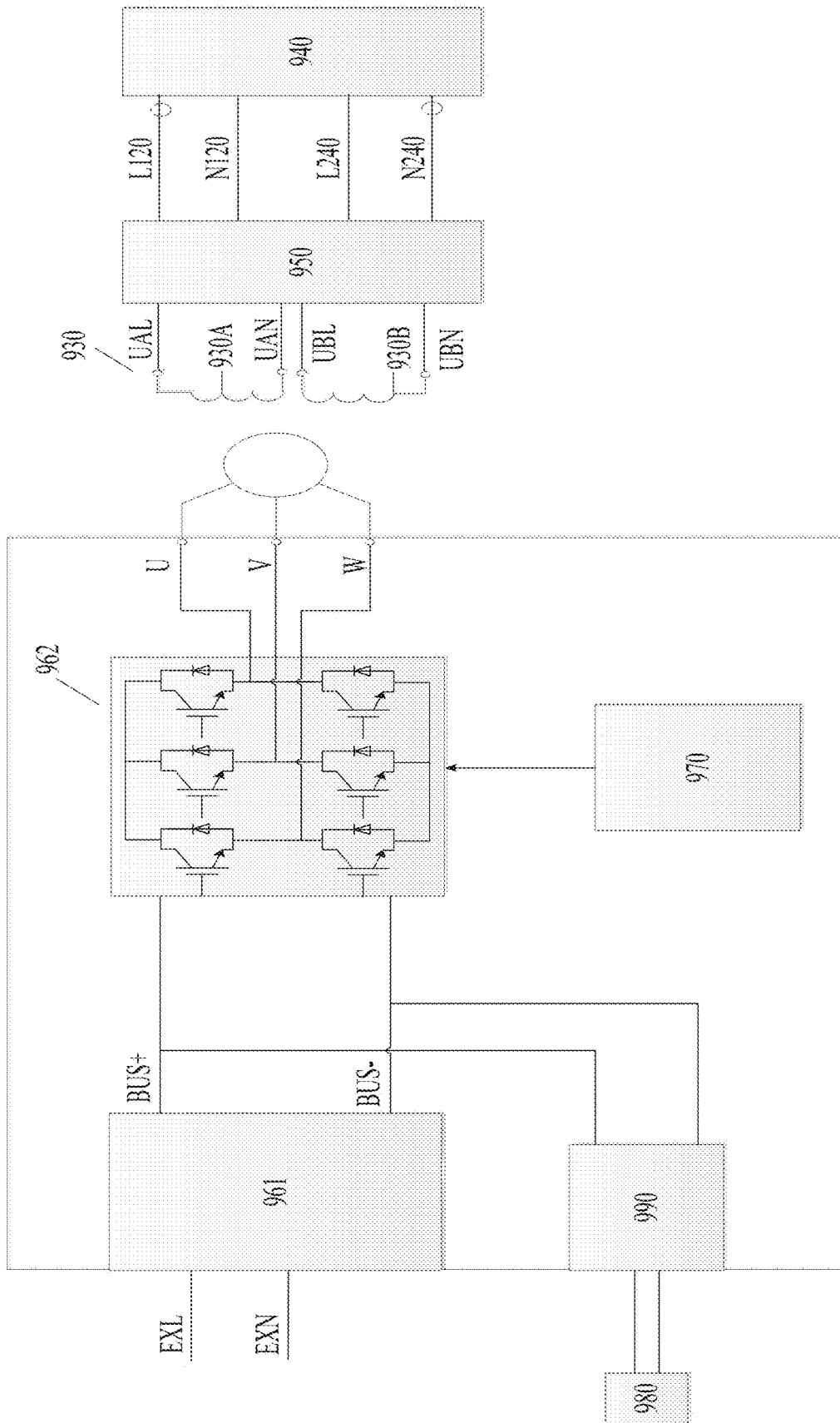


FIG. 9

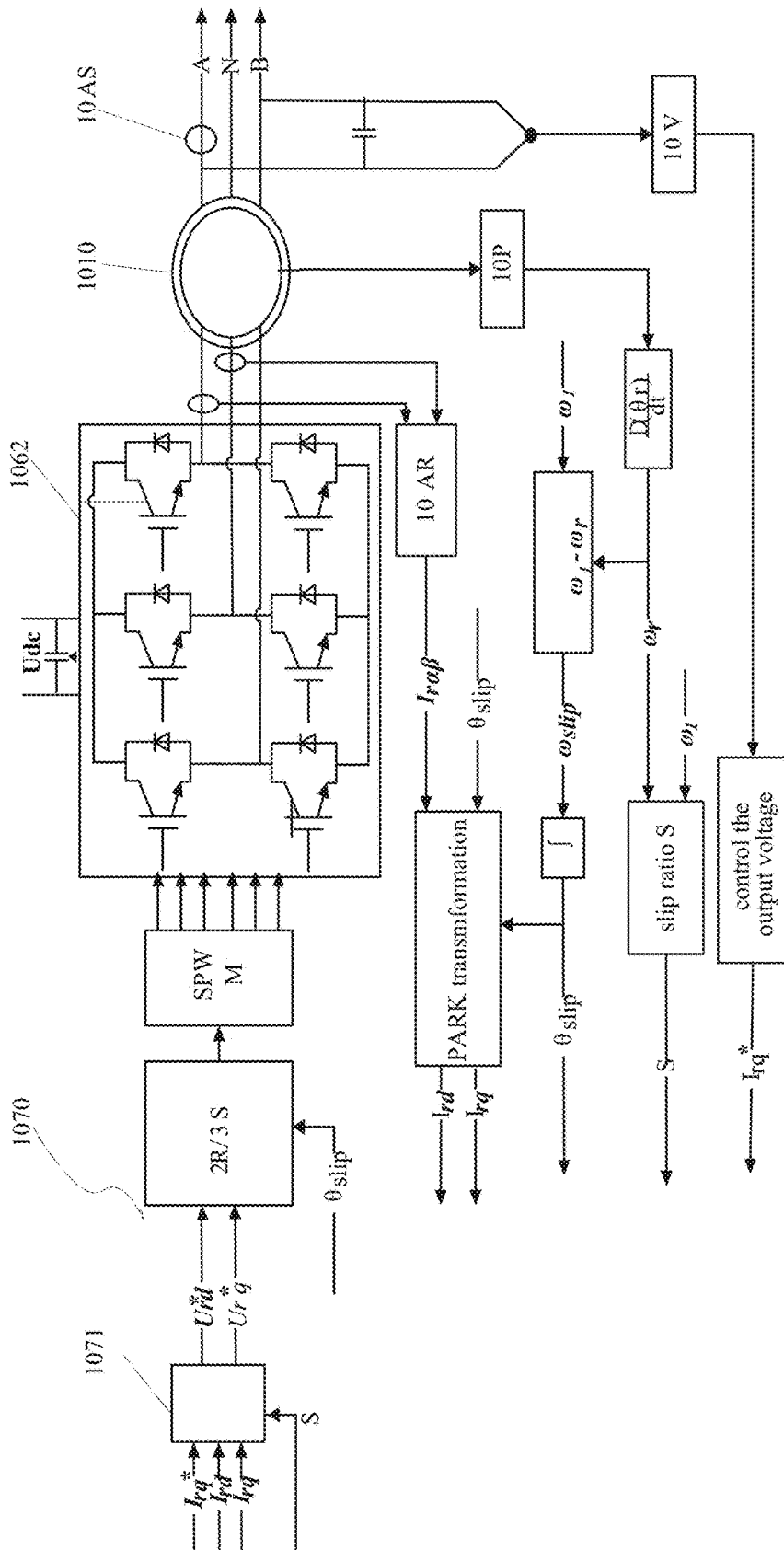


FIG. 10

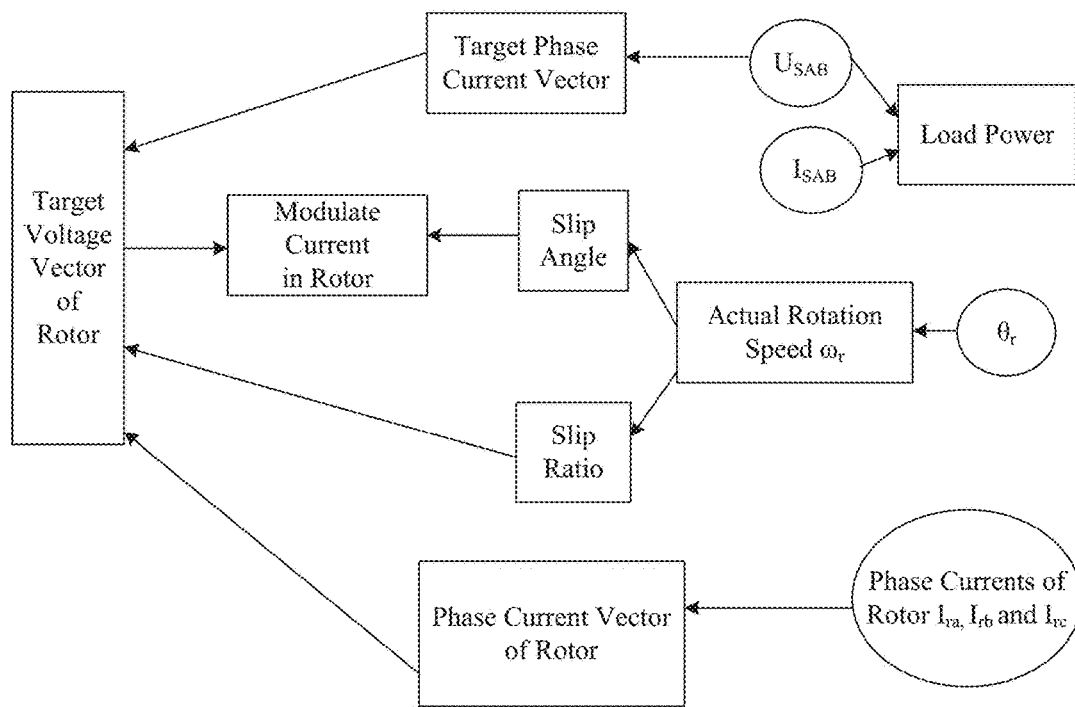


FIG. 11

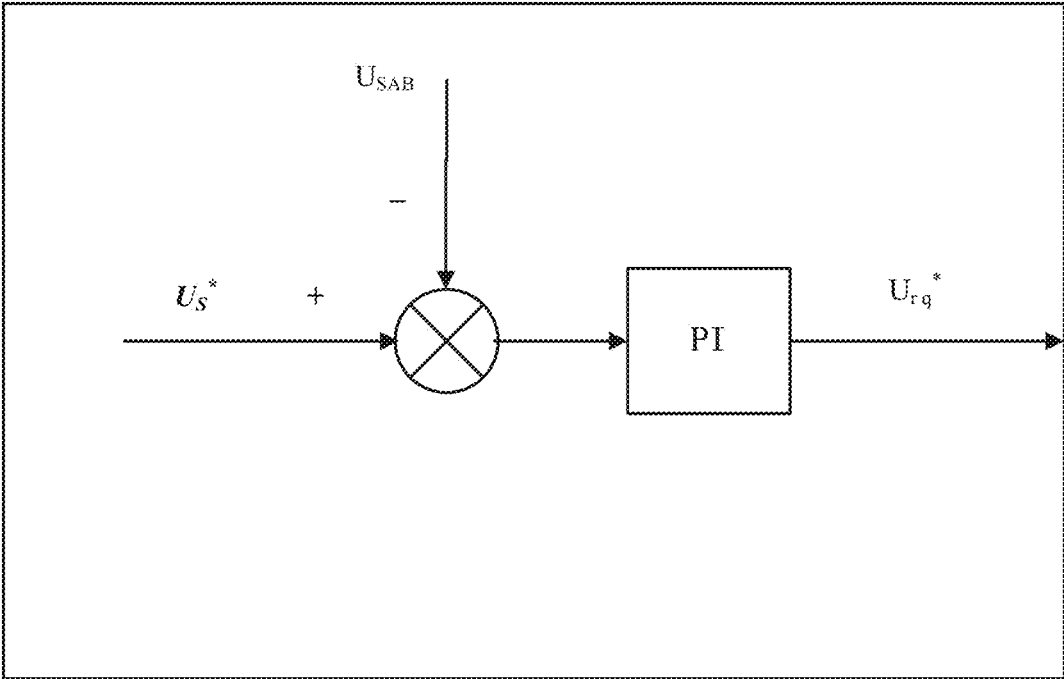


FIG. 12

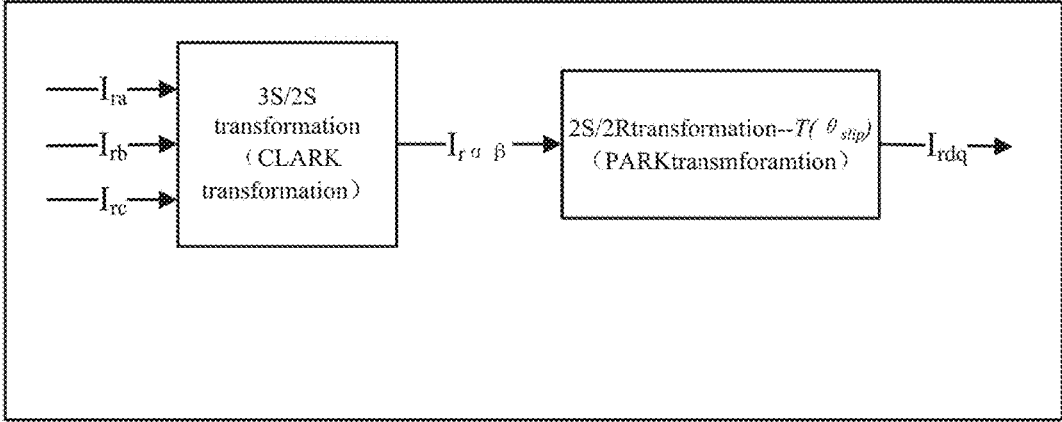


FIG. 13

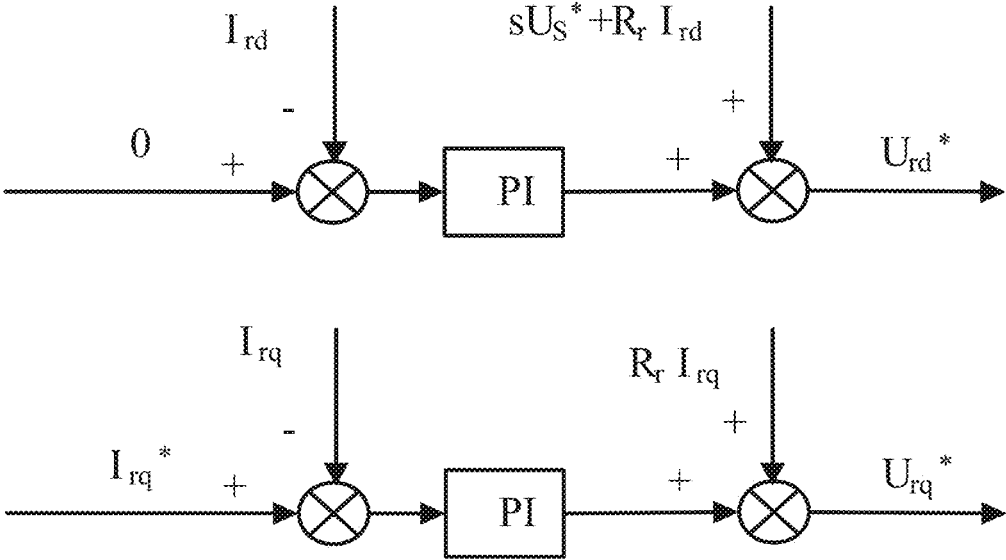


FIG. 14

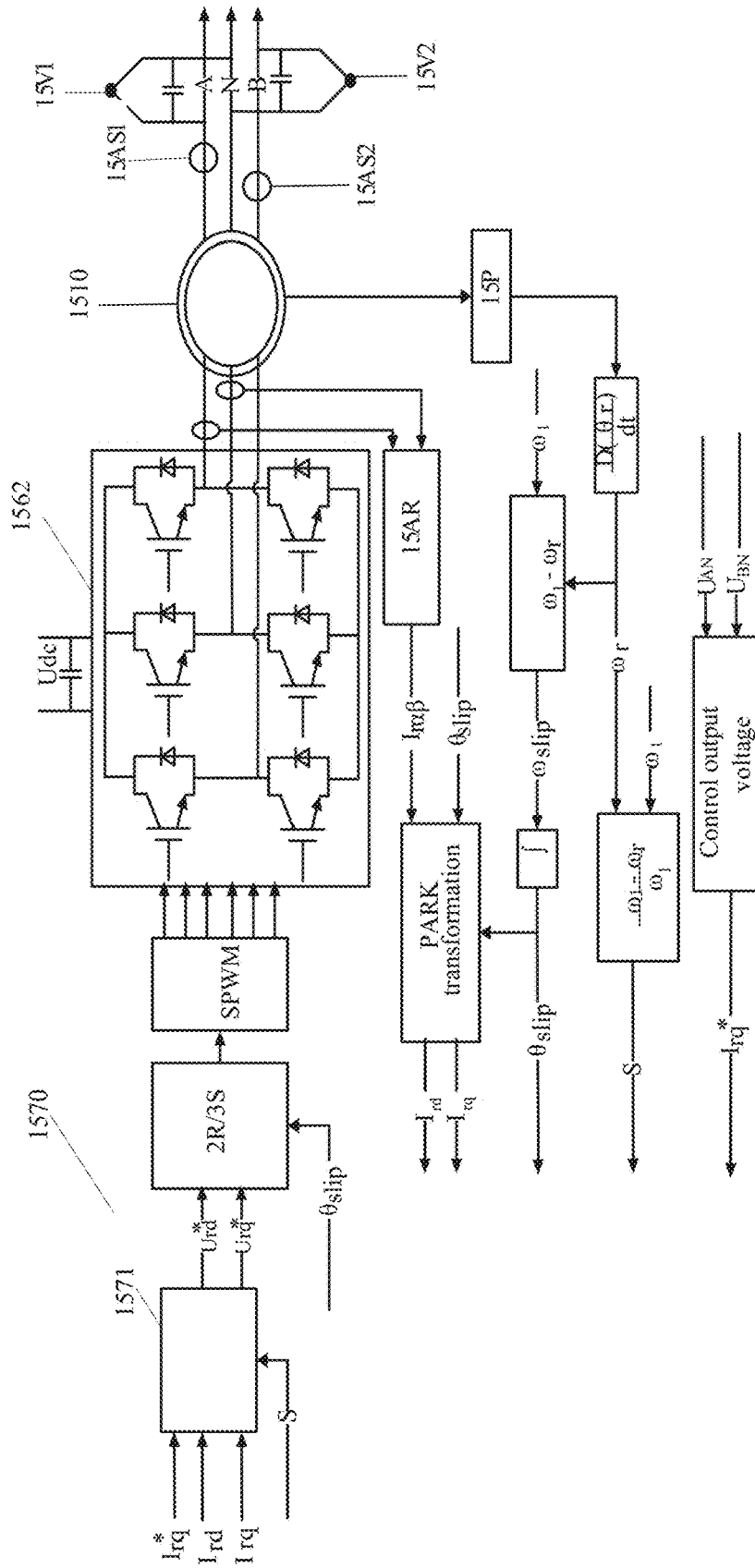


FIG. 15

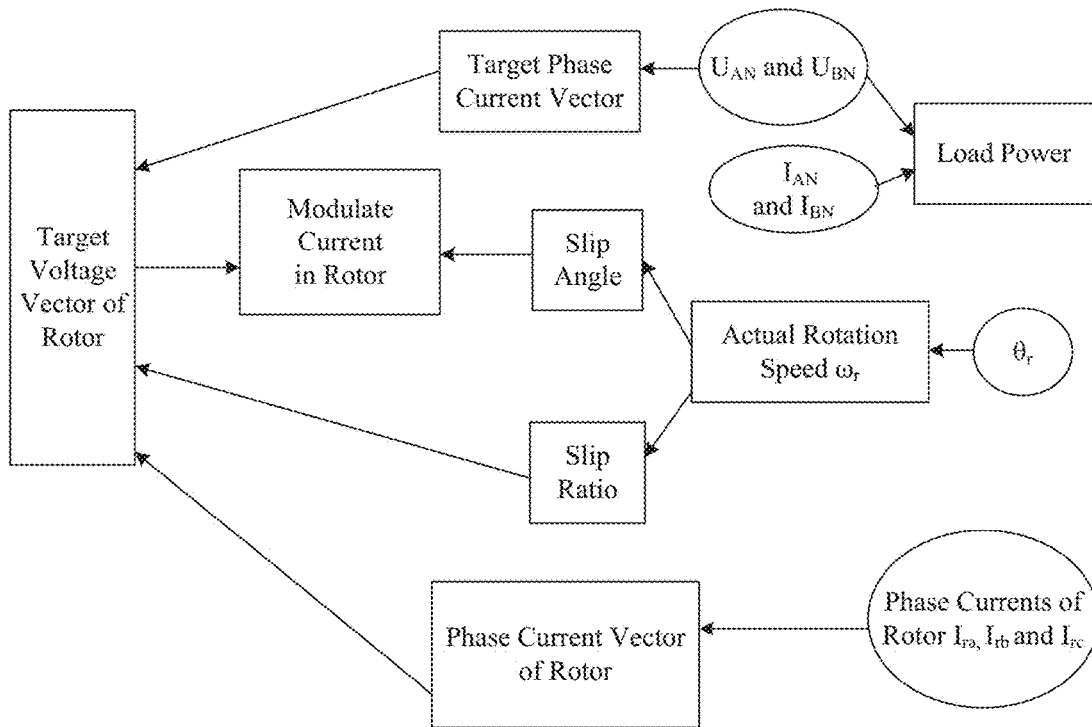


FIG. 16

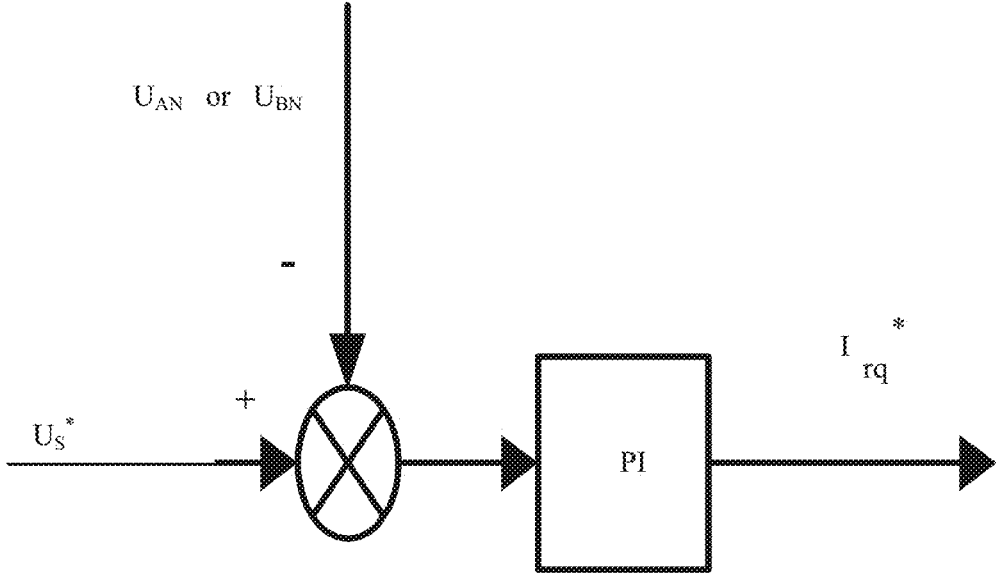


FIG. 17

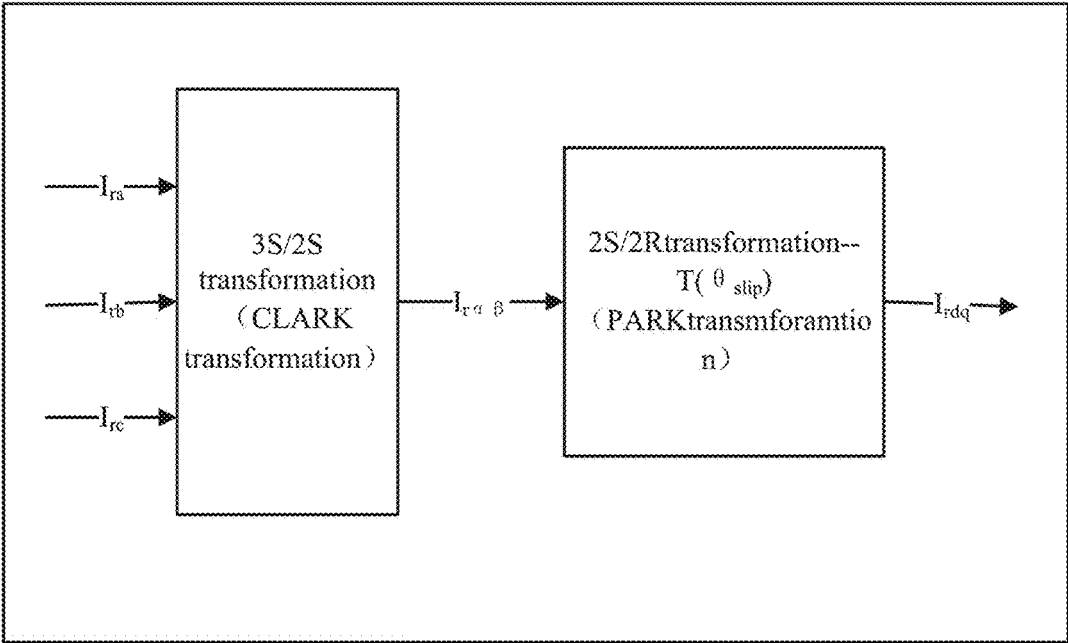


FIG. 18

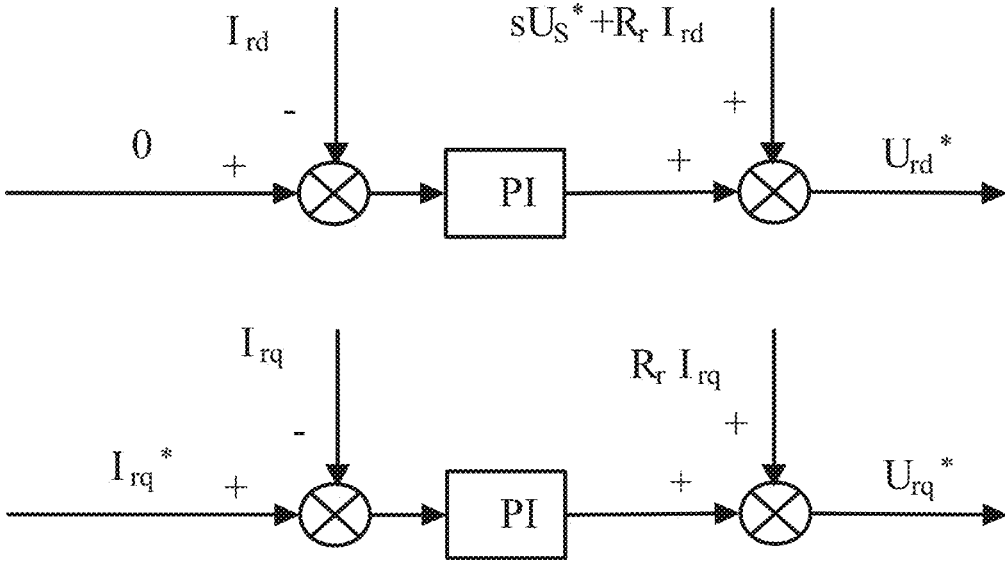


FIG. 19

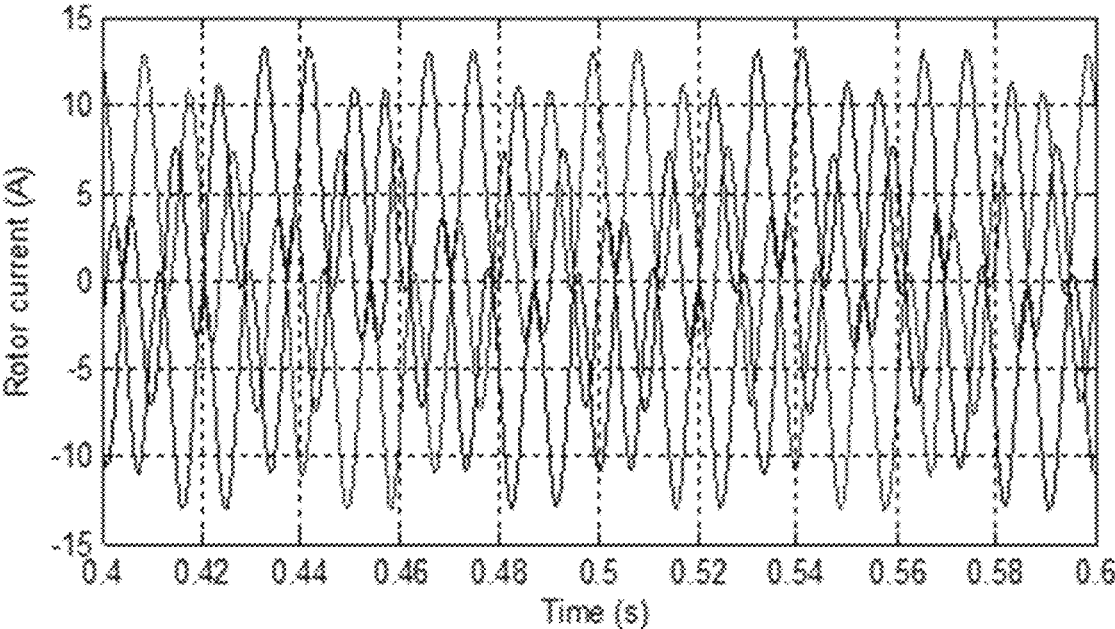


FIG. 20

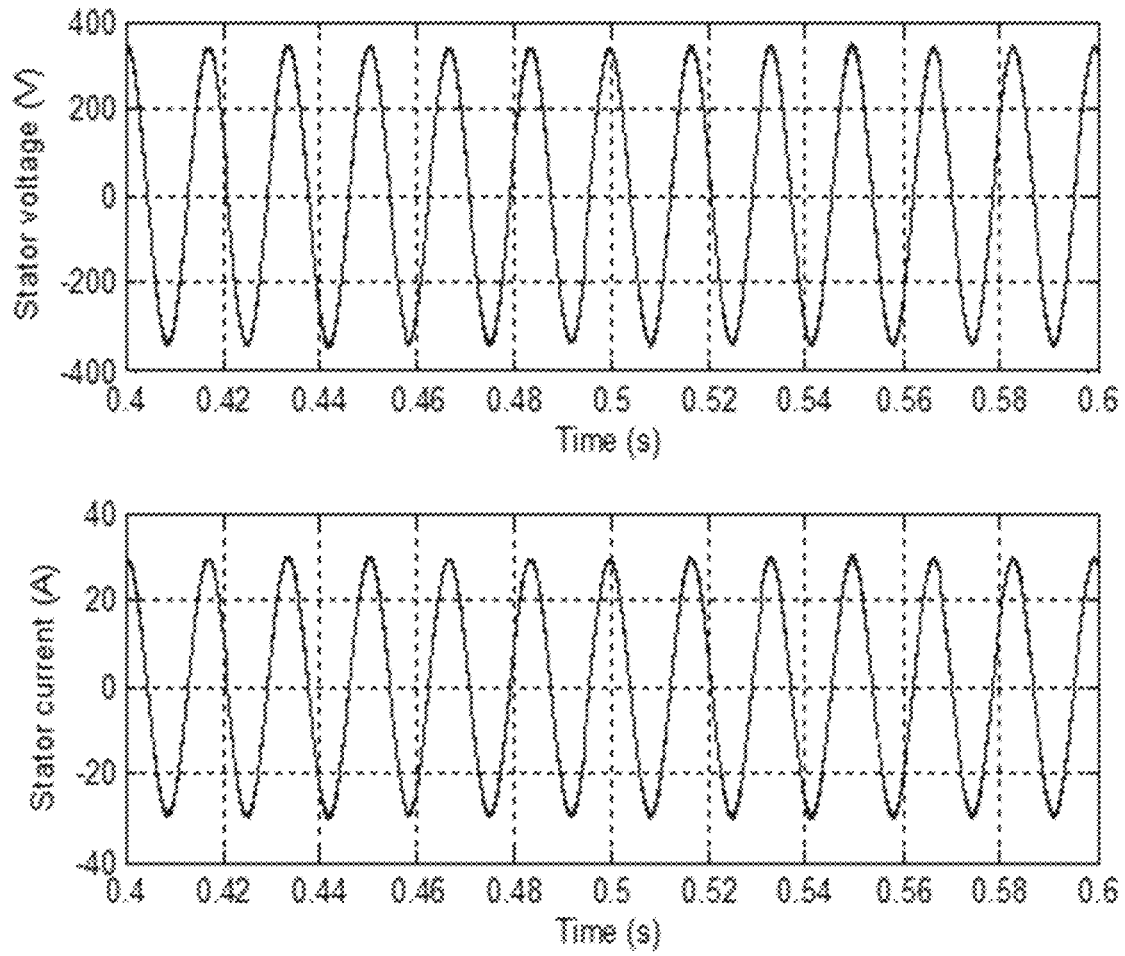


FIG. 21

1

**OFF-GRID POWER GENERATING
APPARATUS AND VECTOR CONTROL
METHOD THEREOF**

RELATED APPLICATION

This application claims priority to Chinese Patent Applications No. 201810073127.4, entitled "Off-Grid Power Generating Apparatus and Vector Control Method Thereof" filed on Jan. 25, 2018 and No. 201810496833.X, entitled "Off-Grid Power Generating Apparatus and Vector Control Method Thereof" filed on May 22, 2018 which are incorporated by reference in their entirety.

FIELD OF TECHNOLOGY

Embodiments disclosed herein relate generally to an electrical power generating apparatus and its control method, and in particular, to an engine-driven and off-grid power generating apparatus and its control method with variable speed and constant frequency.

BACKGROUND

Off-grid generator sets have been widely used. For example, a portable/standby generator set may be utilized to power electrical equipment connected via a circuit with the generator set when people do camping, tailgating and working outside. A similar power generating apparatus provides backup power in emergencies, for example during blackout.

The off-grid generator set usually utilizes a driving engine coupled to a generator (or alternator) through a common shaft. Upon actuation of the engine, the engine rotates the common shaft to drive the alternator that, in turn, generates electrical power. As it is known, most residential electric equipment is designed to be used in connection with electrical power having a fixed frequency, for example, 60 hertz (Hz) in North America and 50 Hz in China. The frequency of the output electrical power is primarily determined by the operating speed of the engine. As a result, the engine's operating speed of some generator sets is fixed as so to keep the frequency of the output electrical power fixed. However, when an electrical load applied to the generator set is less than the rated kilowatt load for which the generator set is designed, the engine's fuel-efficiency deteriorates and the generator set generates loud noise. Additionally, the off-grid generator set usually generates an output voltage at a known level since most electrical loads are designed to work with a voltage of the known level. For example, most household appliances in North America such as ovens, roasters, audio and video displays use nominal voltages of 120 volts or 240 volts, and most household appliances in China use a nominal voltage of 220 volts.

It is therefore desirable to have a power generating apparatus that allows a variable engine speed, an output voltage with a constant amplitude and a constant frequency.

SUMMARY

Embodiments of off-grid power generating apparatus and its control method are described. The off-grid power generating apparatus includes a stator with one single phase winding and a rotor with a plurality of symmetric phase windings. This feature of the apparatus helps to make it lighter and cheaper. This apparatus, however, poses a challenge to conventional control strategies for generators. An off-grid power generating apparatus with a simple and

2

cost-effective control system and a vector control method are provided in this disclosure. The control system modulates the speed of the driving engine in response to load changes for minimizing fuel consumption. Moreover, the amplitude and frequency of the excitation current in the rotor windings are modulated to make the amplitude and frequency of the output voltage from the stator constant (i.e., to achieve constant voltage and constant frequency). In this disclosure, the off-grid power generating apparatus is a power generating system whose connection to an electrical power grid is temporarily or permanently unavailable. A single phase winding of the stator refers to that the coil of the stator has only one axial direction. The single phase winding of the stator may include a plurality of coils but the axial direction of the plurality of coils should coincide. Symmetric phase windings are windings configured to form a rotating magnetic field that is an air gap magnetic field of a motor with a constant magnitude. The plurality of symmetric phase windings may have two or more phases.

The off-grid power generating apparatus includes an engine, an alternator and an excitation control device in accordance with some embodiments. The alternator includes a rotor, a stator, a voltage sensor, a current sensor on the stator side, a current sensor on the rotor side and a position sensor. The rotor is coaxially coupled to the engine and includes a plurality of symmetric phase windings. The stator has a single phase winding configured to generate an induced voltage. The single phase winding is connected with the electrical load and the phase windings of the rotor respectively for providing an output voltage to the electrical load and an excitation voltage to the phase windings of the rotor. The voltage sensor is configured to measure an amplitude of the output voltage. The current sensor on the stator side is configured to measure an amplitude of an alternating current applied by the single phase winding of the stator to the electrical load. The current sensor on the rotor side is configured to measure an amplitude of a phase current of the rotor. The position sensor is configured to measure an angular position of the rotor. The excitation control device is operatively connected with the engine and the alternator, and is configured to control the induced voltage generated in the single phase winding of the stator by regulating the rotating magnetic field generated in the phase windings of the rotor. The excitation control device includes a first calculating element, a second calculating element, a first modulating element, a fourth calculating element, a fifth calculating element, a sixth calculating element and a second modulating element. The first calculating element is configured to calculate a load power of the electrical load at least in accordance with the measured amplitudes of the output voltage and the alternating current, and obtain a desired rotation speed of the engine at least in accordance with the calculated load power. The first calculating element may be implemented by two modules that separately perform the operation of calculating the load power and the operation of obtaining the desired rotation speed. The second calculating element is configured to calculate an operation speed of the rotor at least in accordance with the measured angular position. The first modulating element is configured to modulate a rotation speed of the engine at least in accordance with the desired rotation speed and the operation speed. The third calculating element is configured to determine a target phase current vector of the rotor at least in accordance with the measured amplitude of the output voltage. The fourth calculating element is configured to determine a slip angle and a slip ratio at least in accordance with the operation speed of the rotor. The fifth calculating

3

element is configured to extract a phase current vector of the rotor at least in accordance with the measured amplitude of the phase current of the rotor and the slip angle. The six calculating element is configured to determine a target voltage of the rotor at least in accordance with the phase current vector and the target phase current vector of the rotor and the slip ratio. The second modulating element is configured to generate a modulating signal at least in accordance with the target voltage of the rotor and the slip angle, and modulate a frequency and an amplitude of an excitation current in the phase windings of the rotor.

The alternator includes a frequency conversion device connected with the single phase winding of the stator, and the frequency conversion device includes an inverter configured to provide the excitation voltage to the phase windings of the rotor in accordance with some embodiments.

The alternator includes a switch operatively connected with the electrical load and being movable between a first position and a second position by a user in accordance with some embodiments. The single phase winding of the stator includes a first segment and a second segment each of which has at least one coil that are operatively and separately connected with the switch. The first segment and the second segment are configured to be in series connection at the first position of the switch and in parallel connection at the second position of the switch and provide a high output voltage and a low output voltage respectively to the electrical load via the switch. The voltage sensor is configured to measure the amplitudes of a first and a second output voltage provided respectively by the first segment and the second segment to the electrical load. The current sensor on the stator side is configured to measure the amplitudes of a first and a second alternating current applied respectively by the first and the second segment to the electrical load. The first calculating element is configured to calculate a first and a second load power of the electrical load at least in accordance with the measured amplitudes of the first output voltage and the first alternating current, and the second output voltage and the second alternating current, and a total load power by adding the first and the second load power, and obtain the desired operation speed of the engine at least in accordance with the total load power. The third calculating element is configured to determine a target phase current vector of the rotor at least in accordance with the measured amplitude of the first output voltage or the measured amplitude of the second output voltage.

The third calculating element is configured to determine the target phase current vector of the rotor with a closed control loop in accordance with some embodiments. The alternator includes an electrical circuit connecting the single phase winding of the stator and the electrical load in accordance with some embodiments, The electrical circuit is configured in a way that the induced voltage generated in the single phase winding of the stator and the output voltage applied to the electrical load are at the same frequency.

The alternator is set to operate at a speed equal to or less than the synchronous speed of the alternator in accordance with some embodiments.

A control method of an off-grid power generating apparatus for powering an electrical load is disclosed in accordance with some embodiments. The apparatus includes an engine and an alternator having a stator with a single phase winding that is configured to generate an induced voltage and a rotor with a plurality of symmetric phase windings. The rotor is coaxially coupled to the engine, and the single phase winding of the stator is connected with the electrical load and the phase windings of the rotor respectively for

4

providing an output voltage to the electrical load and an excitation voltage to the phase windings of the rotor. The method includes the operations as follows. Measure the amplitude of the output voltage provided to the electrical load. Measure the amplitude of the alternating current applied by the single phase winding of the stator to the electrical load. Measure the amplitude of the phase current of the rotor. Measure the angular position of the rotor. Calculate the load power of the electrical load at least in accordance with the measured amplitudes of the output voltage and the alternating current. Obtain the desired rotation speed of the engine at least in accordance with the calculated load power. Calculate the operation speed of the rotor at least in accordance with the measured angular position. Modulate the rotation speed of the engine at least in accordance with the desired rotation speed and the operation speed. Determine the slip angle and the slip ratio of the apparatus at least in accordance with the rotation speed of the rotor. Determine the target phase current vector of the rotor at least in accordance with the measured amplitude of the output voltage. Extract the phase current vector of the rotor at least in accordance with the measured amplitude of the phase current of the rotor and the slip angle. Determine the target voltage of the rotor at least in accordance with the phase current vector and the target phase current vector of the rotor and the slip ratio. Generate a modulating signal at least in accordance with the target voltage of the rotor and the slip angle and modulate the frequency and an amplitude of the excitation current in the phase windings of the rotor.

The alternator includes a frequency conversion device connected with the single phase winding of the stator in accordance with some embodiments. The frequency conversion device includes an inverter for providing the excitation voltage to the phase windings of the rotor.

The alternator includes a switch operatively connected with the electrical load and being movable between a first position and a second position by a user in accordance with some embodiments. The single phase winding of the stator includes a first segment and a second segment each of which has at least one coil that are operatively and separately connected with the switch. The first segment and the second segment are configured to be in series connection at the first position of the switch and in parallel connection at the second position of the switch for providing a high output voltage and a low output voltage respectively to the electrical load via the switch. Measuring an amplitude of the output voltage includes measuring the amplitudes of a first and a second output voltage provided respectively by the first and the second segment to the electrical load. Measuring an amplitude of an alternating current includes measuring the amplitudes of a first and a second alternating current applied respectively by the first and the second segment to the electrical load. Calculating a load power of the electrical load includes calculating a first and a second load power of the electrical load at least in accordance with the measured amplitudes of the first output voltage and the first calculating current, and the second output voltage and the second alternating current, and a total load power by adding the first and the second load power. Obtaining a desired rotation speed of the engine at least in accordance with the calculated load power includes obtaining the desired rotation speed of the engine at least in accordance with the total load power. Determining a target voltage of the rotor includes determining the target voltage of the rotor at least in accordance with the measured amplitude of the first or the measured amplitude of the second output voltage.

Determining a target voltage of the rotor includes determining the target voltage of the rotor with a closed control loop in accordance with some embodiments.

The induced voltage generated in the single phase winding of the stator and the output voltage applied to the electrical load are at the same frequency in accordance with some embodiments. The alternator is set to operate at a speed equal to or less than a synchronous speed of the alternator in accordance with some embodiments.

An off-grid portable generator set for powering an electrical load is provided in accordance with some embodiments. The generator set includes an engine, an induction alternator and an excitation control device. The induction alternator includes a rotor, a stator, a voltage sensor, a current sensor on the stator side, a current sensor on the rotor side and a position sensor. The rotor is coaxially coupled to the engine and includes a plurality of symmetric phase windings. The stator has a single phase winding configured to generate an induced voltage. The single phase winding is connected with the electrical load and the phase windings of the rotor respectively for providing an output voltage to the electrical load and an excitation voltage to the phase windings of the rotor. The voltage sensor is configured to measure an amplitude of the output voltage. The current sensor on the stator side is configured to measure an amplitude of an alternating current applied by the single phase winding of the stator to the electrical load. The current sensor on the rotor side is configured to measure an amplitude of a phase current of the rotor. The position sensor is configured to measure an angular position of the rotor. The excitation control device is operatively connected with the engine and the alternator, and is configured to control the induced voltage generated in the single phase winding of the stator by regulating the rotating magnetic field generated in the phase windings of the rotor. The excitation control device includes a first calculating element, a second calculating element, a first modulating element, a fourth calculating element, a fifth calculating element, a sixth calculating element and a second modulating element. The first calculating element is configured to calculate a load power of the electrical load at least in accordance with the measured amplitudes of the output voltage and the alternating current, and obtain a desired rotation speed of the engine at least in accordance with the calculated load power. The second calculating element is configured to calculate an operation speed of the rotor at least in accordance with the measured angular position. The first modulating element is configured to modulate a rotation speed of the engine at least in accordance with the desired rotation speed and the operation speed. The third calculating element is configured to determine a target phase current vector of the rotor at least in accordance with the measured amplitude of the output voltage. The fourth calculating element is configured to determine a slip angle and a slip ratio at least in accordance with the operation speed of the rotor. The fifth calculating element is configured to extract a phase current vector of the rotor at least in accordance with the measured amplitude of the phase current of the rotor and the slip angle. The sixth calculating element is configured to determine a target voltage of the rotor at least in accordance with the phase current vector and the target phase current vector of the rotor and the slip ratio. The second modulating element is configured to generate a modulating signal at least in accordance with the target voltage of the rotor and the slip angle, and modulate a frequency and an amplitude of an excitation current in the phase windings of the rotor.

The off-grid power generating apparatus and the portable generator set (the portable generator set will not be mentioned below for the sake of brevity) have a stator with a single phase winding and a rotor with a plurality of symmetric windings that generate a rotating magnetic field. The combination of a stator with a single winding and a rotor with a plurality of symmetric phase windings enables the apparatus to power single phase electrical devices with small rated powers such as household appliances while keeping the control system of the apparatus simple and easy to implement. The control method modulates the engine speed in response to load changes to minimize fuel consumption. Moreover, the amplitude and frequency of the excitation current in the rotor windings are modulated to keep the output voltages output from the stator side stable.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of an off-grid power generating apparatus in accordance with some embodiments.

FIG. 2A illustrates an arrangement of the rotor in accordance with some embodiments.

FIG. 2B illustrates another arrangement of the rotor in accordance with some embodiments.

FIG. 2C illustrates another arrangement of the rotor in accordance with some embodiments.

FIG. 3 is a schematic diagram illustrating the structure of an excitation control device in accordance with some embodiments.

FIG. 4 is a schematic diagram of another off-grid power generating apparatus in accordance with some embodiments.

FIG. 5 is a schematic diagram of yet another off-grid power generating apparatus in accordance with some embodiments.

FIG. 6A illustrates a DC bus voltage regulator in accordance with some embodiments.

FIG. 6B illustrates another DC bus voltage regulator in accordance with some embodiments.

FIG. 7 illustrates another embodiment of providing an excitation voltage to the phase windings of the rotor in accordance with some embodiments.

FIG. 8 is a schematic diagram of another off-grid power generating apparatus in accordance with some embodiments.

FIG. 9 is a schematic diagram of yet another off-grid power generating apparatus in accordance with some embodiments.

FIG. 10 illustrates a control system for implementing a control strategy in accordance with some embodiments.

FIG. 11 is a flowchart of a control strategy corresponding to the control system illustrated in FIG. 10 in accordance with some embodiments.

FIG. 12 is schematic diagram of a control loop of the output voltage in accordance with some embodiments.

FIG. 13 is a schematic diagram illustrating transformation of the rotor current from a stationary reference frame to a rotating reference frame in accordance with some embodiments.

FIG. 14 is a logic control diagram of the rotor current in accordance with some embodiments.

FIG. 15 illustrates another control system for implementing a control strategy in accordance with some embodiments.

FIG. 16 is a flowchart of a control strategy corresponding to the control system illustrated in FIG. 15 in accordance with some embodiments.

FIG. 17 is schematic diagram of a control loop of the output voltage in accordance with some embodiments.

FIG. 18 is a schematic diagram illustrating transformation of the rotor current from a stationary reference frame to a rotating reference frame in accordance with some embodiments.

FIG. 19 is a logic control diagram of the rotor current in accordance with some embodiments.

FIG. 20 illustrates a waveform of an excitation current of the rotor in accordance with some embodiments.

FIG. 21 illustrates a waveform of a current and a waveform of a voltage output by the apparatus in accordance with some embodiments.

DETAILED DESCRIPTION

References are made to the accompanying drawings that form a part hereof, and in which is shown by way of illustration of the embodiments in which the embodiments may be practiced. Similar reference numbers indicate similar parts in all diagrams. For example, the reference number of 170 in FIG. and the reference number of 570 in FIG. 5 both refer to the excitation control device for controlling and monitoring the alternator and the engine.

FIG. 1 is a schematic diagram of an off-grid power generating apparatus in accordance with some embodiments. An electrical load 140 may be an electrical appliance, e.g., an oven or an audio player that people use while doing camping and electrical appliances used during blackout. The off-grid apparatus includes an engine 110, an alternator and excitation control device 170. The engine 110 may receive fuel such as gasoline, diesel, natural gas, or liquid propane vapor through an intake. The fuel provided to the engine 110 is compressed and ignited to generate reciprocating motion of pistons of the engine 110. The reciprocating motion of the piston of the engine 110 is converted to rotary motion by a crankshaft of the engine 110, which is operatively coupled to the alternator. The alternator may be an induction alternator with a variable speed and constant frequency. Specifically, the alternator includes a rotor 120 and a stator 130. The rotor 120 may be a cylindrical rotor having a plurality of symmetric phase windings. The rotor 120 is received within the stator 130 and coaxially coupled with the crankshaft of the engine 110 through a common shaft 121. As the engine 110 rotates, the common shaft 121 drives the rotor 120 to rotate and a rotating magnetic field is established in the symmetric phase windings of the rotor 120.

The excitation control device 170 controls and monitors the alternator and the engine 110 in accordance with some embodiments. The excitation control device 170 is electrically connected with the alternator and the engine 110. For example, it is physically attached to the alternator, and connected with the engine 110 via a wire or a wireless device. The excitation control device 170 collects operation data measured by a voltage sensor and a current sensor on the stator side, calculates the load power of the alternator based on the measured operation data, and modulates the engine speed in response to the operation data. While the excitation control device 170 directly controls the engine 110, operation of the engine 110 may also be directly controlled by an engine control module (ECM) not shown in the figures. The ECM controls the engine speed, and thereby controls the output power of the alternator. The excitation control device 170 controls the ECM. The ECM may be

physically attached to the engine 110. A communication bus is provided between the excitation control device 170 and the ECM for transmitting communication data between them. In addition to the engine speed, the ECM may also monitors a variety of engine characteristics such as fuel consumption, engine start information and oil pressure. The excitation control device 170 also modulates the excitation current in the phase windings of the rotor so that the output voltage of the apparatus has constant frequency and amplitude. The excitation control device will be described with more detail below.

The stator 130 of the alternator includes a single phase winding in which a single phase voltage is induced responsive to the rotation of the magnetic field established in the plurality of symmetric phase windings of the rotor 120 in accordance with some embodiments. The induced voltage may be delivered directly as an output voltage to the electrical load 140 via an electrical circuit in accordance with some embodiments. The electrical circuit may include power lines L120, N120, L240 and N240 and other electrical parts such as switch 150 illustrated in FIG. 1. The electrical circuit may include a wire and a plug for connecting the single phase winding and the electrical load. Protection mechanisms such as a circuit breaker may be provided in the electrical circuit for breaking the circuit when it is overpowered. The electrical circuit may also include an auto transfer system for switching between different output voltages. The electrical circuit herein does not include a frequency conversion device such as a converter and an inverter that changes the frequency of the voltage in accordance with some embodiments. In other words, the electrical circuit is configured in a way that the induced voltage generated in the single phase winding and the output voltage applied to the load are at the same frequency. The excitation control device 170 modulates the frequency of the induced voltage so that the frequency remains at a predetermined range, for example, 60 hertz (Hz) in North America and 50 Hz in China. Accordingly, the induced voltage is applicable to most electric equipment, which is designed with a fixed nominal frequency. In this manner, the frequency of the output voltage also remains at the predetermined range, since the induced voltage and the output voltage are at the same frequency.

The single phase winding of the stator 130 may provide not only the output voltage, but also an excitation voltage to the phase windings of the rotor 120 to energize the rotating magnetic field induced in the rotor windings in accordance with some embodiments. The output voltage provided to the electric load from the stator side tends to vary when the engine speed changes. The output voltage is induced and affected by the magnetic field. To prevent the output voltage from changing, the current in the phase windings of the rotor is regulated to offset the variation tendency of the induced voltage. In this manner, the amplitude and the frequency of the output voltage output from the stator 130 are kept stable.

The single phase winding of the stator 130 may include an output portion 130A and an excitation portion 130B as illustrated in FIG. 1 in accordance with some embodiments. The output portion 130A and the excitation portion 130B include at least one coil respectively. The output portion 130A and the excitation portion 130B provide the output voltage to the load and the excitation voltage to the rotor windings respectively in accordance with some embodiments.

The rotor 120 may include a plurality of symmetric phase windings in accordance with some embodiments. FIG. 2A illustrates an arrangement of the rotor 220A in accordance

with some embodiments. The rotor **220A** has three phase windings U, V and W in a star connection. The axes of the three phase windings U, V and W are spatially separated at an angular degree of 120° . Each of the three phase windings U, V and W may include one coil with an equal number of coil turns. Terminal of the coils may be connected via binding posts **224U**, **224V** and **224W**. Other symmetric configurations of three phase windings such as a delta connection are also applicable to the power generating apparatus. FIG. **2B** illustrates another arrangement of the rotor in accordance with some embodiments. The rotor **220B** includes five phase windings M, N, O, P and Q arranged in a symmetric manner, i.e., the axes of the five phase windings M, N, O, P and Q are spatially separated at an angular degree of 72° . Each of the five phase windings M, N, O, P and Q may include one coil with an equal number of coil turns. Terminal of the coils may be connected via binding posts **220O**, **220P**, **220Q**, **220M** and **220N**. FIG. **2C** illustrates another arrangement of the rotor **220C** in accordance with some embodiments. Two symmetric phase windings R and S which are separate spatially at an angular degree of 90° are provided. Each of the two phase windings R and S may include one coil with an equal number of coil turns. Terminals of the coils may be connected via binding posts **220R**, **220S** and **220J**. A rotating magnetic field is generated in the phase windings of the rotor when an excitation voltage is imposed on them.

In accordance with some embodiments, the alternator includes a voltage sensor for measuring the amplitude of the output voltage $U_{S\text{ LOAD}}$ output from the single phase winding of the stator, a current sensor on the stator side for measuring the amplitude of the alternating current $I_{S\text{ LOAD}}$ applied to the electrical load, a current sensor on the rotor side for measuring the amplitude of the phase currents of the rotor I_{ra} , I_{rb} and I_{rc} , and a position sensor for measuring the angular position of the rotor θ_r (which is not illustrated in FIG. **1** but in FIGS. **10** and **15**). The amplitudes of the output voltage and the alternating current applied to the load, the phase currents of the rotor and the angular position of the rotor can be real time operation data measured by the sensors, for example, real time values measured every millisecond or every second. They can also be the averages or integrals of some real time operation data measured by the sensors in a period. For example, the sensors measure real time values every second, and the amplitudes of the output voltage, the alternating current applied to the electrical load and the phase currents of the rotor and the angular position of the rotor can be the averages or integrals of the measured real time values in every 10 successive seconds. The measured operation data of the apparatus can be modulated, filtered and then sent to the excitation control device **170**. A microprocessor-based or otherwise computer-driven systems can work as the excitation control device **170**. The excitation control device **170** has a processor and a memory for storing program instructions for implementing the control functions of the excitation device. The processor operates under the direction of the stored program instructions. Alternatively, the excitation control device **170** may be provided with a logic circuit such as CMOS (Complementary Metal Oxide Semiconductor), ASIC (Application Specific Integrated Circuits), PGA (Programmable Gate Array), FPGA (Field-programmable Gate Array) and so on for implementing its control functions.

As illustrated in FIG. **3**, the excitation control device **170** has a first calculating element **171**, a second calculating element **172**, a first modulating element **173** for regulating the engine speed, a third calculating element **175**, a fourth

calculating element **174**, a fifth calculating element **176**, a sixth calculating element **177** and a second modulating element **178** for regulating the excitation current. The first calculating element **171** calculates the load power of the electrical load P_{LOAD} at least in accordance with the measured amplitudes of the output voltage $U_{S\text{ LOAD}}$ and the amplitude of the alternating current $I_{S\text{ LOAD}}$. The first calculating element **171** also obtains a desired rotation speed of the engine at least in accordance with the calculated load power. The second calculating element **172** calculates the actual rotation speed of the rotor ω_r , at least in accordance with the angle of the rotor. The first modulating element **173** modulates the speed of the engine at least in accordance with the desired rotation speed of the engine. Specifically the first modulating element **173** may correct the actual rotation speed of the rotor ω_r with the desired rotation speed of the engine in a closed control loop. The third calculating element **175** calculates the slip angle θ_{slip} and the slip ratio S with the actual rotation speed of the rotor ω_r . The fourth calculating element **174** calculates the target phase currents I_{rq}^* and I_{rd}^* in the rotating dq reference frame at least in accordance with the measured amplitudes of the output voltage $U_{S\text{ LOAD}}$. The fifth calculating element **176** transforms the amplitudes of the phase currents of the rotor I_{ra} , I_{rb} , and I_{rc} in a three-axis stationary reference frame to I_{ra} and $I_{r\beta}$ in a two-axis rotating reference frame. Then, I_{ra} , $I_{r\beta}$ and the slip angle θ_{slip} are employed as inputs of PARK transformation to extract the phase current vector I_{rd} and I_{rq} . The sixth calculating element **177** determines the target voltage vector of the rotor U_{rq}^* and U_{rd}^* at least in accordance with the phase current vector I_{rd} and I_{rq} , the target phase currents I_{rq}^* and I_{rd}^* and the slip ratio S. The second modulating element **178** generates a modulating signal at least in accordance with the target voltage vector of the rotor U_{rq}^* and U_{rd}^* and the slip angle, and modulates the frequency and amplitude of the excitation current in the phase windings of the rotor **120** with the modulating signal.

FIG. **4** is a schematic diagram of another off-grid power generating apparatus in accordance with some embodiments. The output portion **430A** of the stator winding has only one coil in which an output voltage at one single level, e.g., 120 volts or 240 volts, is generated. The output voltage is provided to the electrical load **440** via a circuit that includes the live line UAL and the neutral line UAN in FIG. **4**.

Reference is now made back to FIG. **1**. The output portion has more than one coil to provide an output voltage at dual levels in accordance with some embodiments. The output portion **130A** includes a first segment **130A1** and a second segment **130A2** in FIG. **1**. The first segment **130A1** includes one coil with a first terminal line UAL, which may be a live line, and a second terminal line UAN, which may be a neutral line. The second segment **130A2** may include another coil with a third terminal line UBL and a fourth terminal line UBN, which may be a live line and a neutral line respectively. The first segment **130A1** and the second segment **130A2** may separately include a plurality of coils in series in accordance with some embodiments.

The power generating apparatus includes a switch **150** in accordance with some embodiments as shown in FIG. **1**. The switch **150** may be a manually operated changeover switch or other similar switches. The terminal lines UAL, UAN, UBL and UBN of the first segment **130A1** and the second segment **130A2** are separately connected to the switch **150**. The switch **150** is a packet-type switch. A user may operate the switch **150** to switch over between a first position and a second position so that the first segment **130A1** and the

second segment **130A2** are selectively in parallel connection or series connection. In this manner, an output voltage at dual levels, a low voltage (for example, 120 volts) and a high voltage (for example, 240 volts) are generated and delivered from the switch **150** to the electrical load **140**. Optionally, a plug connected with the electric load and two sockets connected with the first segment **130A1** and the second segment **130A2** may be provided for a user to switch between the low voltage and the high voltage. For example, the user may put the plug in one socket through which the first segment **130A1** and the second segment **130A2** are in series connection to provide the electric load with the high voltage. The user may put the plug in the other socket through which the first segment **130A1** and the second segment **130A2** are in parallel connection (or either of the two segments connected) to provide the electric load with the low voltage. The excitation portion **130B** may include one coil that has terminal lines connected to the phase windings of the rotor U, V and W to apply the induced voltage generated in the excitation portion **130B** to the phase windings for energizing the rotating magnetic field. The excitation portion **130B** is independent of the output portion **130A**. Therefore, the excitation portion **130B** can provide an excitation voltage greater than the output voltage in a simple manner. For example, an excitation voltage of 320 volts (higher than a normal 220 volts) can be provided when the excitation portion **130B** has a sufficient number of winding turns.

FIG. **5** is a schematic diagram of yet another off-grid power generating apparatus in accordance with some embodiments. The single phase winding of the stator **530** may include a first portion **530A1** and a second portion **530A2** in accordance with some embodiments. The first portion **530A1** may include one coil with terminal lines UAL and UAN, and the second portion **530A2** may include another coil with terminal lines UBL and UBN. The terminal lines UAL, UAN, UBL and UBN are separately connected to the switch **550**. A user may switch over the switch **550** to selectively connect the first portion **530A1** and the second portion **530A2** in parallel or in series connection to obtain an output voltage of 120 volts or 240 volts. Unlike the apparatus illustrated in FIG. **1** that has a separate excitation portion, the first portion **530A1** or the second portion **530A2** of this apparatus is also used to provide the excitation voltage. For example, as illustrated in FIG. **5**, the second portion **530A2** has an extra pair of terminal lines EXN and EXL that is connected to the phase windings of the rotor (not illustrated in FIG. **5**).

The second portion **530A2** may include more than one coil in series connection in accordance with some embodiments (not illustrated in FIG. **5**), for example, a first coil and a second coil connected in series. The live line and neutral line of the first coil are connected to the switch to provide the output voltage, and the live lines of the first coil and the second coil are connected to the rotor circuit, i.e., the series voltage generated by the first coil and the second coil in series connection works as the excitation voltage. Compared with a stator with a separate excitation coil, the coil number of the excitation coil in this stator is reduced.

A frequency conversion device **560** may be provided between the second portion **530A2** and the phase windings of the rotor in accordance with some embodiments. The frequency conversion device **560**, which is the so-called converter, regulates the induced voltage generated in the excitation portion **530A2** to generate a voltage with a desired frequency and amplitude to provide to the phase windings of the rotor for energizing the rotating magnetic

field. The frequency conversion device **560** may include a DC bus voltage regulator that receives the excitation voltage from the single phase winding of the stator and outputs a DC voltage to buses BUS+, BUS-. FIG. **6A** illustrates a DC bus voltage regulator **661A** in accordance with some embodiments. The DC bus voltage regulator **661A** includes an uncontrolled Bridge Rectifier **661A** that may have four individual rectifying diodes **661A1** connected in "bridge" configuration to receive the excitation voltage from the excitation portion **630B** or either of the two portions of the single phase winding and generate the desired DC voltage. The main advantage of this bridge rectifier is that it does not require a special center tapped transformer, thereby reducing its size and cost. A bus capacitor **661A2** may be provided for smoothing the output of the uncontrolled Bridge Rectifier **661A** to produce a DC voltage. FIG. **6B** illustrates another DC bus voltage regulator **661B** in accordance with other embodiments. A Power factor correction device **661B1** is used to rectify and boost the excitation voltage received from the single phase winding of the stator. A bus capacitor **661B2** may be provided to store energy and filter out high frequency voltage components.

FIG. **7** illustrates another embodiment of providing an excitation voltage to the phase windings of the rotor in accordance with some embodiments. A DC power source, which may be a battery **710**, is used for supplying a DC voltage. A DC-DC converter **720** is connected with the battery **710** to increase the amplitude of the DC voltage before the DC voltage is applied to the buses BUS+ and BUS- that is connected to the phase windings of the rotor for energizing the rotating magnetic field. A bus capacitor **730** may be provided to store energy and filter out high frequency voltage components.

FIG. **8** is a schematic diagram of another off-grid power generating apparatus in accordance with some embodiments. This exemplary apparatus is similar to those described previously with reference to FIGS. **1** and **5**, and therefore identical and similar parts will not be discussed again herein. The apparatus includes a frequency conversion device **860**. The frequency conversion device **860** mainly includes a DC bus voltage regulator **861** and an inverter **862**. The DC bus voltage regulator **861** is similar to those described above with reference to FIGS. **6A** and **6B**, and therefore the frequency conversion device will not be described again herein.

The inverter **862** can be a two-phase, three-phase, four-phase or five-phase DC/AC inverter corresponding to the number of the symmetric phase windings of the rotor. In FIG. **8**, the inverter **862** is illustrated as a three-phase six-switch DC/AC inverter that receives control pulse signals, for example, in the form of a PWM (pulse-width modulation) (or SVPWM, space vector pulse width modulation) waveform from the excitation control device **870**. The control pulse signals are duty ratios of switching-on time in substance. The excitation control device **870** is programmed to provide the pulse signals that are PWM (or SVPWM) excitation signals with a desired amplitude and frequency. To keep the induced voltage constant, the pulse signals are employed to modulate the amplitude and frequency of the current in the phase windings of the rotor, in order to change the magnetic field in a way that offsets the variation tendency of the induced voltage. The excitation control device **870** applies the excitation signals to the rotor windings to regulate the intensity of the rotating magnetic field generated in the rotor windings and the rotating speed of the rotating magnetic field relative to the rotor. As a result, the amplitude and frequency of the output voltage output

from the stator, i.e., the output voltage of the apparatus, are kept stable. The PWM (or SVPWM) waveform can be a square wave, modified sine wave and sine wave mainly depending on the circuit design of the inverter **862**. Each leg of the inverter **862** may be connected with one phase winding of the rotor through wires. The inverter **862** has one or more switching element on each leg. The switching element can be a semiconductor switching element such as IGBT, BJT, MOSFET, GTO, SCR and IGCT. A pair of IGBTs is provided on each leg of the inverter **862** as illustrated in FIG. **8**. The pulse signals from the excitation control device **870** successively control the switch ON and OFF time of the switching elements with duty ratios. A relatively stable DC voltage from the DC bus voltage regulator **861** is applied to the inverter **862** as illustrated in FIG. **8**. The required input DC voltage of the inverter **862** mainly depends on the design and function of the inverter **862**. Factors that can be considered include the amplitude of the induced voltage, the rotating speed range of the engine, the structure of the rotor windings, the current and voltage parameters of IGBT, etc. The inverter **862** generates PWM (or SVPWM) excitation signals with a desired frequency and amplitude, and the excitation signals are employed to modulate the amplitude and frequency of the current in the phase windings of the rotor so that a rotating magnetic field with a desired intensity and rotating speed relative to the rotor is established.

The frequency conversion device **860**, particularly the inverter **862**, is disposed on the rotor side in the embodiments. In other words, the induced voltage generated in the single phase winding of the stator is delivered to the electrical load without going through any frequency conversion device. The induced voltage and the output voltage applied to the load are at the same frequency. As a result, the rated power of the inverter **862** used in the apparatus with a rated power of 7,000 watts is less than 1,500 watts, usually the rated power of the inverter **862** is 700-800 watts. The rated power of an inverter in a power generator with a rated power of 7,000 watts in which an inverter is used to modulate the overall power generated by the generator is usually 7000 watts. Thus, inverters with a much smaller capacity can be used in the apparatus in the embodiments, since the inverter **862** only modulates a fraction of the overall power that is supplied to the rotor for modulating the amplitude and frequency of the output voltage of the apparatus output from the stator side. Accordingly, the inverter **962** is comparatively light and cost-efficient. It is estimated that the cost of the inverter accounts for 20% to 60% of the cost of a traditional power generator. Therefore, the power generating apparatus in the embodiments described above enjoys a superb advantage in terms of costs.

The excitation control device **870** is programmed to calculate the load power of the engine by using the operation data measured by the current sensor on the stator side and the voltage sensor (not shown in FIG. **8**) and modulate the power of the engine, i.e., the speed of the engine in response to the calculated load power. The power of the engine is modulated to follow a pre-defined engine power-speed characteristic curve of the engine to track the maximum power point. The characteristic curve of the engine is a curve indicating a relationship of operation parameters of the engine, for example, the power, rotation torque and rotation speed of the engine. The characteristic curve can be pre-stored in the excitation control device **870**.

The alternator may also include a battery **880** in accordance with some embodiments. The battery **880** may be electrically separated from the buses BUS+, BUS- for the

sake of safety. The DC voltage of the battery **880** may be applied to the buses BUS+, BUS- through an excitation voltage provider **890** for providing an excitation voltage for establishing a rotating magnetic field in the rotor windings when the power generating apparatus starts. The excitation voltage provider **890** may be structured in the form of a transformer. The amplitude of the excitation voltage may be quite small, for example from 1 volts to 20 volts.

The apparatus is set to operate at a rotation speed equal to or less than the synchronous speed of the alternator in accordance with some embodiments. For example, when the synchronous speed of the alternator is 3600 rpm, the engine (e.g., a gasoline engine) is set to operate at a speed between 3000-3600 rpm in a stable working state. The faster the engine runs, the greater the output power of the engine is. The engine speed of a power generating apparatus will increase up to 3600 rpm as the apparatus picks up its power from an idling state when the apparatus starts to its rated power. When the rotating speed of the engine reaches 3600 rpm, the excitation voltage becomes a DC voltage.

Thus, an apparatus will always operate in a sub-synchronous or synchronous state when the apparatus is set to operate at a rotation speed equal to or less than the synchronous speed of the alternator. The synchronous speed of the alternator refers to the rotation rate of the stator's magnetic field. This means that electrical energy in the apparatus always flows from the stator side to the rotor side. No energy flows in the opposite direction. This feature makes it possible to use low cost devices or parts with a uni-directional characteristic such as the uncontrolled Bridge Rectifier illustrated in FIG. **6A** in the apparatus. It should be appreciated that the apparatus may operate at a speed more than the reference speed in undesirable operation conditions. Protection mechanisms such as a circuit breaker may be provided in the apparatus to stop it from operation when the speed is excessive.

FIG. **9** is a schematic diagram of yet another off-grid power generating apparatus in accordance with some embodiments. The inverter **962** can be two-phase, three-phase, four-phase or five-phase DC/AC inverters corresponding to the number of the symmetric phase windings of the rotor. In FIG. **9**, the inverter **962** is illustrated as a three-phase six-switch DC/AC inverter that receives control pulse signals, for example, in the form of a PWM (pulse-width modulation) (or SVPWM, Space Vector Pulse Width Modulation) waveform from the excitation control device **970**. The control pulse signals are duty ratios of switching-on time in substance. The excitation control device **970** is programmed to provide the pulse signals that are PWM (or SVPWM) excitation signals with a desired amplitude and frequency. To keep the induced voltage constant, the pulse signals are employed to modulate the amplitude and frequency of the current in the phase windings of the rotor, in order to change the magnetic field in a way that offsets the variation tendency of the induced voltage. The excitation control device **970** applies the excitation signals to the rotor windings to regulate the intensity of the rotating magnetic field generated in the rotor windings and the rotating speed of the rotating magnetic field relative to the rotor. As a result, the amplitude of the output voltage of the stator, i.e., the output voltage of the apparatus, is kept stable and the frequency of the output voltage is maintained constant. The PWM (or SVPWM) waveform can be a square wave, modified sine wave and sine wave depending on the circuit design of the inverter **962**. Each leg of the inverter **962** may be connected with one phase winding of the rotor through wires. The inverter **962** has one or more switching elements

on each leg. The switching elements can be semiconductor switching elements such as IGBT, BJT, MOSFET, GTO, SCR and IGCT. A pair of IGBTs is provided on each leg of the inverter **962** in accordance with some embodiments as illustrated in FIG. **9**. The pulse signals from the excitation control device **970** successively control the switch ON and OFF time of the switching elements of the inverter **962** with duty ratios. A relatively stable DC voltage from the DC bus voltage regulator **961** is applied to the inverter **962** as illustrated in FIG. **9**. The required input DC voltage of the inverter **962** depends on the design and function of the inverter **962**. Factors that can be considered include the amplitude of the induced voltage, the rotating speed range of the engine, the structure of the rotor windings, the current and voltage parameters of IGBT used, etc. The inverter **962** generates PWM (or SVPWM) excitation signals with desired frequency and amplitude, and the excitation signals are employed to modulate the amplitude and frequency of the current in the phase windings of the rotor so that a rotating magnetic field with the desired intensity and rotating speed relative to the rotor is established. The rated power of the inverter **962** used in the apparatus with a rated power of 7,000 watts is less than 1,500 watts, usually is 700-800 watts. The rated power of an inverter in a power generator with a rated power of 7,000 watts in which an inverter is used to regulate the overall power generated by the generator is usually 7000 watts. Thus, inverters with a much smaller capacity can be used in the apparatus in the embodiments, since the inverter **962** only regulates a fraction of the overall power that is supplied to the rotor for regulating the amplitude and frequency of the output voltage of the apparatus output from the stator side. Accordingly, the inverter **962** is comparatively light and cost-efficient. It is estimated that the cost of the inverter accounts for 20% to 60% of the cost of a traditional power generator. Therefore, the power generating apparatus in the embodiments described above enjoys a superb advantage in terms of costs.

The excitation control device **970** is programmed to regulate the power of the engine, i.e., the speed of the engine. The excitation control device **970** calculates real time load power with the measured operation data from the sensors that are not illustrated in FIG. **9**, and regulates speed of the engine in response to the calculated real time load power. The power of the engine is regulated to follow a pre-defined engine power-speed characteristic of the engine to track the maximum power point. The pre-defined engine power-speed characteristic of the engine can be stored in the excitation control device **970**.

The alternator may also include a battery **980** in accordance with some embodiments. The battery **980** may be electrically separate from the buses BUS+, BUS- for the sake of safety. The DC voltage of the battery **980** may be applied to the buses BUS+, BUS- through an excitation voltage provider **990** for providing an excitation voltage for establishing a rotating magnetic field in the rotor windings when the power generating apparatus starts. The excitation voltage provider **990** may be structured in the form of a transformer. The amplitude of the excitation voltage may be quite small, for example from 1 volts to 20 volts.

The difference between FIG. **8** and FIG. **9** is that the apparatus in FIG. **9** does not have a separate excitation portion. It is easy for those skilled in the art to understand the principle of the apparatus in FIG. **9**. Thus, no more description will be repeated herein.

The power generating apparatus for powering an electrical load is described with reference to FIGS. **1-9** above. The apparatus, as previously described, having a stator with a

single phase winding and a rotor with a plurality of symmetric phase windings poses a challenge to conventional control strategies for generators. It is particularly difficult to control an apparatus having a stator with a single phase winding in which an output voltage is generated and output without frequency conversion. A simple and cost-effective control system for the apparatus is provided in this disclosure, which will be described with reference to FIGS. **10-19**.

In the control system, an excitation signal is employed to modulate the frequency and amplitude of the current in the rotor windings. Thereby the intensity of the rotating magnetic field and its rotating speed relative to the rotor are modulated. In this manner, the amplitude and frequency of the output voltage are kept stable. Meanwhile, the rotating speed of the engine is variable in response to load changes so that the fuel efficiency of the engine is optimized. This control system enables the power generating apparatus to change its engine speed in a wide range as the load it drives changes.

FIG. **10** illustrates a control system for implementing a control strategy in accordance with some embodiments. FIG. **11** is a flowchart of a control strategy corresponding to the control system illustrated in FIG. **10**. The single phase winding of the stator in these embodiments generates an output voltage of one level. The one leveled output voltage may be live to live high voltage of 240 volt U_{SAB} which is provided to the electrical load through live terminal lines A and B to the load (as illustrated in FIG. **10**). Another example of the one leveled output voltage is live to neutral low voltage of 120 volt which is provided to the electrical load through live terminal line A and neutral terminal line N to the load (not illustrated in FIG. **10**).

In accordance with some embodiments, the level of the output voltage can be changed by regulating the intensity of the rotating magnetic field. For instance, a low output voltage of 120 volts can be boosted to a high output voltage of 240 volts by increasing the intensity of the rotating magnetic field. It should be understood that the control system illustrated in FIG. **10** and the control strategy illustrated in FIG. **11** are applicable to an apparatus that generates an output voltage of 120 volts from the stator side.

The rotor has three windings U, V and W in a symmetric configuration that are connected with three legs of an inverter **1062** separately. A DC voltage U_{dc} from the DC bus voltage regulator (which is not illustrated FIG. **10**) is applied to the inverter **1062** as previously described. A voltage sensor **10V** and a current sensor on the stator side **10AS** are electrically connected with the terminal lines A and B for measuring the output voltage U_{SAB} and the load current I_{SAB} output by the single phase winding of the stator. Specifically, the amplitude of the output voltage U_{SAB} and the load current I_{SAB} are measured. The current sensor on the rotor side **10AR** is connected with the three windings U, V and W for measuring the amplitudes of the phase currents of the rotor I_{ra} , I_{rb} and I_{rc} . The position sensor **10P** is attached to the rotor for measuring the position of the rotor θ_r .

The position sensor **10P** may measure the position of the engine shaft, since the rotor and the engine shaft are coaxially connected. The amplitudes of the output voltage, the load current, the phase currents, and the angle of the rotor can be real time values measured by the sensors, for example, real time values measured every millisecond or every second. They can also be the averages or integrals of some real time values measured by the sensors in a period. For example, the sensors measure real time values every second, and the amplitudes of the output voltage, the load current and the phase currents and the angle of the rotor can

be the averages or integrals of the measured real time values in every 10 successive seconds. The measured operation data of the apparatus may be modulated, filtered and then sent to the excitation control device **1070**.

When the excitation control device **1070** collects the measured operation data, load power P_{load} is calculated using equation 1 below:

$$P_{load} = U_{SAB} * I_{SAB} \quad \text{Equation 1}$$

Where U_{SAB} is the amplitude of the measured output voltage and I_{SAB} is the amplitude of the measured load current. Then a desired rotation speed of the engine can be obtained using the pre-defined characteristic curve of the engine. The characteristic curve of the engine is a curve indicating a relationship of operation parameters of the engine, for example, the power, rotation torque and rotation speed of the engine. The characteristic curve can be obtained with experiments and pre-stored in the excitation control device. For example, for a certain load, the excitation control device identifies the corresponding desired rotation speed on the characteristic curve of the engine. In some embodiments, the characteristic curve can also be a table or a formula describing the corresponding relationships between the load and the optimal rotation speed (sometimes with other parameters such as desired voltage as well).

The actual rotation speed of the rotor ω_r is calculated in accordance with the position angle of the rotor θ_r using equation 2 below:

$$\omega_R = \frac{D(\theta_r)}{dt} \quad \text{Equation 2}$$

Then, the excitation control device **1070** regulates the engine speed based on the desired rotation speed of the engine and the actual rotation speed of the rotor ω_r . Specifically, the excitation control device **1070** employs a closed loop to regulate the engine speed with the actual rotation speed of the rotor ω_r , as a negative feedback. The desired rotation speed of the engine is used to correct the actual rotation speed of the rotor ω_r to optimize fuel consumption in response to load changes.

The excitation control device **1070** calculates the slip angle θ_{slip} and slip ratio S using equations 3, 4 and 5 below:

$$\omega_{slip} = \omega_1 - \omega_r \quad \text{Equation 3}$$

$$\theta_{slip} = \int \omega_{slip} \quad \text{Equation 4}$$

$$S = \frac{\omega_1 - \omega_r}{\omega_1} \quad \text{Equation 5}$$

Where ω_r is the rotation speed of the rotor, and ω_1 is the synchronous speed of the alternator.

FIG. **12** is schematic diagram of a control loop of the output voltage in accordance with some embodiments. The excitation control device calculates the target phase currents of the rotor I_{rd}^* and I_{rq}^* . based on the amplitude of the output voltage U_{SAB} . The target phase current I_{rd}^* is set as zero in the embodiments shown in FIG. **12** for the sake of convenience. The control loop is a closed one which can perform real time correction of the output voltage U_{SAB} so that the amplitude of the output voltage is kept constant. A Proportional-Integral (PI) regulator is provided in the closed control loop to reduce errors of the target phase current

vector I_{rd}^* and I_{rq}^* . The output voltage U_{SAB} , which works as a negative feedback, and the target voltage of the stator U_s^* work as inputs of the PI regulator. The output of the PI regulator is the target phase current vector of the rotor I_{rq}^* .

FIG. **13** is a schematic diagram illustrating transformation of the rotor current from a stationary reference frame to a rotating reference frame in accordance with some embodiments. The excitation control device **1070** extracts the phase current vector of the rotor I_{rd} and I_{rq} in accordance with the amplitude of the phase currents of the rotor I_{ra} , I_{rb} and I_{rc} in the three-axis stationary reference frame and the slip angle θ_{slip} . Specifically, the excitation control device **1070** firstly transforms the amplitude of the phase currents of the rotor I_{ra} , I_{rb} , and I_{rc} in the three-axis stationary reference frame of abc to $I_{r\alpha}$ and $I_{r\beta}$ in the two-axis rotating reference frame of $\alpha\beta$. Then $I_{r\alpha}$, $I_{r\beta}$, $I_{r\beta}$ and the slip angle θ_{slip} are employed as inputs of PARK transformation to extract the phase current vector of the rotor I_{rd} and I_{rq} .

FIG. **14** is a logic control diagram of the rotor current in accordance with some embodiments. The excitation control device **1070** includes a controller of phase current vector **1071** that determines the target voltage vector of the rotor U_{rq}^* and U_{rd}^* in accordance with the phase current vector of the rotor I_{rd} and I_{rq} , the target phase current vector I_{rq}^* and I_{rd}^* (which is set as zero as described previously), the slip ratio S, the resistance of the rotor windings R_r and the target voltage of the stator U_s^* . A PI regulator is used in the closed control loop of the rotor current. The phase current vector of the rotor I_{rd} and I_{rq} serve as a negative feedback, and the target phase current vector I_{rq}^* is employed to correct the phase current vector of the rotor I_{rd} and I_{rq} to reduce errors of the target voltage vector of the rotor U_{rq}^* and U_{rd}^* .

The excitation control device **1070** generates a pulse signal with a certain duty ratio using the target voltage vector of the rotor U_{rq}^* and U_{rd}^* and the slip angle θ_{slip} . The pulse signals are input into the inverter **1062** illustrated in FIG. **10** to regulate the switch ON and OFF time of the switching elements of the inverter. The inverter **1062** regulates the amplitude and frequency of the current in the rotor windings. Thereby the intensity of the rotating magnetic field established in the rotor windings and the rotating speed of the rotating magnetic field relative to the rotor are regulated so that the amplitude and frequency of the induced voltage generated in the stator winding are kept constant.

In the control strategy illustrated in FIG. **11**, a voltage sensor and a current sensor on the stator side are electrically connected with the terminal lines A and B for measuring the output voltage U_{SAB} and the load current I_{SAB} output by the single phase winding of the stator. The current sensor on the rotor side is connected with the three windings of the rotor for measuring the amplitudes of the phase current of the rotor. The position sensor is attached to the rotor for measuring the angular position of the rotor θ_r . The excitation control device (or ECM) calculates the load power with the equation of $P_{load} = U_{SAB} * I_{SAB}$, and determines the desired engine speed according to the load power P_{load} . The excitation control device calculates the actual rotation speed of the rotor ω_r in accordance with the angular position of the rotor, and regulates the engine speed according to the desired rotation speed and the actual rotation speed ω_r . The excitation control device determines the slip angle θ_{slip} and the slip ratio S according to the actual rotation speed ω_r , and the target phase current vector of the rotor I_{rq}^* and I_{rd}^* at least according to the measured output voltage U_{SAB} . The excitation control device extracts the phase current vector of the rotor I_{rd} and I_{rq} at least in accordance with the measured

phase current and the slip angle θ_{slip} . Then, a target voltage vector of the rotor U_{rq}^* and U_{rd}^* is determined at least in accordance with the phase current vector of the rotor I_{rq} and I_{rd} , the target phase current vector of the rotor I_{rq}^* and I_{rd}^* and the slip ratio S. And then, the excitation control device generates a modulating signal according to the target voltage vector of the rotor and the slip angle θ_{slip} , and modulates the frequency and the amplitude of the current in the phase windings of the rotor with the modulating signal.

FIG. 15 illustrates another control system for implementing a control strategy in accordance with some embodiments. FIG. 16 is a flowchart of a control strategy corresponding to the control system illustrated in FIG. 15 in accordance with some embodiments.

FIG. 17 is schematic diagram of a control loop of tin accordance with some embodiments. FIG. 18 is a schematic diagram illustrating transformation of the rotor current from a stationary reference frame to a rotating reference frame in accordance with some embodiments. FIG. 19 is a logic control diagram of the rotor current in accordance with some embodiments. The differences between this power generating apparatus and its control strategy and the previous illustrated in FIGS. 10-14 are as follows.

As illustrated in FIG. 15, the single phase winding of the stator outputs to the electrical load a dual output voltage, i.e., a high voltage and a low voltage, through live terminal lines A, B and neutral terminal line N. The high voltage is live to live voltage U_{sAB} , and the low voltage is live to neutral voltage U_{AN} and U_{BN} . A user can switch over the switch as described previously to select the high voltage or the low voltage. A first and second current sensor on the stator side 15AS1 and 15AS2 are provided to measure the amplitudes of the first and second live to neutral current I_{AN} and I_{BN} . Likewise, a first and second voltage sensor 15V1 and 15V2 are provided to measure the first and second live to neutral voltage U_{BN} and U_{AN} . The live to live voltage, i.e., the high voltage, does not need to be measured in these embodiments. Only the live to neutral voltage, i.e., the low voltage, is measured.

FIG. 16 is a flowchart of a control strategy corresponding to the control system illustrated in FIG. 15 in accordance with some embodiments. In this control strategy, no matter whether the apparatus operates in the high voltage mode or the low voltage mode, the excitation control device 1570 uses the same control manner. Thus, switching signals from the switch are not needed for monitoring the apparatus in these embodiments. The load power of the apparatus $P_{load\ total}$ is calculated with equation 8 below when the apparatus operates in the high and low voltage modes:

$$P_{load\ total} = U_{AN}^* I_{AN} + U_{BN}^* I_{BN} \quad \text{Equation 6}$$

Where U_{AN} and U_{BN} are the first live to neutral voltage and the second live to neutral voltage, and I_{AN} and I_{BN} are the first live to neutral current and the second live to neutral current. The excitation device then obtains the desired engine speed in accordance with the load power $P_{load\ total}$.

FIG. 17 is schematic diagram of a control loop of the output voltage in accordance with some embodiments. The control loop in the embodiments does not switch over between the high voltage mode and the low voltage mode. Rather, this control loop just employs the live to neutral voltage U_{AN} or U_{BN} as a negative feedback input to the PI regulator. The target voltage of the stator U_s^* serves as another input of the PI regulator. The output of the PI regulator is the target phase current vector of the rotor I_{rq}^* . The CLARK-PARK transformation illustrated in FIG. 18

and the control logic illustrated in FIG. 19 are similar to those illustrated in FIGS. 13 and 14. No more description will be repeated herein.

In the control strategy illustrated in FIG. 16, A first and second current sensor on the stator side are provided to measure the amplitudes of the first and second live to neutral current I_{AN} and I_{BN} . Likewise, a first and second voltage sensor are provided to measure the first and second live to neutral voltage U_{BN} and U_{AN} . A current sensor on the rotor side is connected with the three windings of the rotor for measuring the amplitudes of the phase current of the rotor I_{ra} , I_{rb} , I_{rc} . A position sensor is attached to the rotor for measuring the angular position of the rotor. The excitation control device (or ECM) calculates the load power with the equation $P_{load\ total} = U_{AN}^* I_{AN} + U_{BN}^* I_{BN}$, and determines the desired engine speed according to the load power $P_{load\ total}$. The excitation control device calculates the actual rotation speed of the rotor in accordance with the angular position of the rotor, and regulates the engine speed according to the desired rotation speed and the actual rotation speed in a closed loop. The excitation control device determines the slip angle and the slip ratio S according to the actual rotation speed of the rotor, and the target phase current vector of the rotor I_{rq}^* and I_{rd}^* at least according to the first live to neutral voltage U_{BN} or the second live to neutral voltage U_{AN} . The excitation control device extracts the phase current vector of the rotor I_{rd} and I_{rq} at least in accordance with the amplitudes of the phase current I_{ra} , I_{rb} , I_{rc} and the slip angle θ_{slip} . Then, a target voltage vector of the rotor U_{rq}^* and U_{rd}^* is determined at least in accordance with the phase current vector of the rotor I_{rd} and I_{rq} , the target phase current vector of the rotor I_{rq}^* and I_{rd}^* and the slip ratio S. And then, the excitation control device generates a modulating signal according to the target voltage vector of the rotor U_{rq}^* and U_{rd}^* and the slip angle θ_{slip} , and modulates the frequency and the amplitude of the current in the phase windings of the rotor with the modulating signal.

It should be noted that the operations illustrated in FIGS. 11 and 16 can be implemented in an order different from the order illustrated in these figures. Some operations can be conducted substantially simultaneously or in a reverse order, depending on the functions achieved by the operations. For example, the operation of determining the slip angle and slip ratio at least in accordance with the actual rotation speed of the rotor can be conducted after or at the same time as the operation of modulating the engine speed in accordance with the desired engine speed and the actual rotation speed of the rotor is implemented.

The excitation control device can monitor and control the operation of the power generating apparatus in a simple and easy manner. As a result, an excitation control device with a low capability can be used in the apparatus. Thus, the cost of the apparatus is reduced.

FIG. 20 illustrates a waveform of an excitation current for establishing a magnetic field in the rotor windings in accordance with some embodiments. This waveform is achieved by an apparatus with a single phase stator winding and three phase rotor windings which operates at 3000 rpm and outputs 240 volt voltage from the stator side and is applied with a resistive load of 5 kw (kilowatt). FIG. 21 illustrates a waveform of a current and a waveform of a voltage output from the stator side of the apparatus in accordance with some embodiments. The waveforms are achieved by an apparatus having a stator with a single phase winding. The apparatus operates at a speed of 3000 rpm, outputs a voltage of 240 volts from the stator side and is applied with a

resistive load of 5 kw. FIGS. 20 and 21 clearly indicate that the control system yields satisfactory waveforms.

The various embodiments disclosed above have many advantages. The apparatus has a stator with a single winding and a rotor with a plurality of symmetric windings. The combination of a stator with a single winding and a rotor with a plurality of symmetric phase windings enables the apparatus to power single phase electrical devices with small rated powers such as household appliances while keeping the control of the apparatus simple and easy.

The power generating apparatus outputs electrical power directly from the stator without any frequency conversion in accordance with some embodiments. Unlike a generator with an AC-DC-AC converter regulating the full power (overall power) of the generator, the apparatus merely modulates a fraction of its full power with an inverter. The inverter modulates the amplitude and frequency of the current in the rotor windings to offset the variation tendency of the induced voltage (i.e., the output voltage) that is generated in the stator winding. In this manner, the amplitude and frequency of the output voltage from the stator, i.e., the output voltage of the apparatus, are kept stable. It is estimated that the rated power of a power converter disposed on the rotor side of a power generating apparatus accounts for merely around 10% of the rated output power of the power generating apparatus. Thus, an inverter with a lower rated capacity can be used in the apparatus.

The inverter applies an AC voltage to the phase windings of the rotor as an excitation voltage for establishing the rotating magnetic field in the rotor. Both the amplitude of the excitation voltage and its frequency are controllable. This is advantageous given that only the amplitude of the excitation voltage is controllable when a DC voltage is used as the excitation voltage.

The operation speed of the engine in the apparatus is desirably adjustable to maximize fuel efficiency, and thus reduces CO₂ emissions of the engine for a given load. Optimizing the operating speed of the engine corresponding to a given load also reduces the noise associated with operation of the engine-driven apparatus and extends the life of the engine. The output voltage from the stator is substantially kept at a constant frequency.

The amplitude of the output voltage provided by the apparatus is stable given that a closed voltage loop is employed to determine the target rotor voltage for regulating the intensity of the rotating magnetic field. With this feature, the apparatus can be utilized to power electrical devices such as audio and video players and some scientific instruments that are sensitive to voltage and frequency instability. Furthermore, the apparatus can provide an output voltage at dual levels with a single phase winding so that users can use the apparatus to power electrical devices with different nominal voltages.

The apparatus is set to operate at a speed equal to or less than the synchronous speed of the alternator, which means that electrical energy flows uni-directionally, i.e., from the stator to the rotor, not vice versa. This feature renders cheap devices such as uncontrolled bridge rectifier applicable to the apparatus. The feature also makes it possible to control the apparatus with a simple and easy control strategy. Devices with a comparatively low capability can also be used in the apparatus.

The above is only the preferred embodiments of the application and not intended to limit the application, and any modifications, equivalent replacements, improvements and the like within the spirit and principle of the application shall fall within the scope of protection of the application.

While particular embodiments are described above, it will be understood it is not intended to limit the application to these particular embodiments. On the contrary, the application includes alternatives, modifications and equivalents that are within the spirit and scope of the appended claims. Numerous specific details are set forth in order to provide a thorough understanding of the subject matter presented herein. But it will be apparent to one of ordinary skill in the art that the subject matter may be practiced without these specific details. In other instances, well-known methods, procedures, components, and circuits have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

Although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, first ranking criteria could be termed second ranking criteria, and, similarly, second ranking criteria could be termed first ranking criteria, without departing from the scope of the present application. First ranking criteria and second ranking criteria are both ranking criteria, but they are not the same ranking criteria.

The foregoing description, for purpose of explanation, has been described with reference to specific implementations. However, the illustrative discussions above are not intended to be exhaustive or to limit the application to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. The implementations were chosen and described in order to best explain principles of the application and its practical applications, to thereby enable others skilled in the art to best utilize the application and various implementations with various modifications as are suited to the particular use contemplated. Implementations include alternatives, modifications and equivalents that are within the spirit and scope of the appended claims. Numerous specific details are set forth in order to provide a thorough understanding of the subject matter presented herein. But it will be apparent to one of ordinary skill in the art that the subject matter may be practiced without these specific details. In other instances, well-known methods, procedures, components, and circuits have not been described in detail so as not to unnecessarily obscure aspects of the implementations.

What is claimed is:

1. An off-grid power generating apparatus for powering an electrical load, comprising:

an engine;

an alternator including:

a rotor coaxially coupled to the engine, the rotor including a plurality of symmetric phase windings;

a stator with a single phase winding configured to generate an induced voltage, the single phase winding being configured to be connected with the electrical load and the phase windings of the rotor respectively and provide an output voltage to the electrical load and an excitation voltage to the phase windings of the rotor;

a voltage sensor configured to measure an amplitude of the output voltage;

a current sensor on the stator side configured to measure an amplitude of an alternating current applied by the single phase winding of the stator to the electrical load;

a current sensor on the rotor side configured to measure an amplitude of a phase current of the rotor; and

23

- a position sensor configured to measure an angular position of the rotor; and
 an excitation control device operatively connected to the engine and the alternator, wherein the excitation control device is configured to control the induced voltage generated in the single phase winding of the stator by regulating the rotating magnetic field generated in the phase windings of the rotor; the excitation control device includes:
- a first calculating element configured to calculate a load power of the electrical load at least in accordance with the measured amplitudes of the output voltage and the alternating current, and obtain a desired rotation speed of the engine at least in accordance with the calculated load power;
 - a second calculating element configured to calculate an operation speed of the rotor at least in accordance with the measured angular position;
 - a first modulating element configured to modulate a rotation speed of the engine at least in accordance with the desired rotation speed and the operation speed;
 - a third calculating element configured to determine a target phase current vector of the rotor at least in accordance with the measured amplitude of the output voltage;
 - a fourth calculating element configured to determine a slip angle and a slip ratio at least in accordance with the operation speed of the rotor;
 - a fifth calculating element configured to extract a phase current vector of the rotor at least in accordance with the measured amplitude of the phase current of the rotor and the slip angle;
 - a six calculating element configured to determine a target voltage of the rotor at least in accordance with the phase current vector and the target phase current vector of the rotor and the slip ratio; and
 - a second modulating element configured to generate a modulating signal at least in accordance with the target voltage of the rotor and the slip angle, and modulate a frequency and an amplitude of an excitation current in the phase windings of the rotor.
2. The apparatus of claim 1, wherein the alternator comprises a frequency conversion device connected with the single phase winding of the stator, and the frequency conversion device includes an inverter configured to provide the excitation voltage to the phase windings of the rotor.
3. The apparatus of claim 1, wherein the single phase winding of the stator includes a first segment and a second segment;
- the voltage sensor is configured to measure amplitudes of a first and a second output voltage provided respectively by the first segment and the second segment to the electrical load; and
 - the current sensor on the stator side is configured to measure amplitudes of a first and a second alternating current applied respectively by the first and the second segment to the electrical load.
4. The apparatus of claim 3, wherein the first calculating element is configured to calculate a first and a second load power of the electrical load at least in accordance with the measured amplitudes of the first output voltage and the first alternating current, the second output voltage and the second alternating current.
5. The apparatus of claim 1, wherein the third calculating element is configured to determine the target phase current vector of the rotor with a closed control loop.

24

6. The apparatus of claim 1, the alternator comprising an electrical circuit connecting the single phase winding of the stator and the electrical load, wherein the electrical circuit is configured in a way that the induced voltage generated in the single phase winding of the stator and the output voltage applied to the electrical load are at the same frequency.
7. The apparatus of claim 1, wherein the alternator is set to operate at a speed equal to or less than a synchronous speed of the alternator.
8. A control method of an off-grid power generating apparatus for powering an electrical load, the apparatus including an engine and an alternator that includes a stator with a single phase winding configured to generate an induced voltage and a rotor with a plurality of symmetric phase windings, wherein the rotor is coaxially coupled to the engine, and the single phase winding of the stator is configured to be connected to the electrical load and the phase windings of the rotor respectively and provide an output voltage to the electrical load and an excitation voltage to the phase windings of the rotor, the method comprising:
- measuring an amplitude of the output voltage provided to the electrical load;
 - measuring an amplitude of an alternating current applied by the single phase winding of the stator to the electrical load;
 - measuring an amplitude of a phase current of the rotor;
 - measuring an angular position of the rotor;
 - calculating a load power of the electrical load at least in accordance with the measured amplitudes of the output voltage and the alternating current;
 - obtaining a desired rotation speed of the engine at least in accordance with the calculated load power;
 - calculating an operation speed of the rotor at least in accordance with the measured angular position;
 - modulating a rotation speed of the engine at least in accordance with the desired rotation speed and the operation speed;
 - determining a slip angle and a slip ratio at least in accordance with the operation speed of the rotor;
 - determining a target phase current vector of the rotor at least in accordance with the measured amplitude of the output voltage;
 - extracting a phase current vector of the rotor at least in accordance with the measured amplitude of the phase current of the rotor and the slip angle;
 - determining a target voltage of the rotor at least in accordance with the phase current vector and the target phase current vector of the rotor and the slip ratio;
 - generating a modulating signal at least in accordance with the target voltage of the rotor and the slip angle; and
 - modulating a frequency and an amplitude of an excitation current in the phase windings of the rotor.
9. The method of claim 8, the alternator comprising a frequency conversion device connected with the single phase winding of the stator, wherein the frequency conversion device includes an inverter for providing the excitation voltage to the phase windings of the rotor.
10. The method of claim 8, wherein the single phase winding of the stator includes a first segment and a second segment:
- measuring the amplitude of the output voltage includes measuring the amplitudes of a first and a second output voltage provided respectively by the first and the second segment to the electrical load; and
 - measuring the amplitude of the alternating current includes measuring the amplitudes of a first and a

25

second alternating current applied respectively by the first and the second segment to the electrical load.

11. The method of claim 8, wherein determining a target voltage of the rotor includes determining the target voltage of the rotor with a closed control loop.

12. The method of claim 8, wherein the induced voltage generated in the single phase winding of the stator and the output voltage applied to the electrical load are at the same frequency.

13. The method of claim 8, wherein the alternator is set to operate at a speed equal to or less than a synchronous speed of the alternator.

14. An off-grid portable generator set for powering an electrical load, comprising:

an engine;

an induction alternator including:

a rotor coaxially coupled to the engine, the rotor including a plurality of symmetric phase windings;

a stator with a single phase winding configured to generate an induced voltage, the single phase winding being configured to be connected with the electrical load and the phase windings of the rotor respectively and provide an output voltage to the electrical load and an excitation voltage to the phase windings of the rotor;

a voltage sensor configured to measure an amplitude of the output voltage;

a current sensor on the stator side configured to measure an amplitude of an alternating current applied by the single phase winding of the stator to the electrical load;

a current sensor on the rotor side configured to measure an amplitude of a phase current of the rotor; and a position sensor configured to measure an angular position of the rotor; and

an excitation control device operatively connected to the engine and the alternator, wherein the excitation control device is configured to control the induced voltage generated in the single phase winding of the stator by regulating the rotating magnetic field generated in the phase windings of the rotor; the excitation control device includes:

a first calculating element configured to calculate a load power of the electrical load at least in accordance with the measured amplitudes of the output voltage and the alternating current, and obtain a desired rotation speed of the engine at least in accordance with the calculated load power;

a second calculating element configured to calculate an operation speed of the rotor at least in accordance with the measured angular position;

a first modulating element configured to modulate a rotation speed of the engine at least in accordance with the desired rotation speed and the operation speed;

26

a third calculating element configured to determine a target phase current vector of the rotor at least in accordance with the measured amplitude of the output voltage;

a fourth calculating element configured to determine a slip angle and a slip ratio at least in accordance with the operation speed of the rotor;

a fifth calculating element configured to extract a phase current vector of the rotor at least in accordance with the measured amplitude of the phase current of the rotor and the slip angle;

a sixth calculating element configured to determine a target voltage of the rotor at least in accordance with the phase current vector and the target phase current vector of the rotor and the slip ratio; and

a second modulating element configured to generate a modulating signal at least in accordance with the target voltage of the rotor and the slip angle, and modulate a frequency and an amplitude of an excitation current in the phase windings of the rotor.

15. The generator set of claim 14, the alternator comprising a frequency conversion device connected with the single phase winding of the stator, wherein the frequency conversion device includes an inverter for providing the excitation voltage to the phase windings of the rotor.

16. The generator set of claim 14, wherein the single phase winding of the stator includes a first segment and a second segment;

the voltage sensor is configured to measure the amplitudes of a first and a second output voltage provided respectively by the first segment and the second segment to the electrical load; and

the current sensor on the stator side is configured to measure the amplitudes of a first and a second alternating current applied respectively by the first and the second segment to the electrical load.

17. The generator set of claim 16, wherein the first calculating element is configured to calculate a first and a second load power of the electrical load at least in accordance with the measured amplitudes of the first output voltage and the first alternating current.

18. The generator set of claim 14, wherein the third calculating element is configured to determine the target phase current vector of the rotor with a closed control loop.

19. The generator set of claim 14, the alternator comprising an electrical circuit connecting the single phase winding of the stator and the electrical load, wherein the electrical circuit is configured in a way that the induced voltage generated in the single phase winding of the stator and the output voltage applied to the electrical load are at the same frequency.

20. The generator set of claim 14, wherein the alternator is set to operate at a speed equal to or less than a synchronous speed of the alternator.

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