PERMANENT MAGNET MOTOR SYSTEMS AND METHODS

TECHNOLOGICAL FIELD

The present disclosure, in some embodiments, thereof relates to a motor system including a permanent magnet rotor and, more particularly, but not exclusively, to a system where the stator is configured to receive multiphase electrical power from either an inverter or an electrical grid.

GENERAL DESCRIPTION

Following is a non-exclusive list of some exemplary embodiments of the disclosure. The present disclosure also includes embodiments which include fewer than all the features in an example and embodiments using features from multiple examples, even if not listed below.

Example 1. An electrical motor system comprising:

a rotor comprising one or more elements configured to provide a rotor magnetic field and an induction structure including at least one closed conduction loop, the rotor sized and shaped to occupy a bore of a stator which, when receiving alternating current provides a stator rotating magnetic field, the stator rotating magnetic field:

interacting with the rotor magnetic field to produce torque; and

crossing the at least one closed conduction loop;

an inverter configured to receive a three phase power supply and to deliver a variable frequency three phase power supply to the stator through a plurality of inverter electrical pathways;

a bypass module configured to selectively deliver the three phase power supply directly to the stator through a plurality of bypass electrical pathways;

a controller configured to control transition between supplying the stator through the inverter and through the bypass module by generating control signals for activation and deactivation of the plurality of inverter electrical pathways and the plurality of bypass electrical pathways, the controller configured to:

identify a phase state of the three phase power supply;

activate bypass pathways and deactivate inverter pathways, while continuously maintaining power through at least one pathway to the stator, timing of individual activations and deactivations based on the phase state.

Example 2. The electrical motor system according to Example 1, wherein the one or more elements configured to provide the rotor magnetic field comprises a plurality of permanent magnets.

Example 3. The electrical motor system according to Example 2, wherein the rotor comprises flux barriers formed by non-magnetic material positioned between said permanent magnets.

Example 4. The electrical motor system according to Example 3, wherein the induction structure provides the flux barriers, the induction structure including electrically conductive and non-magnetic material which is positioned between ends of the permanent magnets.

Example 5. The electrical motor system according to any one of Examples 2-4, wherein the plurality of permanent magnets are elongate elements extending along a rotor body.

Example 6. The electrical motor system according to Example 5, wherein the plurality of permanent magnets each occupy a slot in the rotor body.

Example 7. The electrical motor system according to any one of Examples 5-6, wherein the induction structure includes a plurality of elongate conductors extending along the rotor body.

Example 8. The electrical motor system according to Example 7, wherein the plurality of elongate conductors each occupy a slot in the rotor body in a position between two of the plurality of permanent magnets.

Example 9. The electrical motor system according to any one of Examples 7-8, wherein said plurality of elongate conductors are electrically insulated from the rotor body to confine induced currents to within the conductive loops.

Example 10. The electrical motor system according to any one of Examples 2-9, wherein the plurality of permanent magnets are arranged circumferentially about a rotor axis of rotation to form alternating north and south poles.

Example 11. The electrical motor system according to any one of Examples 1-10, wherein the controller is configured to control the inverter to increase frequency and voltage according to a predetermined voltage-to-frequency profile during motor startup.

Example 12. The electrical motor system according to any one of Examples 1-11, wherein the controller is configured such that commutation from inverter supply to grid supply is in a closed transition in which both the inverter and the bypass module supply power in parallel during at least part of the transition.

Example 13. The electrical motor system according to any one of Examples 1-12, wherein the controller is configured to time activation and deactivation of electrical pathways during the transition based on polarities of the different phases of the electrical voltages and currents, and is selected to supply power to the load continuously.

Example 14. The electrical motor system according to Example 13, wherein the controller is configured to activate a bypass pathway while an inverter pathway remains activated only if both pathways are delivering a same-polarity voltage to a phase of the stator.

Example 15. The electrical motor system according to any one of Examples 1-14, wherein the controller is configured to:

monitor a sector of the three phase supply;

select a first phase for transition based on said sector; and

activate a first pathway through the bypass module corresponding to said first phase and deactivate a corresponding first pathway through the inverter, while at least one inverter pathway remains activated.

Example 16. The electrical motor system according to any one of Examples 1-15, wherein the controller is configured to select a second phase for transition based on said sector, and to activate a second pathway through the bypass module corresponding to said second phase while deactivating a corresponding second pathway through the inverter.

Example 17. The electrical motor system according to any one of Examples 1-16, wherein the controller is further configured to select a third phase for transition based on said sector, and to activate a third pathway through the bypass module corresponding to said third phase while deactivating a corresponding third pathway through the inverter.

Example 18. The electrical motor system according to any one of Examples 15-17, wherein the selecting, activating, and deactivating for the first and second phases are performed during a same sector of the three phase supply.

Example 19. The electrical motor system according to Example 18, wherein, after a time delay corresponding to a sector duration, the activating and deactivating for the third phase are performed.

Example 20. The electrical motor system according to any one of Examples 15-19, wherein the controller is configured such that the selecting, activating, and deactivating for the first phase are performed in a first sector, and the selecting, activating, and deactivating for the second and third phases are performed in a subsequent sector.

Example 21. The electrical motor system according to any one of Examples 15-20, wherein the controller is configured so that deactivating a pathway occurs after activating a corresponding pathway.

Example 22. The electrical motor system according to any one of Examples 15-21, wherein the inverter is a first supply module and the bypass module is a second supply module configured to deliver the three phase power supply directly to the stator.

Example 23. The electrical motor system according to Example 22, wherein the inverter comprises a switched-mode variable-frequency power supply configured to receive three phase power from a grid.

Example 24. The electrical motor system according to any one of Examples 15-23, wherein the controller is configured, in an alternative commutation direction, to deactivate, based on said sector, a first pathway through the bypass module and, once said first pathway is deactivated, to activate a corresponding first pathway through the inverter.

Example 25. The electrical motor system according to Example 24, wherein the controller is configured to deactivate a second pathway through the bypass module and, during a subsequent sector, to activate a corresponding second pathway through the inverter.

Example 26. The electrical motor system according to Example 25, wherein the controller is configured to deactivate a third pathway through the bypass module and, during a sector following said subsequent sector, to activate a corresponding third pathway through the inverter.

Example 27. The electrical motor system according to any one of Examples 24-26, wherein the controller is configured to verify deactivation of a pathway prior to activating a corresponding pathway.

Example 28. The electrical motor system according to Example 27, wherein the controller is configured to verify that a measurement of current through a deactivated pathway is below a threshold.

Example 29. The electrical motor system according to Example 28, wherein the controller is configured to receive said measurement of current through the deactivated pathway.

Example 30. A method of operating an electrical motor system comprising a stator, a synchronous-type rotor including an induction structure, an inverter, a bypass module, and a controller, the method comprising:

supplying a three phase power supply to the inverter;

delivering, from the inverter, a variable-frequency three phase power supply to the stator through a plurality of inverter pathways;

monitoring a phase state of the three phase power supply; and

transitioning supply of power to the stator from the inverter to the bypass module by activating a bypass pathway and deactivating a corresponding inverter pathway while continuously maintaining power to the stator through at least one pathway, where timing of each activation and deactivation is based on the monitored phase state.

Example 31. The method according to Example 30, wherein the transitioning includes activating a bypass pathway only when both the inverter pathway and the bypass pathway corresponding to a given stator phase are delivering voltages of the same polarity.

Example 32. The method according to any one of Examples 30-31, further comprising:

identifying a sector of the three phase supply;

selecting a first phase for commutation based on the identified sector; and activating a first bypass pathway and deactivating a corresponding first inverter pathway while at least one inverter pathway remains activated.

Example 33. The method according to any one of Examples 30-32, further comprising:

in an alternative commutation direction, deactivating a first pathway through the bypass module based on the identified sector;

verifying deactivation of the first pathway; and

after verification, activating a corresponding first pathway through the inverter.

Example 34. The method according to any one of Examples 30-33, further comprising monitoring current through a deactivated pathway and determining that the current is below a threshold prior to activating a corresponding pathway through an alternative supply module.

Unless otherwise defined, all technical and/or scientific terms used within this document have meaning as commonly understood by one of ordinary skill in the art/s to which the present disclosure pertains. Methods and/or materials similar or equivalent to those described herein can be used in the practice and/or testing of embodiments of the present disclosure, and exemplary methods and/or materials are described below. Regarding exemplary embodiments described below, the materials, methods, and examples are illustrative and are not intended to be necessarily limiting.

Some embodiments of the present disclosure are embodied as a system, method, or computer program product. For example, some embodiments of the present disclosure may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a “circuit,” “module” and/or “system.”

Implementation of the method and/or system of some embodiments of the present disclosure can involve performing and/or completing selected tasks manually, automatically, or a combination thereof. According to actual instrumentation and/or equipment of some embodiments of the method and/or system of the present disclosure, several selected tasks could be implemented by hardware, by software or by firmware and/or by a combination thereof, e.g., using an operating system.

For example, hardware for performing selected tasks according to some embodiments of the present disclosure could be implemented as a chip or a circuit. As software, selected tasks according to some embodiments of the present disclosure could be implemented as a plurality of software instructions being executed by a computational device e.g., using any suitable operating system.

In some embodiments, one or more tasks according to some exemplary embodiments of method and/or system as described herein are performed by a data processor, such as a computing platform for executing a plurality of instructions. Optionally, the data processor includes a volatile memory for storing instructions and/or data and/or a non-volatile storage e.g., for storing instructions and/or data. Optionally, a network connection is provided as well. User interface/s e.g., display/s and/or user input device/s are optionally provided.

Some embodiments of the present disclosure may be described below with reference to flowchart illustrations and/or block diagrams. For example illustrating exemplary methods and/or apparatus (systems) and/or and computer program products according to embodiments of the present disclosure. It will be understood that each step of the flowchart illustrations and/or block of the block diagrams, and/or combinations of steps in the flowchart illustrations and/or blocks in the block diagrams, can be implemented by computer program instructions. These computer program instructions may be provided to a processor of a general-purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart steps and/or block diagram block or blocks.

These computer program instructions may also be stored in a computer readable medium that can direct a computer (e.g., in a memory, local and/or hosted at the cloud), other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the computer readable medium can be used to produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

The computer program instructions may also be run by one or more computational device to cause a series of operational steps to be performed e.g., on the computational device, other programmable apparatus and/or other devices to produce a computer implemented process such that the instructions which execute provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

Some of the methods described herein are generally designed only for use by a computer, and may not be feasible and/or practical for performing purely manually, by a human expert. A human expert who wanted to manually perform similar tasks, might be expected to use different methods, e.g., making use of expert knowledge and/or the pattern recognition capabilities of the human brain, potentially more efficient than manually going through the steps of the methods described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

FIG. 1 is a simplified schematic of a power supply system configured to drive an electrical motor, according to some embodiments of the disclosure;

FIG. 2A is a method of starting and powering a hybrid permanent-magnet motor, according to some embodiments of the disclosure;

FIG. 2B is a simplified schematic top view of a hybrid permanent-magnet motor, according to some embodiments of the disclosure;

FIG. 2C is a simplified schematic view of a hybrid permanent-magnet motor rotor, according to some embodiments of the disclosure;

FIG. 3 is a method of operating a hybrid motor system, according to some embodiments of the disclosure;

FIGs. 4A-E are a series simplified schematics illustrating transitioning of power supply to a load from through a variable frequency drive (VFD) to through a bypass module, according to some embodiments of the disclosure;

FIG. 4F is a method of transitioning power supply to a load from through a VFD to through a bypass module, according to some embodiments of the disclosure;

FIGs. 5A-E are a series of simplified schematics illustrating transition from power supply to a load through a bypass module to through a variable frequency drive (VFD) according to some embodiments of the disclosure;

FIG. 6 is a method of transitioning power supply to a load from through a bypass module to through a VFD, according to some embodiments of the disclosure;

FIGs. 7A-B are flow charts of a detailed power supply method, according to some embodiments of the disclosure;

FIGs. 8A-B are simplified schematics of a power supply system, according to some embodiments of the disclosure;

FIG. 9 is a plot of supply voltage with angle, for a three phase power supply, according to some embodiments of the disclosure;

FIG. 10 is a diagram illustrating inverter input and output states, according to some embodiments of the disclosure;

FIGs. 11A-D are simplified schematics illustrating voltages for exemplary system states, according to some embodiments of the disclosure;

FIG. 12 is a plot of supply current and voltage to a load, with time, according to some embodiments of the disclosure;

FIGs. 13A-C are simplified schematics illustrating voltages for exemplary system states, according to some embodiments of the disclosure;

FIGs. 14-17 are simplified schematic top views of exemplary hybrid permanent-magnet motors, according to some embodiments of the disclosure;

FIG. 18 is a simplified schematic top view of a synchronous operation motor, according to some embodiments of the disclosure;

FIG. 19 is a simplified schematic top view of a synchronous operation motor, according to some embodiments of the disclosure;

FIGs 20A-C are views of an exemplary implementation of a rotor, according to some embodiments of the disclosure;

FIG. 21 illustrates motor measurements acquired during motor startup, according to some embodiments of the disclosure; and

FIG. 22 illustrates motor measurements acquired during a gradual motor stop, according to some embodiments of the disclosure.

In some embodiments, although non-limiting, in different figures, like numerals are used to refer to like elements, for example, element **152** in FIG. 1 corresponding to element **252** in FIG. 2B.

DETAILED DESCRIPTION OF EMBODIMENTS

The present disclosure, in some embodiments, thereof relates to a motor system including a permanent magnet rotor and, more particularly, but not exclusively, to a system where the stator is configured to receive multiphase electrical power from either an inverter or an electrical grid.

Overview

An aspect of some embodiments of the disclosure relates to a motor system including a rotor designed for synchronous operation (e.g., having permanent magnets) and having an induction structure (also herein termed “induction cage” and “damper cage”), and where a stator of the rotor is configured to receive multiphase electrical power from either an inverter or an electrical grid. In some embodiments, the rotor is accelerated (e.g., from stationary) by a controlled-frequency power supply delivered to the stator via the inverter. Commutation from inverter supply to direct grid supply is then performed gradually such that at least one phase of electrical power remains continuously supplied to the motor during the transition. The combination of features including the synchronous operation-type rotor (e.g., rotor using permanent magnets), the induction structure, inverter-assisted startup, and gradual commutation potentially provides highly efficient and/or stable motor operation.

The synchronous rotor is configured to rotate at substantially the same mechanical speed as a rotating magnetic field produced by the stator during steady-state operation. The rotor includes a field-producing structure such as permanent magnets and/or a wound excitation assembly adapted to magnetically lock the rotor to the stator’s rotating field to provide slip-free operation under normal load.

In some embodiments, the synchronous rotor may be implemented as a permanent-magnet rotor, a wound-field rotor, a reluctance-type rotor, or a hybrid rotor, where the rotor is configured to operate with minimal slip by remaining magnetically locked to the rotating stator field during steady-state operation.

A permanent-magnet rotor includes magnets arranged to produce a fixed magnetic field. A wound-field rotor includes excitation windings that receive direct current to generate an electromagnetic field. A reluctance-type rotor includes saliencies or flux barriers that develop torque through magnetic-reluctance alignment. A hybrid rotor combines two or more of these field-producing structures.

Although, generally, within this document, description is of permanent magnet rotors, it should be understood that the methods and system described may be employed with other synchronous rotor types.

In some embodiments, the rotor includes permanent magnets and one or more flux barrier located between the permanent magnets. The flux barriers may be provided by the induction structure which is formed, in some embodiments, from an electrically conducting but non-magnetic material (e.g., copper).

The induction structure, although not required for startup when an inverter is used nor is required for steady state synchronous operation when torque is provided by permanent magnets provides damping. For example, damping associated with torque asynchronism between a rotating magnetic field generated by the stator and a rotor magnetic field (e.g., of rotor permanent magnets) where the induction structure produces currents opposing the asynchronism. A potential benefit being reduction of torque oscillations and/or preventing speed oscillations (hunting) e.g., during rotor acceleration and/or under transients e.g., load transients.

Induction structure damping together with gradual commutation (power supply is maintained to the rotor) potentially provide smooth and low-loss transfer commutation from inverter to grid operation.

In some embodiments, the inverter supplies variable-frequency and variable-voltage power to the stator to gradually provide startup acceleration. During startup the rotor is accelerated from stationary or below synchronous speed to synchronous speed (synchronous speed defined as the speed at which the rotor rotates at the same electrical frequency as the stator rotating field). Currents may be induced in conductive loop/s of the induction structure due to relative motion between the stator's rotating magnetic field and the rotor, resulting in an induced magnetic field, the interaction of the induced magnetic field interacting with the stator field to provide torque that dampens torque oscillations.

Gradual acceleration of the rotor potentially eases maintaining synchronism between the rotating magnetic field generated by the stator and the rotor magnetic field of the rotor permanent magnets. This may result in lack of (or low) braking torque generated by the permanent magnets and/or lack of (or low) induced current losses both of which are associated with lack of synchronization between the rotor and stator magnetic fields. Gradual acceleration may be associated with low mechanical stresses on parts during startup.

Once the rotor reaches synchronous speed, that is, when the rotor's mechanical rotation frequency equals the electrical frequency of the stator's rotating magnetic field and the motor voltages match the supply grid voltages and frequency, the stator power supply may be transferred to the grid (e.g., via a bypass module). In some embodiments, the transfer is gradual where operation is progressively transferred from inverter supply to grid supply. This commutation process may be performed in a closed-transition mode, in which electrical supply to the motor load is continuously maintained. During at least part of the transition, both the inverter and the grid may supply the motor simultaneously. In some embodiments, the same stator phase is supplied in parallel by both the inverter and the grid to maintain phase continuity. In other embodiments, one or more stator phases are supplied by the inverter while one or more other phases are supplied directly by the grid. This gradual commutation potentially prevents one or more of current surges, torque discontinuities, or transient desynchronization that could otherwise occur during abrupt or open-transition switching.

At synchronous speed torque is produced primarily by the interaction between the grid-supplied stator field and the rotor's permanent magnetic field. Efficiency during this synchronous operation benefits from the absence of inverter-switching and conduction losses, since the inverter is bypassed, and from rotor losses, since the magnetic field is mainly provided by the permanent magnets rather than induced current. During grid-powered synchronous operation, the induction structure continues to provide damping torque in response to perturbations such as load fluctuations, grid transients, or minor speed deviations, thereby suppressing oscillatory behavior and/or maintaining stable synchronism.

The described system potentially combines the efficiency and torque density of a synchronous motor (e.g., a permanent-magnet synchronous motor) with stability typically provided by an induction machine directly connected to the grid. In comparison to conventional line-start permanent-magnet motors, which can experience difficulty achieving stable synchronization, for example, difficulty with synchronizing if the magnets are too strong and provide too high braking torque, or suffering high inrush current and torque pulsations, the disclosed system achieves synchronization smoothly and/or predictably through controlled inverter operation. Use of an inverter during startup also allows the induction structure to be smaller and lighter than that of a line starting permanent magnet synchronous motor, potentially improving overall system efficiency.

In some embodiments, the motor, when operating in steady state and connected directly to the grid has a power factor near unity e.g., above 0.9.

In some embodiments, the rotor is used to retrofit an existing induction motor rotor and/or configured to be used with an existing induction motor stator. For example, where an existing system may be updated or retrofitted by incorporating a rotor according to embodiments of this disclosure, the stator is connected to both an inverter and the grid where the inverter has been configured to operate according to embodiments of this disclosure.

A broad aspect of some embodiments of the disclosure relates to commutation strategies having gradual transitions between supply of a three phase electrical power supply (e.g., grid supply e.g., supplied through a bypass module) to a three phased load (e.g., motor including three coils, each coil corresponding to a phase) and a variable frequency three phase electrical power supply, also herein termed “variable frequency drive” and “inverter”. Where, during the transition, electrical supply to the load is maintained.

In some embodiments, one or more portions of the transition may be a “closed transition” where both the bypass module and the inverter are supplying the load in parallel. In some embodiments, parallel supply may be for a same phase of the three phase supply. In some embodiments, parallel supply may be where the inverter and bypass module are both supplying different phases to the load, at the same time. This may contrast with “open transition”, also termed “dead-time” transition techniques, where both the inverter and grid supplies (e.g., for all phases thereof) may be disconnected when transitioning therebetween.

In some embodiments, a controller controls the delivery of power to the load, by controlling the activation and deactivation of electrical pathways through the inverter and through the bypass module. Where, in some embodiments, control is via switches (e.g., including transistors) which receive control signals from the controller. In some embodiments, the control signals include voltages applied to gates of the transistors. Where, for example, an activating gate signal may allow and/or establish a current channel through the transistor switch and a deactivating gate signal may deplete and/or block a current channel through the transistor switch. Where switches are turned on or closed to activate a pathway, and turned off or opened to deactivate a pathway. For ease of description, reference will be hereinbelow to “activated”, and “deactivated” switches.

In some embodiments, timing of activation and deactivation of electrical pathways during the transition is based on polarities of the different phases of the electrical voltages and currents, where activation and deactivation of pathways and timing thereof is selected to supply power to the load continuously, but without producing short-circuit/s.

An aspect of some embodiments of the disclosure relates to transitioning between supplying a load via the inverter and supplying a load via the bypass module, where during the transition, power supply to the load is maintained e.g., through at least one electrical pathway of the inverter or bypass module.

In some embodiments, the inverter includes a switching unit receiving outputs of a rectifier connected to the three phase power supply, where the inverter has a switching leg corresponding to each phase of the three phased load. In some embodiments, the controller controls the legs of the switching module to selectively deliver positive and negative voltages (and currents) to phases of the three phase load to generate a load voltage vector.

In some embodiments, the transition occurs where at least one bypass module electrical pathway is activated while the inverter continues for example, for a short period of time (e.g., for 0.1-**1000**μs) to provide power to the load through all three legs of the inverter. In this situation, a phase of the bypass module and a corresponding phase of the inverter are activated at the same time, where, in some embodiments, a duration of this parallel supply may be of up to **120** degrees e.g., about 6.67ms (for 50Hz supply). In some embodiments, timing of activation of the bypass module electrical pathway/s and/or which phase pathways are activated is based on the power supply phase state e.g., to avoid short circuits. Where, a short circuit may occur when a leg of the inverter is delivering a polarity of voltage to a phase of the load and the bypass module is delivering a different polarity voltage supply to the phase of the load.

An aspect of some embodiments of the disclosure relates to transitioning from driving the load through the inverter to driving the load with the grid supply (e.g., through the bypass module) where, while the inverter (e.g., at least one leg thereof) is still supplying power to the load, one or two phases of the grid power supply are delivered to the load (e.g., through the bypass module).

In some embodiments, only after connecting the one or two phases of the grid power supply are the corresponding phase/s of the inverter disconnected. A potential advantage being reduction in time for which the load is not powered for all phases. Where, in some embodiments, a delay between connecting the grid power supply and deactivating inverter phase pathways is of short duration.

In some embodiments, disconnection of corresponding phase/s of the inverter is at the same time as (or preceding) activation of phase pathway/s of the grid power supply e.g., through the bypass module. A potential advantage being prevention of short-circuit/s through the inverter.

Then, in some embodiments, the third and final phase is connected e.g., following a same procedure where the third phase of the grid supply is connected and then the third phase of the inverter is disconnected. Timing of stages of the process and/or selection of phases in the process may be based on the identified stage within the three phase grid power supply. In some embodiments, inverter leg disconnection occurs during a same voltage input sector as that in which the corresponding bypass phase is activated. Where voltage input sectors are each a sixth of a full grid power supply cycle (e.g., where the power supply oscillates at 50Hz, a sector has 3.3ms duration) where each sector corresponds to two phases being, for the entire sector, different polarity.

In some embodiments transitioning from driving the load through the grid (e.g., via the bypass module) to driving the load with the inverter is performed according to a reverse procedure as that described regarding inverter to grid transition. For example, where two phases may be activated and deactivated at once. For example, in embodiments, where the bypass module includes MOSFET and/or IGBT transistors.

An aspect of some embodiments of the disclosure relates to transitioning from grid supply driving of a load (e.g., through a bypass module) to driving the load through an inverter, where, a phase of the inverter is connected, while the grid is still supplying power to the load via one or more electrical pathways through the bypass module (e.g., through pathway/s of the bypass module associated with phases other than the phase for which the inverter has been connected).

In some embodiments, (e.g., associated with a type of switch used in the bypass module e.g., when the bypass module includes thyristor switches) control signals are timed so that a bypass module electrical pathway corresponding to a phase is disconnected prior to connection of a corresponding pathway of the inverter.

For example, in some embodiments, timing of control signals for switches take into account a delay between opening/closing of a switch and the switch receiving a control signal instructing the opening/closing. For example, where the bypass module includes thyristors, which deactivate only after the thyristor has received a control signal (e.g., at the thyristor gate) instructing the thyristor switch to deactivate <u>and</u> current through the thyristor has dropped to zero (or below a threshold value).

In embodiments where bypass switching is sufficiently rapid (e.g., a bypass electrical pathway is disabled within a single sector of the grid power supply), transition between the bypass to the inverter, in some embodiments, mirrors that as described hereinabove regarding transition from inverter to grid. For example, where one or two phases of the inverter are activated, and then the corresponding phases of the bypass module are deactivated e.g., after the activation of the inverter phase/s. Followed by the remaining one or two inverter phases being activated and corresponding phase/s of the bypass module being deactivated.

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not necessarily limited in its application to the details of construction and the arrangement of the components and/or methods set forth in the following description and/or illustrated in the drawings and/or the Examples. The invention is capable of other embodiments or of being practiced or carried out in various ways.

Exemplary System

FIG. 1 is a simplified schematic of a power supply system **100** configured to drive an electrical motor **106**, according to some embodiments of the disclosure.

In some embodiments, power supply system **100** includes a multi-phase power source, for example a fixed-frequency power supply (FFPS) **112**, also herein termed a “grid supply” or simply “grid.” In some embodiments, power from grid supply **112** is delivered to motor **106** through a plurality of electrical routes controlled by a controller **102**.

In some embodiments, the plurality of routes include grid power passing to motor **106** (also herein termed “motor”) through a first module **108** which controls characteristics of the power supply delivered to motor **106**. First module **108** (also herein termed “inverter” and “variable-frequency drive” (VFD)), in some embodiments, includes an inverter. Inverter **108** may include switching circuitry controlled by controller **102** and configured to generate variable frequency outputs. Inverter **108**, in some embodiments, is a switched mode variable frequency power supply receiving three phase power from grid supply **112**.

In some embodiments, the plurality of routes include routes transferring grid power “directly” (e.g., without frequency changes) to motor **106** through a second module **110** also herein termed “bypass module”. Bypass module **110** may include a plurality of switches controlled by controller **102**.

Optionally, in some embodiments, power supply system **100** further includes a relay module **128**, the plurality of routes including routes from the power supply through relay module **128** to motor **106**. Relay module **128** may include one or more high-power relay switches or contactors for each phase of the power supply.

In some embodiments, controller **102** controls switching elements of inverter **108**, bypass module **110**, and/or relay module **128** to control which power pathways to motor **106** are active.

In some embodiments, inverter **108** is configured to provide controlled-frequency, three phase power to motor **106** for start-up and acceleration. Where, when motor **106** reaches near-synchronous speed, controller **102** may activate electrical pathways through bypass module **110**, and deactivate inverter **108** coupling motor **106** directly to grid supply **112**. The commutation e.g., as described elsewhere in this document.

In some embodiments, motor **106** includes a stator **152** having a stator bore **166**, and a rotor **158**, the rotor disposed within stator bore **166**.

Stator **152** may include stator windings **160** configured to receive three phase power and generate a rotating magnetic field (RMF) within stator bore **166**.

Rotor **158** may include permanent magnets **154** which provide a constant flux. Rotor **158** may include flux barriers **156** e.g., located at and/or between ends of permanent magnets **154**. In some embodiments, rotor **158** includes conductive elements **156**, also herein termed "conductors" and "rotor conductors" (e.g., conductors **256** FIGs. 2B-C) which form an induction structure (e.g., an induction cage). In an exemplary embodiment, conductive elements **156** are configured to act as flux barriers **156** e.g., are positioned at and/or between ends of the permanent magnets and/or are formed of non-magnetic material.

In some embodiments, one or more current or voltage sensors (not shown in FIG. 1) provide measurements to controller **102** e.g., enabling verification of activation and/or deactivation of electrical pathways and/or to enable monitoring of motor performance.

In some embodiments, one or more of controller **102**, inverter **108**, and bypass module **110** are housed together e.g., within a common enclosure. Optionally, relay module **128** may be hosted in the same housing.

Exemplary Method

FIG. 2A is a method of starting and powering a hybrid permanent-magnet motor, according to some embodiments of the disclosure.

At **201**, in some embodiments, a first module comprising an inverter (e.g., inverter **108** FIG. 1) is activated to supply controlled-frequency, three phase power to a load, for example, to stator windings (e.g., windings **160** FIG. 1 e.g., windings **260** FIG. 2B) of a motor (e.g., motor **106** FIG. 1, e.g., motor **206** FIG. 2B), the rotor including permanent magnets and conductive elements. Where the rotor may initially be stationary (not rotating).

At **203**, in some embodiments, the inverter gradually increases the supply frequency and voltage in a controlled manner (e.g., the inverter is controlled by a controller to follow a predetermined (e.g., fixed) voltage-to-frequency (V/f) profile). Inverter control of supplied voltage and frequency potentially maintains synchronization between the stator rotating magnetic field and the magnetic field of the rotor permanent magnets. This potentially prevents development of permanent magnet braking torque opposing the acceleration of the rotor which would be induced when the stator and rotor permanent magnetic fields are not synchronized.

During this time, as slip between the stator rotating field and the permanent magnet fields may be nominal, with at most nominal currents being induced in the conductors of the induction cage However, should slip increase (e.g., transients, power surges etc.) currents may be induced in the induction cage to produce “damping” torque which tends to oppose the slip, thereby acting in a direction that restores synchronism between the stator and rotor fields.

At **205**, in some embodiments, once a speed associated with the grid frequency is achieved, a first electrical pathway through a second module comprising a bypass coupled to an AC line supply is activated while at least one inverter pathway remains active, and the corresponding inverter pathway is deactivated.

At **207**, in some embodiments, activation and deactivation are repeated for remaining phases so that the motor is powered through the bypass module directly from the AC line, the inverter deactivated or placed in standby.

At **209**, in some embodiments, the induction cage may act as a damper maintaining synchronization e.g., during transients and/or load changes and/or power supply fluctuations. Where the induction cage potentially acts as a self-stabilizing, damping mechanism that resists relative motion between the stator field and rotor magnets.

Exemplary Rotors

FIG. 2B is a simplified schematic top view of a hybrid permanent-magnet motor **206**, according to some embodiments of the disclosure.

FIG. 2C is a simplified schematic view of a hybrid permanent-magnet motor rotor **258**, according to some embodiments of the disclosure.

In some embodiments, an electrical motor **206** includes a stator **252** having a stator bore **266** and a rotor **258** configured (e.g., sized and/or shaped) to occupy bore **266**. Rotor **258** may be coupled to (for example connected to, e.g., mounted on) a shaft **262**.

In some embodiments, rotor **258** includes a plurality of permanent magnets **254** which may be distributed around a central longitudinal axis and/or axis of rotation of the rotor and/or shaft e.g., distributed evenly. The number of permanent magnets **254** may, for example, correspond to a number of magnetic poles of the motor. In various embodiments, the rotor may include two, four, six, eight, or more permanent magnets arranged circumferentially about the rotor axis of rotation. In certain embodiments, the magnets may be positioned in pairs of opposite polarity to form alternating north and south poles around the rotor e.g., around the rotor periphery.

Permanent magnets **254** may extend along a body of rotor **258** e.g., partially or along an entire length of the body. Permanent magnets **254** may have uniform size and/or geometry and/or be formed from the same materials.

In some embodiments, magnets **254** are elongate elements where a central longitudinal **272** axis of a magnet may be skewed with respect to the rotor central longitudinal axis **270** and/or axis **270** of rotation. For example, by a magnet skew angle θ. Where magnets **254** may each be orientated with about the same skew angle. In some embodiments, magnets **254** have an elongate cross section e.g., are bar magnets. Skewing the permanent magnets and/or the conductors of the induction structure causes the magnetic forces from different rotor sections to act slightly out of phase, so torque pulsations partially cancel. In some embodiments, skewing is provided in the coils/windings of the stator e.g., and not the rotor, or where skewing in the rotor is minimal. A potential advantage being ease of manufacture of the rotor without skewing.

In some embodiments, rotor **258** includes electrical conductors **256** which form an induction structure. The induction structure includes at least one closed conductive loop positioned on and/or within the rotor to couple the air-gap flux (the magnetic field crossing the air gap passes through the conductive loop/s, inducing current in the loop).

In some embodiments, rotor conductors **256** are arranged to provide closed current paths, such that when the rotating magnetic field of the stator sweeps past the rotor, a time-varying magnetic flux links the conductors and induces circulating currents within these closed loops, the interaction of the induced currents with the stator magnetic field producing electromagnetic forces and torque on the rotor.

The loop/s may include any closed conductive structure including longitudinally extending (along the rotor body and/or parallel to the rotor axis of rotation) conductors. For example, two longitudinally extending structures bridged at both axial ends by conductive end pieces. For example, peripheral conductive ring structure attached to and/or embedded near the rotor surface.

In an exemplary embodiment, the loops are provided by a plurality of conductive elements **256** which extend through the rotor body and are electrically connected together by end structures **267**, **268**. The end structures, in an exemplary embodiment, formed by conductive plates (which could be replaced by conductive rings). Conductors **256** may be electrically insulated from the rotor body e.g., to prevent induced currents in the conductors from circulating in the rotor body.

In an exemplary embodiment, conductors **256** extend along (e.g., partially or along an entire length of) the rotor body, and/or may have uniform size and/or geometry and/or be formed from the same material and/or may be orientated with a conductor skew angle, which may be aligned with (e.g., within 1-5° of) magnet skew angle θ. In an exemplary embodiment, conductors **256** are electrically (and optionally mechanically) connected by conducting elements **267**, **268** at either end of rotor **258** e.g., to form a closed electrical circuit.

In an exemplary embodiment conductors **256** are connected to end structures **267**, **268** mechanically (e.g., by hammering and/or riveting and/or peening) a potential advantage of which is to prevent demagnetization of the permanent magnets (associated with heat-based connecting techniques such as soldering).

In some embodiments, rotor **258** includes non-magnetic flux barriers which are configured to interrupt a magnetic path between adjacent ends of permanent magnets **254**.

In some embodiments, adjacent (e.g., circumferentially adjacent) ends of two or more magnets **245** are circumferentially separated by non-magnetic flux barriers. The non-magnetic material of the flux barriers impedes magnetic flux leakage across the rotor surface, to concentrate magnetic flux within the intended magnet-stator air-gap path and/or impeding magnetic flux leakage e.g., to increases torque per ampere provided by permanent magnets **254**.

In some embodiments, a flux barrier is positioned between a north pole of a first magnet and a south pole of a second magnet, the flux barrier preventing flux from passing directly between these poles to force the flux to pass through the air gap between rotor **258** and stator **252**. In some embodiments, flux barriers **256** extend between an entire length of a pole of at least one magnet e.g., extending along a length of the stator body.

In some embodiments, conductors **256** of the induction structure have a dual function and also act as flux barriers. For example, in some embodiments, conductors **256** are formed of non-magnetic material (e.g., copper, aluminum) and are positioned in between ends of the magnets to function as flux barriers. In an exemplary embodiment conductors **256** are formed of copper. In some embodiments, rotor **258** includes flux barriers in addition to conductors **256** (which may be placed elsewhere on the rotor), e.g., the flux barriers provided by air gaps.

In some embodiments magnets **254** and/or conductors **256** and/or flux barriers are disposed within hollow slots in the rotor body. Each slot may be sized and/or shaped to host one or more magnet **254** and provide one or more flux barrier. In some embodiments, the slots are sized and/or shaped to house and/or orient magnets **254** at desired positions and/or orientations with respect to the rotor body.

In an exemplary embodiment the rotor body is formed from laminations (e.g., steel laminations) which may be stacked together. The laminations may be arranged on a shaft **262**. The laminations may be separated by electrically insulating material (e.g., to prevent eddy currents in the rotor body) for example, in some embodiments the laminations are adhered together by insulating material e.g., by epoxy. Where laminations are adhered together the stack may be compressed, a potential advantage of which is increased mechanical integrity and/or dimensional precision of the stack. Each lamination may have a same slot pattern, skew for slots provided by rotating successive laminations with respect to each other e.g., prior to connection thereof.

In some embodiments, stator **252** includes a plurality of stator coils **260** configured to generate a rotating magnetic field when energized. Stator **252** may include a plurality of circumferentially spaced slots for receiving stator coils **260**. Coils **260** may be connected to one or more power source in a three phase configuration (e.g., three phase outputs of an inverter, three phases of grid supply). Coils **260** may be wound with insulated copper wire. When alternating current is supplied to coils **260**, a rotating magnetic field is produced within an air gap in bore **266** located between stator bore walls and rotor **258**.

Exemplary Detailed Method

FIG. 3 is a method of operating a hybrid motor system, according to some embodiments of the disclosure.

At **301**, a permanent magnetic field (PMF) generated by rotor-mounted permanent magnets (e.g., magnets **254** FIGs. 2B-C) provides a constant flux. Without power being supplied to the stator coils and if the rotor is stationary, slip is 100%.

At **303**, in some embodiments, stator coils (e.g., coils **260** FIG. 2B) are powered by a three phase output of an inverter (e.g., inverter **108** FIG. 1). Where three electrical inverter pathways connected to three sets of stator coils are activated. The three phase power received by the stator coils induces a rotating magnetic field in the stator bore.

At **305**, in some embodiments, the rotating magnetic field interacts with the permanent magnet magnetic field (PMMF) to produce torque which acts to accelerate the rotor.

At **307**, in some embodiments, the inverter is controlled to change the frequency of power supplied to the stator coils. For example, according to a V/f control scheme. For example, the inverter is controlled to gradually ramp output voltage and frequency from zero to the synchronous operating frequency.

At **309**, the rotor approaches a speed associated with grid operation (rotational speed at which the rotor turns at the same angular velocity as the rotating magnetic field produced by the stator when the stator supplied with power at the grid frequency). At this stage, the motor can be efficiently driven directly from the main AC supply without requiring inverter control.

Accordingly, at **311**, in some embodiments, a first electrical pathway through a second module (e.g., a bypass module directly coupled to the AC power supply) is activated, while at least one electrical pathway of the inverter (the first module) remains active.

At **313**, in some embodiments, the corresponding electrical pathway through the first module (the inverter) is deactivated.

At **315**, in some embodiments, steps **311-313** are repeated for the second and third phases, thereby transferring all three stator phases from inverter supply to grid supply.

At **317**, the load is powered by the second module, receiving three phase power through the three activated electrical pathways of the bypass module. The inverter may then be isolated or placed in standby e.g., until the next start-up cycle.

At **319**, during commutation and/or steady operation the induction cage generates torque tending to oppose slip. The induction cage potentially dampens the effects of power oscillations associated with commutation and/or the effects of load changes and/or transients and/or power supply variation. The damping may suppress oscillations (e.g., hunting oscillations).

Exemplary Commutation

FIGs. 4A-E are a series simplified schematics illustrating transitioning of power supply to a load **306** from through a variable frequency drive (VFD) **308** to through a bypass module **310**, according to some embodiments of the disclosure.

FIG. 4F is a method of transitioning power supply to a load from through a VFD to through a bypass module, according to some embodiments of the disclosure.

At **400**, and, for example, illustrated by FIG. 4A, power is supplied to a load through an inverter where, for example, a bypass module is disabled.

At **402**, and, for example, illustrated by FIG. 4B, based on a time point in the three phases of a grid supply **312**, two phases of grid supply are connected (as indicated by solid lines) through bypass module **310** where inverter **308** remains connected, for all three phases. Where connection of phases is also herein termed "activation of electrical pathways".

In some embodiments, the time point in the three phases and/or the two phases are selected (e.g., by a controller e.g., controller **102** FIG. 1, controller **802** FIG. 8B) based on signal/s received by the controller for example, from power supply sensing circuitry.

At **404**, and, for example, illustrated by FIG. 4C, in some embodiments, the corresponding inverter pathways to those activated for bypass module **310** at step **402** are deactivated. In some embodiments, step **404** occurs prior to or concurrent with step **402**.

At **406**, and, for example, illustrated by FIG. 4D, in some embodiments, based a time point in the three phases of grid supply **312**, a third and final pathway through bypass module **310** is activated, e.g., optionally, where the third pathway through inverter **308** remains active.

At **408**, and, for example, illustrated by FIG. 4E, in some embodiments, the third and final path through inverter **308** is deactivated. In some embodiments, step **408** occurs prior to or concurrent with step **406**.

At **410**, (e.g., illustrated in FIG. 4E) the transition is now complete, and power is supplied to load **306** only through bypass module **310** and not through inverter **308**.

In some embodiments, alternatively to activating and deactivating pathways for two phases of the power supply, then activating and deactivating pathways for the remaining phase, in some embodiments, a pathways for a single phase are activated (step **402**) and deactivated (step **404**). Where, subsequently, pathways for the two remaining phases are then activated (step **406**) and deactivated (step **408**).

The method of FIG. 4F illustrates exemplary embodiments, where pathways for two phases are activated through bypass module **310** at once. However, embodiments where a pathway for a single phase is activated at a time, for example, there being a delay between activation of each pathway (and deactivation of a corresponding inverter pathway) through bypass **310** are envisioned and encompassed.

FIGs. 5A-E are a series of simplified schematics illustrating the transition from power supply **512** to a load **506** through a bypass module **510** to through a variable frequency drive (VFD) **508** according to some embodiments of the disclosure.

FIG. 6 is a method of transitioning power supply to a load from through a bypass module to through a VFD, according to some embodiments of the disclosure.

At **600**, and, for example, illustrated by FIG. 5A, power is supplied to a load through a bypass module where, for example, a VFD is disabled (e.g., each electrical power supply pathway through VFD is disabled).

At **602**, and, for example, illustrated by FIG. 5B, based on a time point in the three phases of grid supply **512**, a single phase of bypass module **510** is deactivated. Where other phases of bypass module **510** remain activated.

At **604**, and, for example, illustrated by FIG. 5C, based on a time point in the three phases of grid supply **512**, a corresponding phase of VFD **508** to that deactivated in bypass module **510** at step **602** is activated.

At **606**, and, for example, based on a time point in the three phases of the grid supply, steps **602** and **604** are repeated for the other two phases. Where, in some embodiments, FIG. 5D illustrates the system after step **606** has been performed.

At **608**, and, for example, illustrated by FIG. 5E, power supply to load **506** is through VFD **506**, where all of pathways through bypass module **510** are deactivated.

FIGs. 5A-E and FIG. 6 correspond to embodiments where (e.g., associated with deactivation characteristics of thyristor switch/es of a bypass module) deactivation of bypass phase pathways and corresponding activation of inverter phase pathways is one at a time. However, in some embodiments, (e.g., where the bypass module includes transistors which deactivate more rapidly than thyristors e.g., includes IGBTs and/or BJTs and/or MOSFETs) deactivation of bypass phase pathways and corresponding activation of inverter phase pathways may be performed for two phases at once e.g., corresponding to a reverse of the procedure described regarding FIGs. 4A-E and/or FIG. 4F.

FIGs. 7A-B are flow charts of a detailed power supply method, according to some embodiments of the disclosure.

Referring to FIG. 7A, at **700**, in some embodiments, initially, a load e.g., a motor is stationary and/or is not receiving electrical power. Although other types of load are envisioned and encompassed by this disclosure, discussion herein below will be with respect to a motor, and power supply to motor coils.

At **701**, according to some embodiments, switching of transistors of an inverter (e.g., of switching module **820** FIGs. 8A-B) is controlled to supply a variable magnitude and variable frequency voltage to the motor. For example, to accelerate the motor (e.g., rotation of the motor rotor) with controlled current.

In some embodiments, switching of the transistors controllably delivers positive or negative voltage to coils of the motor, where the polarity and duration of pulses delivered to coils is controlled to provide a selected frequency power supply to the coils. In some embodiments, the supply received at the motor coils provides a rotating magnetic field (e.g., to drive rotational of the motor). Where, in some embodiments, the frequency of the rotating magnetic field is related to speed at which rotor/s of the motor rotate.

In some embodiments, control of pulses delivered is according to a Pulse Width Modulation (PWM) scheme e.g., Space Vector Modulation (SVM), Sinusoidal Pulse Width Modulation (SPWM) with optional 3rd harmonic injection/compensation.

In some embodiments, third harmonic injection is provided by measuring the voltage level at the effective ground (the effective ground also herein termed “DC link voltage mid-point”) at the inverter input at node **854** (or deriving the effective ground voltage level from measured supply voltages). Where control signals generated by the inverter controller (e.g., duty cycles of the PWM) are adjusted (e.g., the adjustment being “feed-forward compensation”) to compensate for fluctuation (e.g., at triple the grid frequency, hence “third harmonic”) in the effective ground level at the DC link (at node **854**).

Alternatively, in some embodiments, third harmonic compensation, in some embodiments, is provided by hardware. Where, for example, a neutral cable connection (e.g., a connection between node **854** and node **856** FIG. 8A), where supply to the inverter as provided to by the DC link is grounded via the neutral cable e.g., potentially boosting the DC link voltage.

In some embodiments, switching of the transistors is controlled to provide power supply to the motor having increasing frequency e.g., to accelerate the motor to a speed compatible with the grid power supply frequency. In some embodiments, frequency for driving the motor (e.g., ramping up of speed of the motor) is using V/f control e.g., open loop V/f control. Where control of the frequency is employed to maintain a constant ratio between the motor voltage (which is for example, measured the measurements supplied to a controller e.g., measured by load supply sensing circuitry) and frequency e.g., to provide constant (or low variation in) motor flux. A potential benefit of low variation in motor flux is reduced motor inrush current during start-up, which may affect the power supply and e.g., other device/s connected to the same power supply.

In some embodiments, for example, alternatively or additionally to employing V/f based control, closed loop vector control (e.g., closed loop sensor-less vector control) is employed. Where, closed loop vector control, in some embodiments, includes using machine back-EMF (e.g., using voltage measurements) or magnetic rotor saliency to estimate rotor flux angle and e.g., therefrom estimating motor rotor position. The motor current may be controlled so that rotor flux and motor current phasors intersect at a selected angle (e.g., 90 degrees). A potential benefit of which is that motor torque may be maximized with minimal inrush current to the motor.

In an exemplary embodiment, both V/f control and closed loop vector control are employed. Where, for an initial part of the acceleration of the motor, V/f control is employed, and then for the higher frequency portion of the acceleration sensor-less vector control is employed. Where, for example, acceleration from 0Hz-5Hz is implemented using V/f control and from 5Hz-grid frequency up to e.g., 50Hz, is sensor-less vector control. Where, a maximal acceleration may be achieved within 2 seconds at full power, e.g., if such accelerations are desired.

In an exemplary embodiment, closed loop vector control of the inverter provides an initial frequency of 1-3Hz, or about 5Hz, or lower or higher or intermediate ranges, or frequencies, and is ramped up to grid frequency (e.g., about 50Hz or about 60Hz) in 1--20s, or 1-15s, or about 10s, or within lower, or higher, or intermediate times, or ranges.

In some embodiments, once the frequency of the load voltages and currents supplied by the inverter is the same as (or sufficiently close to e.g., within 10mHz of) the grid frequency is reached, the phase of the inverter output is aligned to that of the grid. For example, by increasing and/or decreasing the inverter frequency. Where, in some embodiments, deviation of the inverter output frequency is maintained to within a threshold deviation of the grid frequency. Where, in an exemplary embodiment, a maximal allowed deviation is about **200**mHz. In some embodiments, once the phase is synchronized, the inverter frequency is returned to the grid frequency. In some embodiments, phase matching is an iterative process where the inverter frequency is adjusted a plurality of times. In some embodiments, one or more phase locked loop (PLL) is used to track the phase of the inverter output voltage vector and/or grid voltage vectors where the phase error between the two voltage vectors is driven towards 0 e.g., using an integral controller.

At **702**, in some embodiments, feature/s of motor and/or inverter operation are verified. For example, verification is that the inverter generated output voltage vector matches the power supply input voltage vector. In some embodiment, e.g., prior to or as part of verifying, a time delay is introduced e.g., to allow transients (e.g., torque transients) to decay. A potential benefit being smoother transition.

At **703**, optionally, once synchronized, the inverter output is locked to the grid vector e.g., and will not lose synchronism, e.g., unless the inverter speed is reduced. In some embodiments, synchronism of the inverter output with the grid vector is maintained during supply via the grid, for example, potentially enabling transition from the grid to the inverter e.g., without re-synchronization step/s.

In some embodiments, an inverter locking procedure includes deriving a suitable inverter output voltage vector e.g., from the phase of the grid voltage vector directly. Where, in some embodiments, deriving of the inverter output voltage vector takes into account phase delays associated with measurement of the grid voltage vector and/or delay/s (e.g., digital delay) associated with generation by the inverter of switching control signals to provide suitable output voltage vectors. Where the measurement phase delay/s may include that introduced by analog to digital conversion (ADC) in supply of measurements of grid voltages to the inverter controller e.g., where ADC filter/s may introduce a phase delay.

At **704**, in some embodiments (e.g., upon verification in step **702**) based on a time point in the three phases of the power supply e.g., sector of the supply voltage, one or two paths through a bypass module are activated, for example, without deactivating the remaining path or paths (non-corresponding) of the inverter. For example, where phases A and B of the bypass module are activated, phase C of the inverter remains activated.

Optionally, in some embodiments, the activation of the bypass module path/s is carried out without deactivating corresponding paths through the inverter. For example, according to one or more feature of step **402** FIG. 4E.

At **706**, in some embodiments, the corresponding inverter pathway/s to those activated at step **704** are deactivated e.g., according to one or more feature of step **404** FIG. 4E. In some embodiments, step **704** is performed prior to step **706**, a potential advantage being preventing inductive discharge peak/s in current associated with inductive currents e.g., of the motor windings.

Alternative, in some embodiments, steps **704** and **706** are performed at about the same time, or step **706** is performed prior to step **704**.

At **708**, in some embodiments, based on a time point in the three phases of the power supply, the remaining one or two path/s through the bypass module are activated, without deactivating corresponding path/s through the inverter. For example, according to one or more feature of step **406** FIG. 4E.

At **710**, in some embodiments, the corresponding inverter pathway/s to those activated at step **708** are deactivated e.g., according to one or more feature of step **408** FIG. 4E.

Potential benefit/s of disconnecting and/or deactivating switching of the inverter is reduction of introduced power losses and/or reduction of electromagnetic interference (EMI) signals associated with high voltage inverter transistor switching.

At **712**, optionally, in some embodiments, relay switches of a relay module (e.g., relay module **128** FIG. 1) are activated. After a time period (e.g., sufficient time to ensure the relays are latched, e.g., 5-**100** ms, or 5-50 ms, or lower, or higher, or intermediate ranges, or durations) pathways of the bypass module are deactivated.

In some embodiments, the bypass module switching is implemented using thyristors, a potential benefit of which is that activation of the bypass module may be more rapid than that of a relay module e.g., enabling a rapid switch over from inverter supply to grid supply via the bypass module. Where, for example, activation of bypass module thyristors (also herein termed “switching on”) is performed, for example, in about 1-5 μs, whereas reaction time of relays may be up to 5-50 ms. In some embodiments, relay switches of the relay module are activated/closed when bypass channels (e.g., thyristors) are fully activated/on. A potential benefit being, for example, what can be termed as the relays closing under a “soft switching” condition potentially reducing wear (e.g., associated with arching) on (potentially increasing lifetime of) the relays.

Now referring to FIG. 7B, at **714**, according to some embodiments, the motor is used e.g., in one or more of a fan, conveyer, belt, compressor, pump.

At **716**, according to some embodiments, for example, depending on feature/s of the use of the motor and/or motor features, the method splits into two paths, depending on whether a soft stop or reduction in speed for the motor is desired and/or required.

At **718**, in some embodiments, if a soft stop or reduction in speed of the motor is not required, relay switches (or bypass module switches in embodiments lacking a relay module) are deactivated. Power supply to the motor is then ceased and rotation of the motor ceases e.g., the motor coasting to a stop.

At **720**, optionally, for example, if the system includes a relay module, in some embodiments, pathways of the bypass module are activated and those of the relay module are deactivated.

At **721**, in some embodiments, the motor is powered via the bypass module. Where, for example, three bypass module pathways, one for each phase of the power supply, are activated.

At **722**, in some embodiments, a single pathway of the bypass module is deactivated e.g., by a controller (e.g., controller **102** FIG. 1) providing a deactivation control signal to the bypass module (e.g., to switch/s of the bypass module, e.g., gate voltage/s for one or more transistor of the bypass module). Where, in some embodiments, e.g., as described regarding FIGs. 13A-C, there may be a delay between a switch of the bypass module pathway receiving a control signal instructing the deactivation of the switch and the pathway actually being deactivated e.g., without current flow therethrough.

At **724**, in some embodiments, a corresponding pathway of the inverter is activated.

In some embodiments, for example, to ensure that the pathway of the bypass module is deactivated, the corresponding pathway of the inverter is enabled a time delay after the deactivation control signal is sent to and/or received by the bypass module. In some embodiments, the time delay (e.g., associated with time required for bypass module switch/es to deactivate) corresponds to a fraction of a phase cycle of the grid supply, e.g., a time delay of 5°-30°, or about 15°, or up to a duration of a sector, 60°, where a full phase cycle is **360**° e.g., refer to FIG. 9. In some embodiments, the time delay is selected to ensure that the pathway of the bypass module is closed, while having a minimal “dead” time duration where the power phase concerned is not provided to the load.

Optionally, in some embodiments, deactivation of the pathway of the bypass module is verified. Where, in some embodiments, deactivation is verified if current flow through the pathway drops to zero, and/or to below a threshold, the threshold also herein termed “holding current”. Where, in an exemplary embodiment, holding current is **100**mA. For example, where, in embodiments including bypass module sensor/s, verification (e.g., performed by a controller e.g. controller **102**, FIG. 1) is using measurements provided by the sensor/s.

Optionally, in some embodiments, for example, alternatively or additionally to enabling the inverter pathway after a time delay, step **724** is performed upon verification that the bypass module pathway has been deactivated.

At **726**, in some embodiments, steps **722**, **724** are repeated until each pathway of the bypass module is deactivated and each pathway of the inverter is activated.

In some embodiments, for example, alternatively to steps **722**, **724**, and **726**, for example, where the bypass module has MOSFET transistor switches, deactivation of the bypass module may include deactivation of two phases at one time, preceded or followed by deactivation of the third phase. Where the deactivation may be at the same time as activation of a corresponding leg of the inverter. The method, for example, mirroring, in reverse, that of transition between inverter to grid e.g., including (in reverse) feature/s of step/s **704**, **706**, **708**, **710**.

At **728**, in some embodiments, speed of motor rotation is controlled e.g., by control of switching at the inverter. For example, where in some embodiments, the motor speed is reduced gradually (e.g., more gradually than would occur if performing step **718**). For example, where in some embodiments, motor speed is reduced to a lower speed than that provided by the characteristic/s (e.g., frequency) of the grid power supply.

Detailed exemplary system

FIGs. 8A-B are simplified schematics of a power supply system **800**, according to some embodiments of the disclosure.

Includes one or more feature of system **100** FIG. 1, for example, a grid supply **812**, an inverter **808**, a load **806**, and a bypass module **810** each of which corresponding to grid supply **112**, inverter **108**, load **106**, and bypass module **110** of FIG. 1.

For ease of illustration, controller/s **802a**, **802b** are not illustrated in FIG. 8A, but are illustrated in FIG. 8B.

In some embodiments, grid supply **812** provides a three phase power supply as illustrated by three power sources **A**, **B**, **C**. Where, in some embodiments, the supply is grounded **856**.

In some embodiments, inverter **808** includes a rectifier module **816** having diodes **D1-D6**, and a switching module **820** having transistors **T1-T6**. Where, in some embodiments, rectifier module **816** provides an input stage of inverter **808** and/or switching module **820** provides an output stage of inverter **808**.

Optionally, in some embodiments, rectifier module **816** and switching module **820** are connected via a DC link module **818**. Where, in some embodiments, the DC link module **818** includes one or more capacitors. In some embodiments, the DC link module **818** includes a plurality (e.g., two) of series connected capacitors. In some embodiments, the DC link module **818** includes a ground node **854**.

Optionally, in some embodiments, (and not illustrated) ground node **854** is connected to ground e.g. to ground **856** by a neutral cable.

In some embodiments, one or more of inverter **808** transistors includes, (e.g., each of **T1-T6**) an insulated-gate bipolar transistor (IGBT).

In some embodiments, one or more of the inverter **808** transistors **T1-T6** includes one or more parallel connected component which allows current flow in a direction opposite to that enabled when the transistor is activated e.g., the one or more parallel connected component including a diode. For example, where transistor **T1** has a parallel connected diode **852**. In some embodiments the parallel connected components (e.g., diodes) provide discharge routes for stored electrical energy. For example, allowing discharge of one or more capacitive and/or inductive element. For example of inductive energy stored on motor coil/s **MA**, **MB**, **MC**.

In some embodiments, bypass module **810** includes a switch **ThA**, **ThB**, **ThC** per phase channel for each phase channel of grid power supply **812**. In some embodiments, the switches each include two anti-parallel connected switches, e.g., semiconductor switches, e.g., transistors. Where, in an exemplary embodiment, the two switches include two thyristors connected in anti-parallel. Anti-parallel connection enables supply through the switch in both directions e.g., to apply both positive and negative half-cycles of supply voltages to load **806**.

In some embodiments, load **806** is a three phase load having a load **MA**, **MB**, **MC** per phase of grid supply **812**. For example, where, in some embodiments, load **806** includes a motor (e.g., synchronous motor e.g., induction motor) where each of **MA**, **MB**, and **MC** include motor coils (e.g., stator coils).

Illustrated in FIG. 8B is controller circuitry **802a**, **802b** which may be hosted by more than one controller (e.g., as illustrated in FIG. 8B) or may be hosted by a single controller module. Where controller circuitry **802a**, **802b** controls switching signals (e.g. gate signals) for switching of bypass switches and/or switching of inverter switches. For example, where connections **822**, **824**, **826** respectively, carry gate control signals from controller **802b** for switching of transistors **T1**, **T2**, of phase A, transistors **T3**, **T4**, of phase B, and transistors **T5**, **T6**, of phase C.

Controller circuitry **802b**, in some embodiments, controls switching of transistors of switching module **820** of inverter **808** using one or more pulse width modulation (PWM) scheme. Where, in some embodiments, switching of transistors **T1-T6** is controlled to deliver positive and negative voltages to load portions **MA**, **MB**, **MC**.

Where the switching is controlled to provide an effective selected frequency voltage e.g., using PWM.

To understand operation of the inverter circuit let us examine a single phase of grid supply **812**, phase A. When voltage from **A** is positive, **D1** is active allowing current from phase A to flow towards switching module **820**. Controlling switching of **T1** and **T2** controls when the phase A load coil **MA** receives this positive voltage. When voltage from grid supply **812** phase A is negative, switching of **T1** and **T2** controls when the phase A load coil **MA** receives this negative voltage.

FIG. 9 is a plot of supply voltage with angle, for a three phase power supply, according to some embodiments of the disclosure.

On FIG. 9 are annotated which diodes are conducting e.g., of diodes **D1-D6** corresponding, in some embodiments, to diodes **D1-D6** of FIGs. 8A-B, based on the polarity of the associated phase/s of the power supply. Sectors are also annotated, where each sector corresponds to 60 degrees or a sixth of a power supply cycle. Where each sector has a different combination of active diodes.

In FIG. 9, a peak of phase voltage A is designated 0°.

Referring back to FIGs. 8A-B, diode **D1** conducts between **300**° and 60° as during this period phase voltage A is of the highest positive amplitude out of all three phases of the power supply. The conduction periods of diodes **D3** and **D5** correspond to when the phase voltages B and C are of the highest positive amplitude, respectively. The same principle applies for diodes D4, D6 and D2 conducting during the negative phase voltage amplitudes for phases A, B and C respectively. All diode conduction periods are of **120**° and overlap with two conduction periods of diodes from the opposite leg of the diode rectifier. For example, when **D3** from the upper leg of the rectifier conducts, it overlaps with the conduction periods of **D2** and **D4** from the lower leg of the rectifier. Hence, the inverter input can be split into six states or sectors, I-VI, marked on FIG. 9, a sector for each 60°. During each sector, two diodes are conducting and connecting two supply voltage phases e.g., referring to FIGs. 8A-B, to an input of switching module **820** of inverter **808**.

FIG. 10 is a diagram illustrating inverter input and output states, according to some embodiments of the disclosure.

Referring back to FIG. 8A, in some embodiments, rectifier module **816** e.g., along with DC link **818** provides positive DC link voltage or the negative DC link voltage to the inverter input, where switching of transistors of switching module **820** controllably delivers the positive and negative DC link voltage to motor coils MA, MB, MC. Referring to FIG. 9, the positive and negative voltages supplied by the rectifier module (e.g., to the DC link) respectively, may be upper and lower envelopes of the three phases together illustrated in FIG. 9. In some embodiments, an effective ground produced (e.g., at node **854** FIG. 8) may fluctuate e.g., with the envelopes (e.g., at triple the grid frequency).

In some embodiments, switching is controlled to provide power to the motor coils which generates a rotating magnetic field (e.g., to drive rotation of the motor). By controlling switching of the inverter transistors the frequency of the rotating magnetic field, and that of the motor may be controlled.

FIG. 10 illustrates output states V**000**-V**111** of the inverter corresponding to the rotating magnetic field of the motor, along with input states to the inverter, of the power supply, sectors I-VI.

Where the hexagon illustrated in FIG. 10 represents an output voltage range of the inverter with the corresponding discrete output states (also herein termed “space vectors” illustrated with arrows) of the inverter.

For example, arrow V**100** represents an inverter output state, where, referring to FIG. 8A phase A has the high-side of the inverter leg **T1** activated, applying positive DC link voltage to motor winding A MA. Phases B and C have the low-side of the inverter legs **T4**, **T6** activated, delivering negative DC link voltage to motor windings B and C respectively **MB**, **MC**.

Space in between the discrete space vectors (illustrated as arrows) represents a combination of the two adjacent inverter output states. For example, in sector VI the inverter output state varies between ‘V**001**’ and ‘V**101**’. The null vectors ‘V**000**’ and ‘V**111**’ may also be applied in each sector e.g., depending on the desired voltage amplitude.

In FIG. 10, the two circles represent the conduction periods of the diodes in the rectifier. The inner circle represents the upper diodes (**D1**, **D3** and **D5**, FIG. 8A), while the outer circle represents the lower diodes (**D2**, **D4**, and **D6**, FIG. 9B).

The diagram shown is in the synchronized state, where the inverter is synchronized to the grid frequency.

The inverter output states consist of eight configurations of the inverter's six transistors **T1-T6**. These eight output states are denoted by V**000**-V**111**. For each inverter phase leg, only one transistor may be active/switched on at any time. Hence, the configuration V**110** represents the configuration where transistors **T1**, **T3** and **T6** are activated and **T2**, **T4** and **T5** are deactivated. The configurations or voltage vectors V**000** and V**111** represent the null vectors, as during these voltage vectors the motor windings are short-circuited.

Table 1 also shows relationships between inverter input state (sector), inverter output state (voltage vectors), which diodes are active.

Table 1

Sector	**Voltage vectors**	**Diodes**
I	V**101** V**100**	D1 D6
II	V**100** V**110**	D1 D2
III	V**110** V**010**	D3 D2
IV	V**010** V**011**	D3 D4
V	V**011** V**001**	D5 D4
VI	V**001** V**101**	D5 D6

Exemplary transition from inverter to grid

FIGs. 11A-D are simplified schematics illustrating voltages for exemplary system states, according to some embodiments of the disclosure.

In some embodiments, FIGs. 11A-D illustrate a power supply system **1100** which includes one or more feature of system **100** FIG. 1 and/or system **800** FIGs. 8A-B. For example, where a bypass module **1110** including switches ThA, ThB, ThC includes one or more feature of bypass module **110** FIG. 1 and/or bypass module **810** FIGs. 8A-B. For example, where a power supply **1112** includes one or more feature of power supply **112** FIG. 1 and/or power supply **812** FIGs. 8A-B. For example, where an inverter **1108** including a rectifier **1116** and a switching module **1120** includes one or more feature of inverter **108** FIG. 1 and/or rectifier **1116** and/or switching module **1120** including one or more feature of rectifier **816** and/or switching module **820** FIGs. 8A-B respectively. For example, where a load **1106** includes one or more feature of load **106** FIG. 1 and/or load **806** FIGs. 8A-B.

For simplicity of illustration, in FIGs. 11A-D switches **T1-T6** of an inverter **1108** and switches **ThA**, **ThB**, **ThC** of bypass module **1110** are illustrated as either closed or open current paths. Where the opening/closing of the switches is controlled by a controller (e.g., controller **102** FIG. 1). For simplicity of illustration, diodes **D1-D6** of rectifier **1116** are illustrated as either closed or open (corresponding to conducting and non-conducting/reverse biased states, associated with polarity of the connected power supply/ies and the diode electrical orientation).

Referring now to FIG. 11A which, in some embodiments, illustrates where, e.g., according to step **402** FIG. 4E where two phases are both connected through the bypass module **1110** and inverter **1108**.

In detail; both phase A and phase B pathways through bypass module **1110** are activated, where phase A of the power supply passes through switch ThA and phase B passes through switch **ThB**. While switching module **1120** is in a <u>**V100** inverter state</u>, with transistors **T1**, **T4**, <u>**T6**</u> activated and transistors **T2**, **T3**, and <u>**T5**</u> are deactivated. The power supply is also within <u>sector I</u> where phase A of power supply **1112** is positive, phase B is negative, and phase C transitions from positive to negative. Corresponding to polarities of phases A and B, diodes **D1** and **D6** are conducting meaning that load **1106** is receiving power supply phases A and B both through bypass module **1110** and through inverter **1108**. Where phase A current paths/voltage supply is illustrated with heavy solid lines, and phase B current paths/voltage supply is illustrated with heavy dotted lines. Considering phase C, short circuiting does not occur for either polarity, positive polarity of phase C supply passing into the inverter path of phase A, and negative polarity of phase C supply passing into the inverter path of phase B. In some embodiments, switching module legs associated with phase A and B are deactivated (**T1**, **T2**, **T3**, and **T4** are disabled) during the sector in which the phase A and B bypass pathways via **ThA**, **ThB** are activated.

Referring now to FIG. 11B which, in some embodiments, illustrates why, in some embodiments, activation of all three pathways through the bypass module **1110** and inverter **1108** is not performed e.g., potentially preventing short circuiting of phases of the power supply.

In detail, FIG. 11B illustrates a same situation as that illustrated in FIG. 11A where the inverter state is V**100**, and the power supply is in sector I. However, in FIG. 11B, bypass module **1110** pathway for phase C is activated with switch ThC closed. This results in a short circuit at **1132** where, for example, at the beginning of sector I positive polarity of phase C meets negative polarity of phase B.

Referring now to FIG. 11C which, in some embodiments, illustrates another inverter state, V**101** where, e.g., according to step **402** FIG. 4E where two phases are both connected through the bypass module **1110** and inverter **1108**. V**101**, in some embodiments, is the second voltage vector present in Sector I, apart from V**100**.

In detail; both phase A and phase B pathways through bypass module **1110** are activated, where phase A of the power supply passes through switch **ThA** and phase B passes through switch **ThB**. While switching module **1120** is in a V**101** inverter state, with transistors **T1**, **T4**, **T5** activated and transistors **T2**, **T3**, and **T6** are deactivated. The power supply is also within sector I where phase A of power supply **1112** is positive, phase B is negative, and phase C transitions from positive to negative. Corresponding to polarities of phases A and B, diodes D1 and D6 are conducting meaning that load **1106** is receiving power supply phases A and B both through bypass module **1110** and through inverter **1108**. Where phase A current paths/voltages are illustrated with heavy solid lines, and phase B current paths/voltages are illustrated with heavy dotted lines. Considering phase C, short circuiting does not occur for either polarity, positive polarity of phase C supply passing into the inverter path of phase A, and negative polarity of phase C supply passing into the inverter path of phase B.

Referring now to FIG. 11D which illustrates later activation of the final bypass module pathway. Where FIG. 11D illustrates sector II of the power supply (subsequent to sector I) and both inverter states V**100** and V**110**.

Corresponding, for example, to completion of step **404** of FIG. 4E, inverter pathways for both phase A and B have been deactivated and all of transistors **T1**, **T3**, **T2**, and **T4** are deactivated.

Exemplary transition from grid to inverter

FIG. 12 is a plot of supply voltage and current to a load, with time, according to some embodiments of the disclosure.

FIG. 12, in some embodiments, illustrates supply voltage and current to an exemplary load having an exemplary inductance when the load is grid-supplied (e.g., not power-supplied by the inverter). Where in FIG. 12, time for both plots is aligned. On FIG. 12, sectors I-VI e.g., as described regarding diode conduction and/or regarding FIG. 9 and/or FIG. 10 are illustrated. FIG. 12 illustrates lag of the current with respect to the voltage, the lag, for example, associated with motor inductance. Where, the lag is visible, for example, as a slight misalignment of sinusoids of the current with respect to the voltage.

FIGs. 13A-C are simplified schematics illustrating voltages for exemplary system states, according to some embodiments of the disclosure.

In some embodiments, FIGs. 13A-D illustrate a power supply system **1300** which includes one or more feature of system **100** FIG. 1 and/or system **800** FIGs. 8A-B and/or system **1100** FIGs. 11A-D. For example, where a bypass module **1310** including switches ThA, ThB, ThC includes one or more feature of bypass module **110** FIG. 1 and/or bypass module **810** FIGs. 8A-B and/or bypass module **1110** FIGs. 11A-D. For example, where a power supply **1312** includes one or more feature of power supply **112** FIG. 1 and/or power supply **812** FIGs. 8A-B and/or power supply **1112** FIGs. 11A-D. For example, where an inverter **1308** including a rectifier **1316** and a switching module **1320** includes one or more feature of inverter **108** FIG. 1 and/or rectifier **1316** and/or switching module **1320** including one or more feature of rectifier **816** and/or switching module **820** FIGs. 8A-B respectively. For example, where a load **1306** includes one or more feature of load **106** FIG. 1 and/or load **806** FIGs. 8A-B and/or load **1106** FIGs. 11A-D.

For simplicity of illustration, in FIGs. 13A-D switches T1-6 of an inverter **1308** and switches ThA, ThB, ThC of bypass module **1310** are illustrated as either closed or open current paths. Where the opening/closing of the switches is controlled by a controller (e.g., controller **102** FIG. 1). For simplicity of illustration, diodes **D1-D6** of rectifier **1316** are illustrated as either closed or open (corresponding to conducting and non-conducting/reverse biased states, associated with polarity of the connected power supply/ies and the diode electrical orientation).

In some embodiments, switching at bypass module **1310** is by thyristors, timing of control signals instructing deactivation of the thyristors for deactivation of bypass module pathways and activation of corresponding pathways of inverter **1308** are timed so that the thyristors are no longer conducting when the inverter pathway is activated. For example, to prevent short circuiting of phases of the power supply.

For example, as described in more detail hereinbelow, in some embodiments, a bypass pathway is deactivated prior to activation of a corresponding inverter pathway, where, in some embodiments, timing of control signal/s for deactivation of the bypass pathway is based on a phase lag of motor current with respect to motor voltage, which may be dependent on the motor inductance.

Referring now to FIG. 13A which illustrates system **1300** during an exemplary sector I of the input supply, where a phase A bypass pathway has been deactivated e.g., by sending a control signal to ThA in sector VI prior to zero crossing **1200** FIG. 12 of current of phase A. In some embodiments, control signals are initiated for switching of phase A portions of switching module **1320** (**T1** and **T2**). Where control signals, in some embodiments, include PWM signals. Control signals for switching module portions related to phases B and C are still disabled where both possible voltage vectors V**100** and V**101** result in only **T1** being switched on, e.g., as shown in FIG. 13A.

Bypass module switch for phase C may be disabled in this sector (sector I), e.g., in preparation for the following sector.

Referring now to FIG. 13B which illustrates a short circuit **1332** between phases A and B. This scenario may occur, for example, if the control signal to deactivate thyristor switch **ThA** is received after the zero crossing for the current of phase A. For example, if, in sector I both the phase A inverter path is activated (**T1** on) and **ThA** is instructed to deactivate, **ThA** will remain activated (e.g., conducting) until the next zero crossing of current of phase A, which referring back to FIG. 12, is at **1202** in sector III. FIG. 13B illustrates short circuit **1332** occurring, in sector III prior to this zero crossing **1202**. Where, since in sector III phase B is positive, **D3** being active, **T1** is activated, and phase A is negative.

If phase A of the inverter output is to be connected during sector I, then the thyristor gate signals for phase A are disabled during sector VI in order to allow their current to reach 0A.

This procedure is repeated for each phase with the next zero-crossing occurring for phase C, followed by phase B.

Referring now to FIG. 13C, which illustrates system **1300** during sector II for both V**100** and V**110** voltage vectors, as control signals for switching module phase B (**T3** and **T4**) remains disabled. Phase C of inverter output **1320** has been enabled, after deactivating of bypass module pathway for phase C (ThC) in the previous sector.

For example, in preparation for the last sector to complete the transition, the gate signal for the phase B thyristor is then disabled. In some embodiments, once the power supply enters sector III control signals for switching module **1320** phase C (**T5** and **T6**) is enabled e.g., to complete the transition from the grid to the inverter connected operation.

Although a transition where first phase A, then phase B, and then phase C are transitioned from bypass supply to inverter supply sequentially has been described, other orders e.g., B-C-A, or C-A-B are envisioned and encompassed. In an exemplary embodiment, transitions are in sequential sectors, a potential benefit being maintained motor current and/or torque with minimal disturbance during the transition.

Additional exemplary rotors

In this section various exemplary rotors having a 4 pole (2-pole pair) configuration are described however it should be understood that the illustrated designs could be adjusted for configurations for other numbers of pole pairs.

FIGs. 14-17 are simplified schematic top views of exemplary hybrid permanent-magnet motors, according to some embodiments of the disclosure.

In some embodiments, each of the illustrated electrical motors **1406**, **1506**, **1606**, and **1706** includes a stator (respectively **1452**, **1552**, **1652**, and **1752**), each stator having a stator bore (respectively **1466**, **1566**, **1666**, and **1766**) and stator windings (respectively **1460**, **1560**, **1660**, and **1760**). Each motor includes a rotor (respectively **1458**, **1558**, **1658**, and **1758**) configured (e.g., sized and/or shaped) to occupy the corresponding stator bore. Each rotor may be coupled to a shaft (respectively **1462**, **1562**, **1662**, and **1762**). In some embodiments, each rotor includes a plurality of permanent magnets (respectively **1454**, **1554**, **1654**, and **1754**). In some embodiments, each rotor includes flux barriers (respectively **1456**, **1556**, **1656**, and **1756**). In some embodiments, the flux barriers are conductors which form an induction structure for example, arranged to provide a closed current path e.g., electrically connected according to one or more feature as described regarding FIGs. 2B-C.

FIG. 14 and FIG. 15 illustrate rotor embodiments where, alternatively or additionally to flux barriers **1456**, **1556** being conductive, include an induction structure **1450**, **1550**. In some embodiments, the induction structure includes one or more conductive elongated elements **1450**, **1550** (e.g., bar/s) which extend along the rotor body. In some embodiments, the induction structure includes conductive elements distributed (e.g., evenly) around the rotor. The conductive elements may be electrically connected in one or more closed loop e.g., by one or more end element and/or structure (e.g., including feature/s of end structures **267**, **268** FIG. 2C) at each end of the rotor. In some embodiments, the rotor bars **1450**, **1550** are embedded within a body of the rotor.

FIG. 14 illustrates an embodiment where permanent magnets **1454** are angled inwards towards shaft **1462**. Each magnet **1454** may be magnetically insulated from other magnets by a flux barrier **1456** positioned therebetween where the angled magnets may each have a flux barrier, one positioned closer to (e.g., adjacent to) a rotor outer surface (defining air gap **1466**) and another positioned closer to (e.g., adjacent to) shaft **1462**. In this embodiment, a number of magnets may be double that of the number of poles of the rotor configuration. FIG. 15 illustrates an embodiment including a separate induction structure **1550** and where permanent magnets **1556** are arranged defining an effective square profile within the circular rotor cross-section. This corresponds to a four pole configuration, in higher number pole configurations the magnets may define a correspondingly numbered side shape (e.g., octagon for an eight pole configuration e.g., illustrated in FIG. 2B). The ends of one or more (e.g., each of) the permanent magnets are separated by flux barriers **1556**. In some embodiments, each permanent magnet occupies a portion of a channel within the rotor body and along with flux barriers at each end of the permanent magnet. Alternatively, in some embodiments, each channel may house a magnet and a single flux barrier, each channel providing a single flux barrier between two magnets.

FIG. 16 illustrates an embodiment where flux barriers **1656** and permanent magnets **1654** are surface-mounted. The flux barriers may be conductive, forming the induction structure. Alternatively or additionally, in some embodiments, motor **1606** includes an embedded induction structure (not illustrated) including one or more feature as illustrated in and/or described regarding induction structure/s **1450**, **1550**. When motor **1606** includes an induction structure (e.g., bars forming a damper cage) flux barriers may be formed of electrically insulating material (e.g., may be air gaps). Although FIG. 16 illustrates curved magnets and flux barriers, in some embodiments, embedded magnets (and/or flux barriers) may not be curved and may protrude from or be recessed into the rotor body.

FIG. 17 illustrates an embodiment including a double-layer of permanent magnets, where the magnets describe two square shapes an inner square including inner permanent magnets **1754**a, and an outer square including outer magnets **1754**b. Channels housing the magnets may house induction structure parts (e.g., bars), for example, an inductor cage bar for each end of each magnet. For example, bars **1756**a-b in a channel housing magnet **1754**a, bars **1756**c-d in a channel housing magnet **1754**b. Air gaps may extend between the magnets and the induction structure bars. The induction structure may be disposed closer to the air gap than the magnets. In some embodiments, the induction structure bars may also provide flux barriers between the magnets.

FIG. 18 is a simplified schematic top view of a synchronous operation motor, according to some embodiments of the disclosure.

In some embodiments, motor **1806** includes a stator **1852** including a stator bore **1866** and stator windings **1860**. Motor includes a rotor **1858** configured (e.g., sized and/or shaped) to occupy stator bore and coupled to a shaft **1862**. Rotor includes an induction structure **1850**.

FIG. 18 illustrates a synchronous reluctance rotor including an induction structure **1850** which may include one or more features of induction structures as described elsewhere in this document. The induction structure may occupy portions of flux barrier channels **1856**. For example, each flux barrier channel (which many be air filled or filled with another flux blocking material) hosting an elongated element (e.g., bar) of the induction structure.

FIG. 19 is a simplified schematic top view of a synchronous operation motor **1906**, according to some embodiments of the disclosure.

In some embodiments, motor **1906** includes a stator **1952** including a stator bore **1966** and stator windings **1960**. Motor **1906** includes a rotor **1958** configured (e.g., sized and/or shaped) to occupy stator bore **1966** and coupled to a shaft **1962**. Rotor includes an induction structure **1950** which may include one or more features of induction structures as described elsewhere in this document. FIG. 19 illustrates an electrically excited synchronous rotor **1958** where the rotor magnetic field is established by supplying windings **1954** with current.

Exemplary Implementation

In an exemplary implementation a conventional 4 kW, 4-pole, **400** V, 50 Hz induction motor stator having star-connected windings was used. The stator comprised laminated electrical-steel sheets having 36 uniformly spaced slots, each slot receiving turns of enamel-insulated copper wire arranged in three groups corresponding to the three electrical phases.

FIGs 20A-C are views of an exemplary implementation of a rotor, according to some embodiments of the disclosure.

FIGs. 20A-B illustrate a rotor **2058** mounted onto a shaft **2062** prior to insertion of conductors into air spaces **2055** between permanent magnets **2054**. FIG. 20C illustrates rotor **2058** after insertion of conductors **2056**, where conductors **2056** are electrically connected by conductive end structures **2067**, **2068**.

In some embodiments, the rotor body includes one or more flanges configured to prevent movement of the permanent magnets. Where, for example, a space in the rotor body housing a permanent magnet may have a cross sectional dimension (e.g., thickness t1) which is larger than a space housing conductors (e.g., thickness t2).

An exemplary rotor was constructed for use with the stator. The rotor was formed of a plurality of skewed lamination sections mounted on a machined shaft. The laminations define slots for receiving the permanent magnets and conductive bars. The magnets were bonded within the laminations using an epoxy resin adhesive, and the lamination stack was axially compressed during curing to ensure mechanical rigidity and dimensional precision. Where nine 15 mm electrical-steel lamination sections were each offset by approximately 1.1°, yielding a total rotor skew of about 10° which corresponds to the angular spacing of one stator slot. The rotor outer diameter was about 90 mm. The rotor included a plurality of permanent magnets and a copper induction cage. Where the induction cage was formed by a set of copper conductors inserted in rotor slots adjacent to the permanent magnets. The conductors were copper bars approximately 5 mm × 4 mm in cross section, positioned between NdFeB permanent magnets and electrically connected through copper end plates.

After assembly, the rotor was dynamically balanced to minimize vibration at operating speed, for example 1500 rpm, and is then inserted into the stator. Copper bars of the induction cage were mechanically flared into end plates without thermal joining.

The motor was operated with inverter startup based on a V/f scheme linearly ramping to 1500 rpm over 1s and where commutation was gradual as described regarding FIGs. 4-13C.

FIG. 21 illustrates motor measurements acquired during motor startup, according to some embodiments of the disclosure.

FIG. 21 includes four plots, with time, on a same time scale, the uppermost plot is a plot of 3-phase grid voltages during motor startup, the plot directly underneath is a plot of inverter voltages during motor startup, the plot directly underneath is a plot of resulting 3-phase motor winding currents during motor startup and the bottommost plot is a plot of measured motor speed during motor startup.

Illustrated on the plots are time points **A**, **B**, and **C**. At point **A** the inverter is switched on and motor voltage and frequency are constantly increased to 50Hz. At point **B**, the motor reaches 50 Hz operation and the HID switches to grid voltage synchronization mode to align the motor voltage magnitude and phase. At point **C**, the bypass path is enabled by switching on thyristors and bypass relays. After point **C**, the motor is directly grid-connected, and the inverter is switched off.

FIG. 22 illustrates motor measurements acquired during a gradual motor stop, according to some embodiments of the disclosure.

At point **D**, the bypass relays and thyristors are turned off, and the inverter supplies the motor voltages, which are still synchronised to the grid voltages. At point **E**, the inverter control is set to independent, not grid-synchronised voltage control, and the motor voltage magnitude and frequency are linearly reduced to reduce the motor speed. At point **F**, the motor speed is close to zero, and the inverter is switched off.

It should be noted that in the shown exemplary operation, only a simple V/f control scheme is used to change the speed of the motor. This operation can be improved by using closed-loop current control or sophisticated sensorless vector control. This will allow better control of the torque and speed of the motor. However, the main part of this invention is the used motor grid voltage synchronisation and smooth switch over to direct grid-connected bypass operation.

General

As used within this document, the term “about” refers to±20%

The terms “comprises”, “comprising”, “includes”, “including”, “having” and their conjugates mean “including but not limited to”.

The term “consisting of” means “including and limited to”.

As used herein, singular forms, for example, “a”, “an” and “the” include plural references unless the context clearly dictates otherwise.

Within this application, various quantifications and/or expressions may include use of ranges. Range format should not be construed as an inflexible limitation on the scope of the present disclosure. Accordingly, descriptions including ranges should be considered to have specifically disclosed all the possible subranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed subranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within the stated range and/or subrange, for example, 1, 2, 3, 4, 5, and 6. Whenever a numerical range is indicated within this document, it is meant to include any cited numeral (fractional or integral) within the indicated range.

It is appreciated that certain features which are (e.g., for clarity) described in the context of separate embodiments, may also be provided in combination in a single embodiment. Where various features of the present disclosure, which are (e.g., for brevity) described in a context of a single embodiment, may also be provided separately or in any suitable sub-combination or may be suitable for use with any other described embodiment. Features described in the context of various embodiments are not to be considered essential features of those embodiments, unless the embodiment is inoperative without those elements.

Although the present disclosure has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art. Accordingly, this application intends to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims.

All references (e.g., publications, patents, patent applications) mentioned in this specification are herein incorporated in their entirety by reference into the specification, e.g., as if each individual publication, patent, or patent application was individually indicated to be incorporated herein by reference. Citation or identification of any reference in this application should not be construed as an admission that such reference is available as prior art to the present disclosure. In addition, any priority document(s) and/or documents related to this application (e.g., co-filed) are hereby incorporated herein by reference in its/their entirety.

Where section headings are used in this document, they should not be interpreted as necessarily limiting.

CLAIMS:

1. An electrical motor system comprising:

a rotor comprising one or more elements configured to provide a rotor magnetic field and an induction structure including at least one closed conduction loop, the rotor sized and shaped to occupy a bore of a stator which, when receiving alternating current provides a stator rotating magnetic field, the stator rotating magnetic field:

interacting with the rotor magnetic field to produce torque; and

crossing the at least one closed conduction loop;

an inverter configured to receive a three phase power supply and to deliver a variable frequency three phase power supply to the stator through a plurality of inverter electrical pathways;

a bypass module configured to selectively deliver the three phase power supply directly to the stator through a plurality of bypass electrical pathways;

a controller configured to control transition between supplying the stator through the inverter and through the bypass module by generating control signals for activation and deactivation of the plurality of inverter electrical pathways and the plurality of bypass electrical pathways, the controller configured to:

identify a phase state of the three phase power supply;

activate bypass pathways and deactivate inverter pathways, while continuously maintaining power through at least one pathway to the stator, timing of individual activations and deactivations based on the phase state.

2. The electrical motor system according to claim 1, wherein the one or more elements configured to provide the rotor magnetic field comprises a plurality of permanent magnets.

3. The electrical motor system according to claim 2, wherein the rotor comprises flux barriers formed by non-magnetic material positioned between said permanent magnets.

4. The electrical motor system according to claim 3, wherein the induction structure provides the flux barriers, the induction structure including electrically conductive and non-magnetic material which is positioned between ends of the permanent magnets.

5. The electrical motor system according to any one of claims 2-4, wherein the plurality of permanent magnets are elongate elements extending along a rotor body.

6. The electrical motor system according to claim 5, wherein the plurality of permanent magnets each occupy a slot in the rotor body.

7. The electrical motor system according to any one of claims 5-6, wherein the induction structure includes a plurality of elongate conductors extending along the rotor body.

8. The electrical motor system according to claim 7, wherein the plurality of elongate conductors each occupy a slot in the rotor body in a position between two of the plurality of permanent magnets.

9. The electrical motor system according to any one of claims 1-8, wherein the controller is configured to:

monitor a sector of the three phase supply;

select a first phase for transition based on said sector; and

activate a first pathway through the bypass module corresponding to said first phase and deactivate a corresponding first pathway through the inverter, while at least one inverter pathway remains activated.

10. A method of operating an electrical motor system comprising a stator, a synchronous-type rotor including an induction structure, an inverter, a bypass module, and a controller, the method comprising:

supplying a three phase power supply to the inverter;

delivering, from the inverter, a variable-frequency three phase power supply to the stator through a plurality of inverter pathways;

monitoring a phase state of the three phase power supply; and

transitioning supply of power to the stator from the inverter to the bypass module by activating a bypass pathway and deactivating a corresponding inverter pathway while continuously maintaining power to the stator through at least one pathway, where timing of each activation and deactivation is based on the monitored phase state.

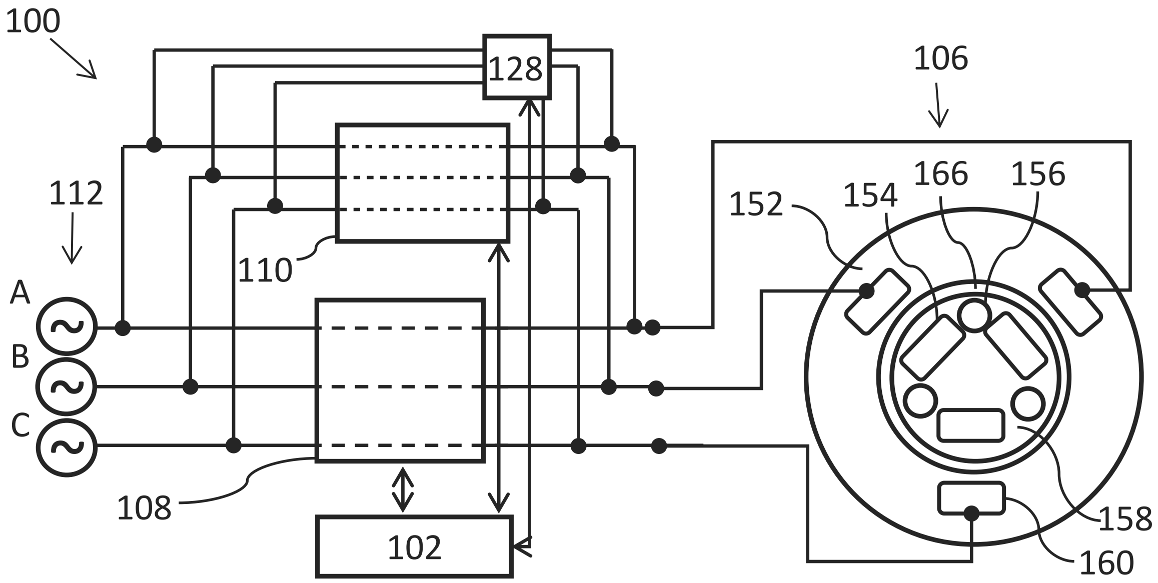
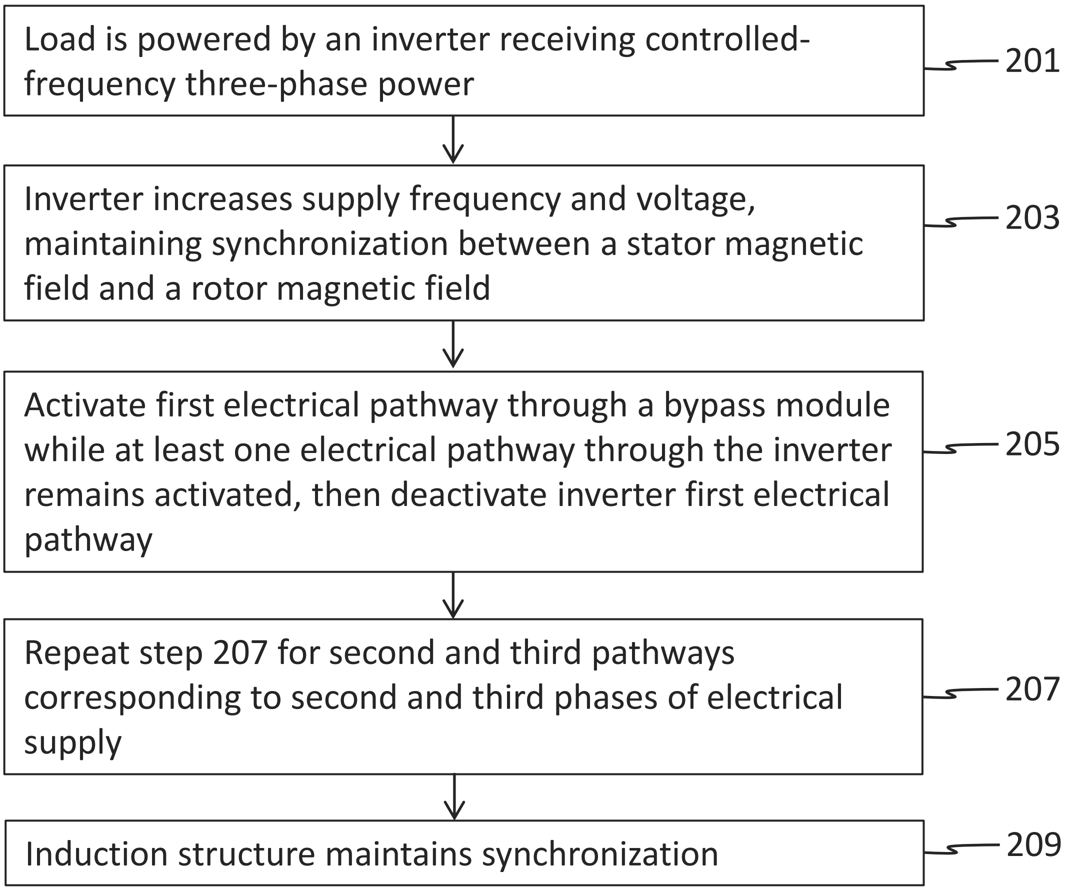


FIG. 1



Load is powered by an inverter receiving controlled-frequency three-phase power

Inverter increases supply frequency and voltage, maintaining synchronization between a stator magnetic field and a rotor magnetic field

Activate first electrical pathway through a bypass module while at least one electrical pathway through the inverter remains activated, then deactivate inverter first electrical pathway

Repeat step 207 for second and third pathways corresponding to second and third phases of electrical supply

Induction structure maintains synchronization

FIG. 2A

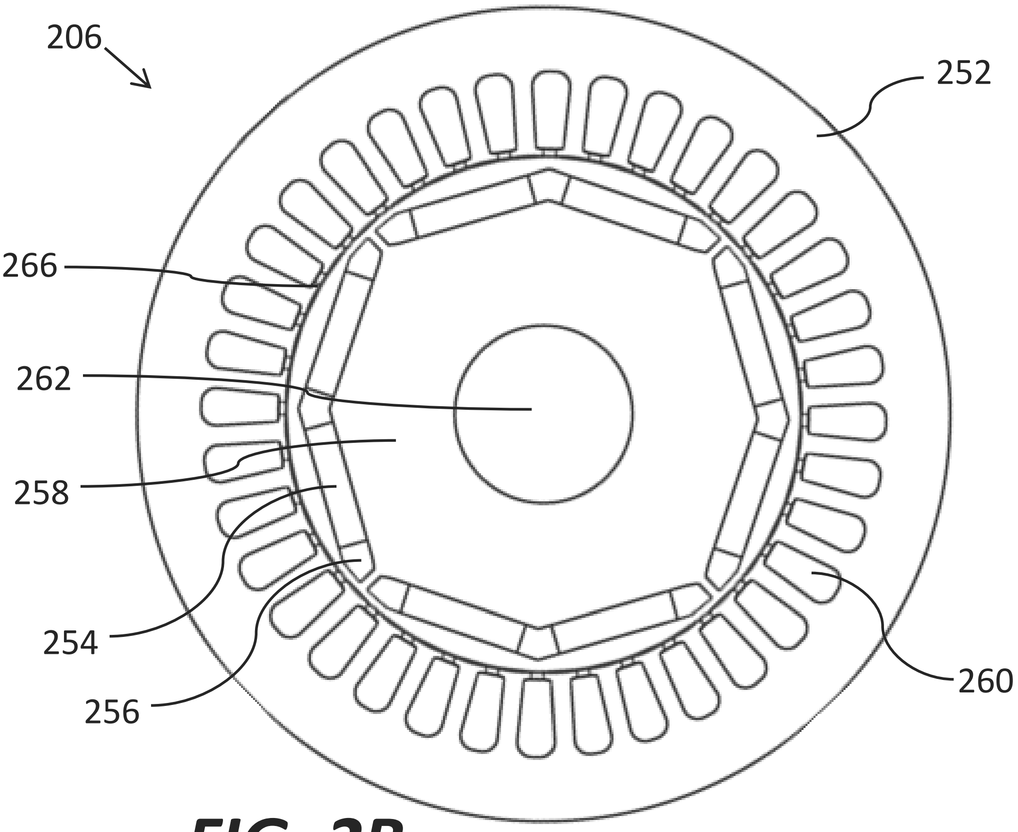


FIG. 2B

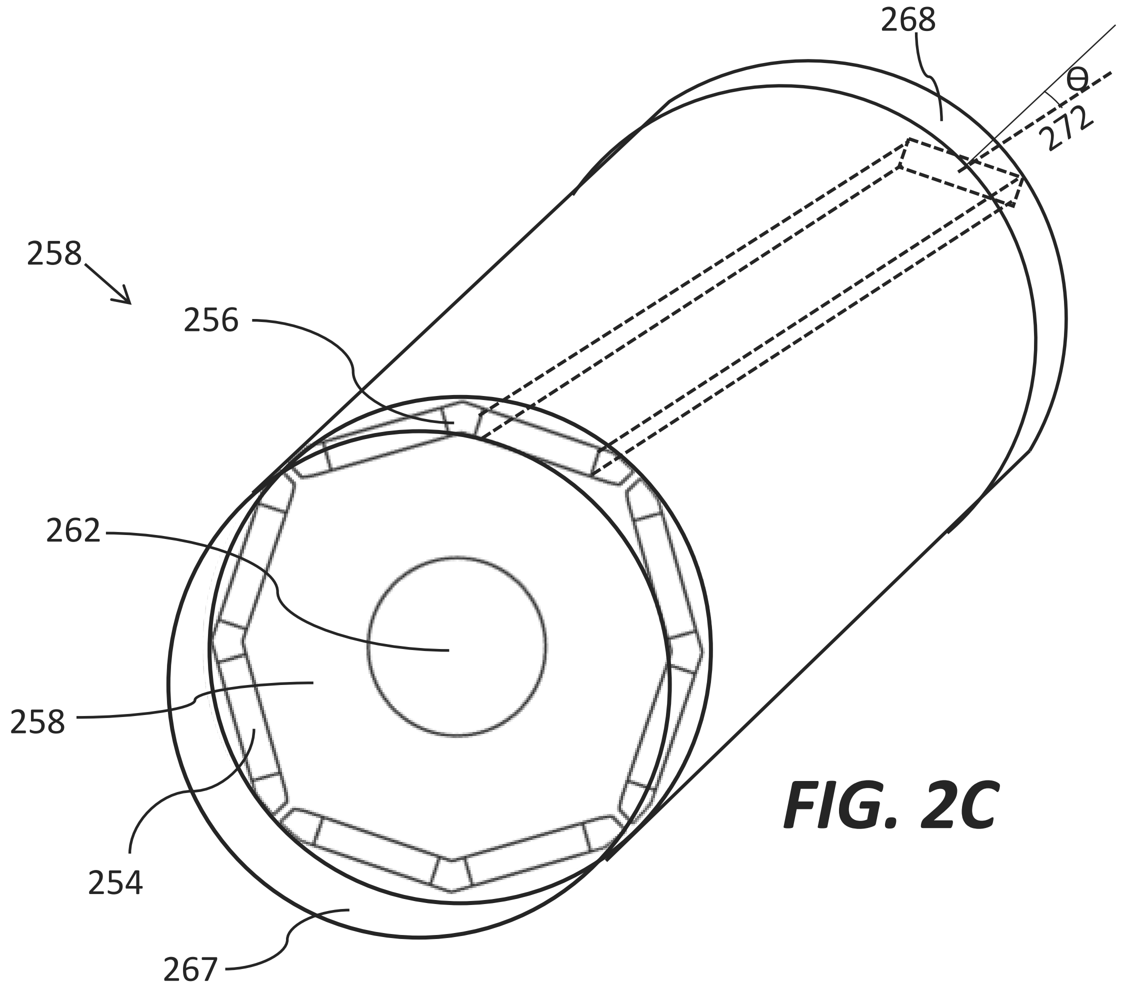


FIG. 2C

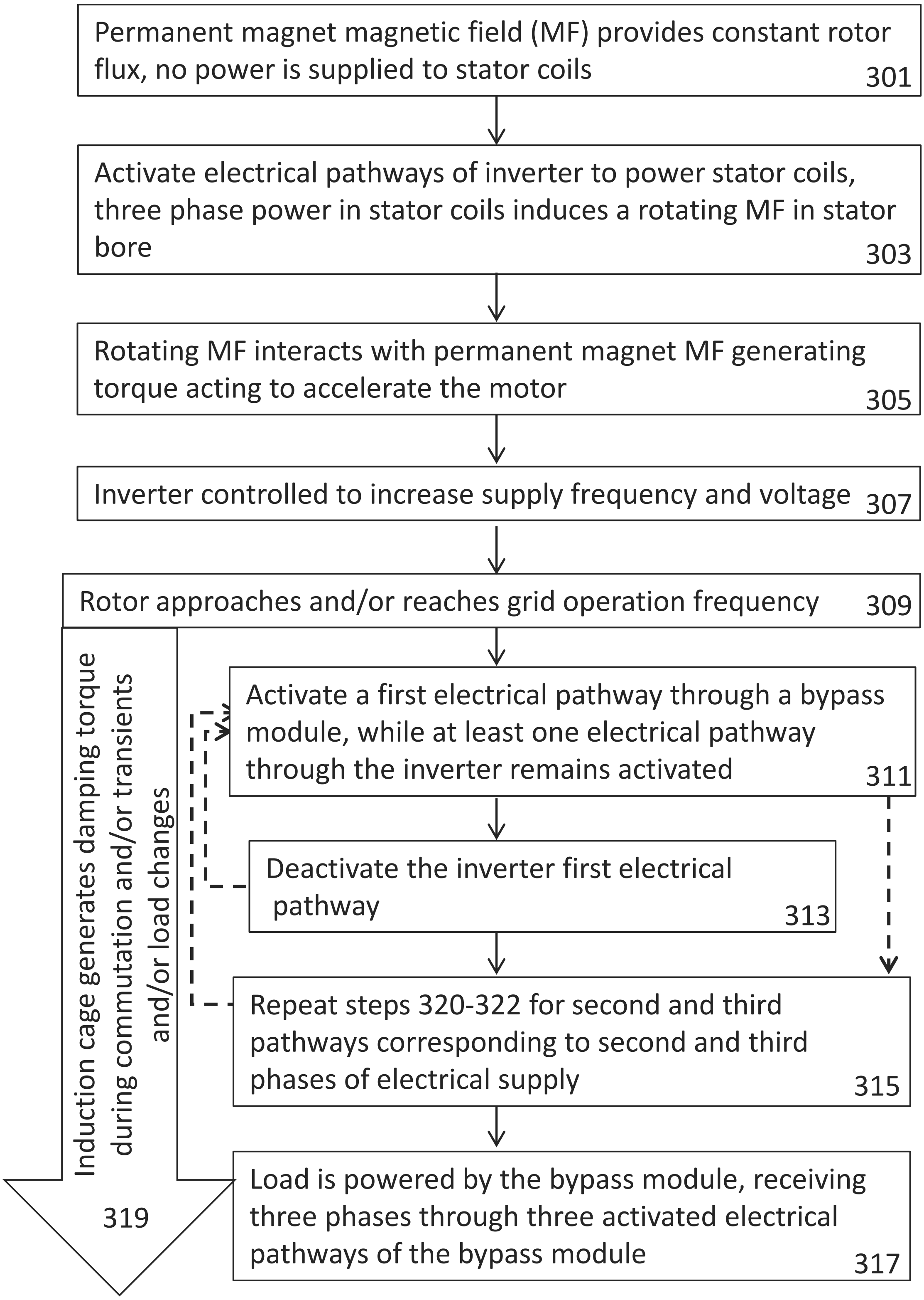

Permanent magnet magnetic field (MF) provides constant rotor flux, no power is supplied to stator coils
301
Activate electrical pathways of inverter to power stator coils, three phase power in stator coils induces a rotating MF in stator bore
303
Rotating MF interacts with permanent magnet MF generating torque acting to accelerate the motor
305
Inverter controlled to increase supply frequency and voltage
307
Rotor approaches and/or reaches grid operation frequency
309
Activate a first electrical pathway through a bypass module, while at least one electrical pathway through the inverter remains activated
311
Deactivate the inverter first electrical pathway
313
Repeat steps 320-322 for second and third pathways corresponding to second and third phases of electrical supply
315
Load is powered by the bypass module, receiving three phases through three activated electrical pathways of the bypass module
317
Induction cage generates damping torque during commutation and/or transients and/or load changes
319

FIG. 3

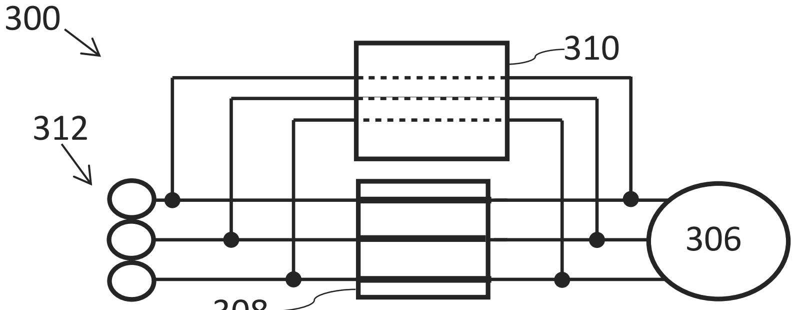


FIG. 4A

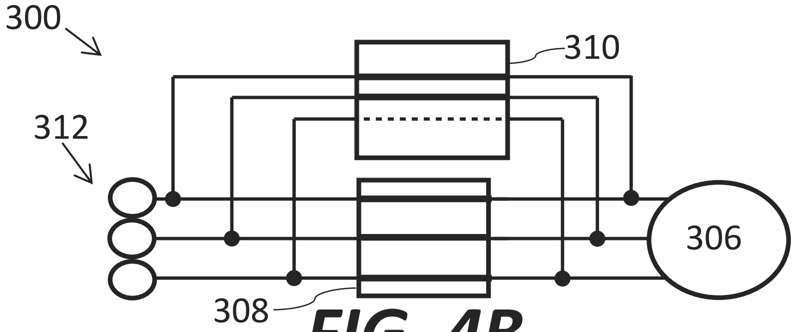


FIG. 4B

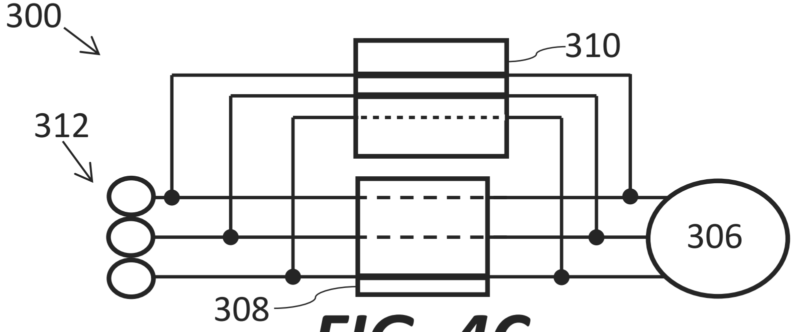


FIG. 4C

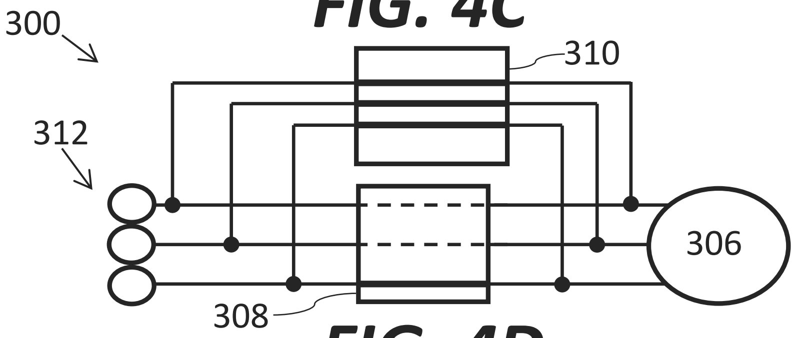


FIG. 4D

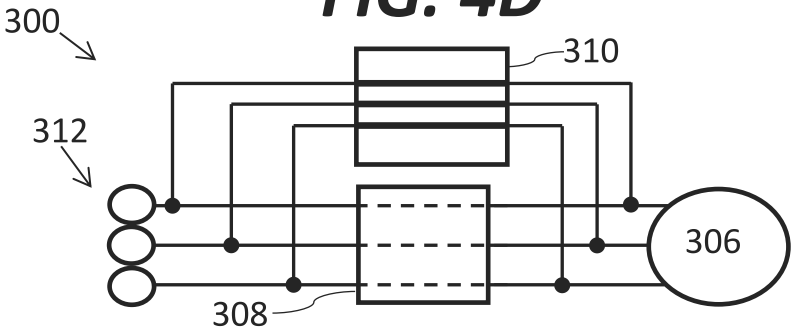


FIG. 4E

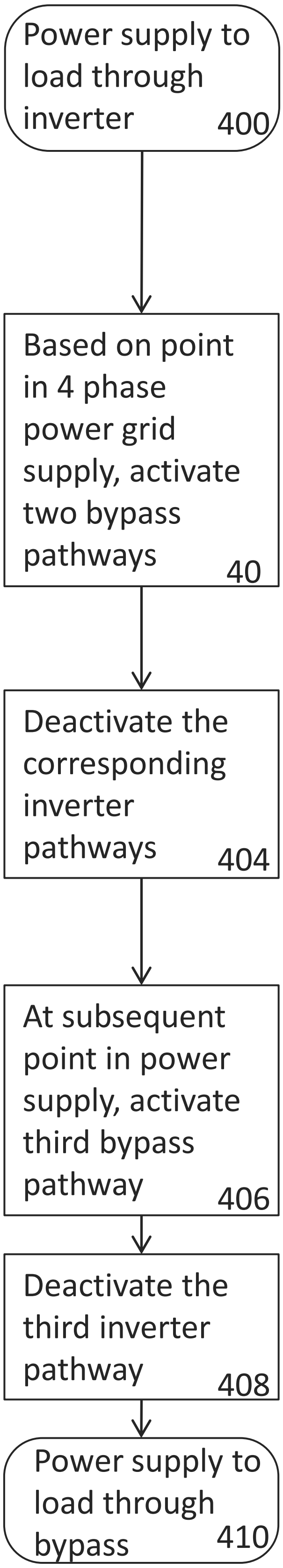


FIG. 4F

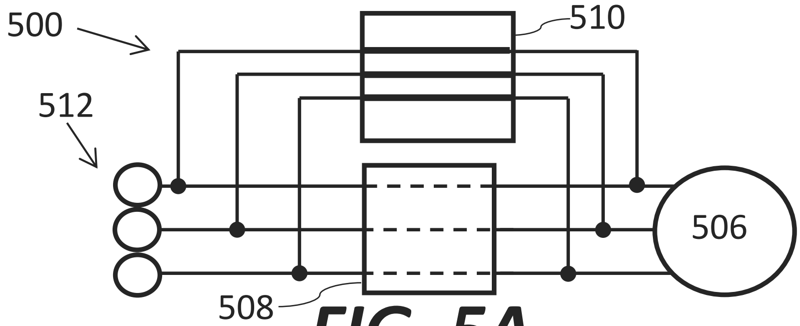


FIG. 5A

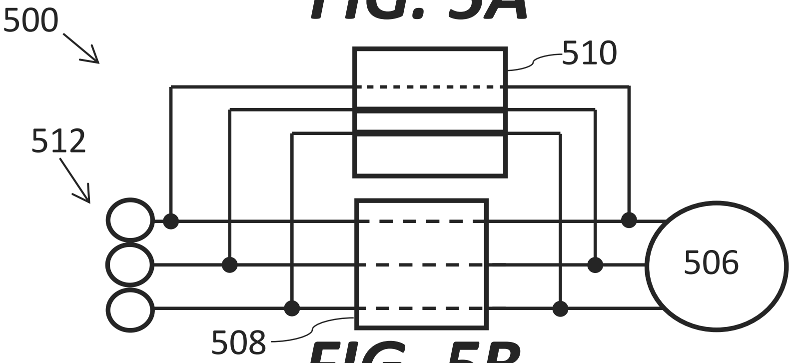


FIG. 5B

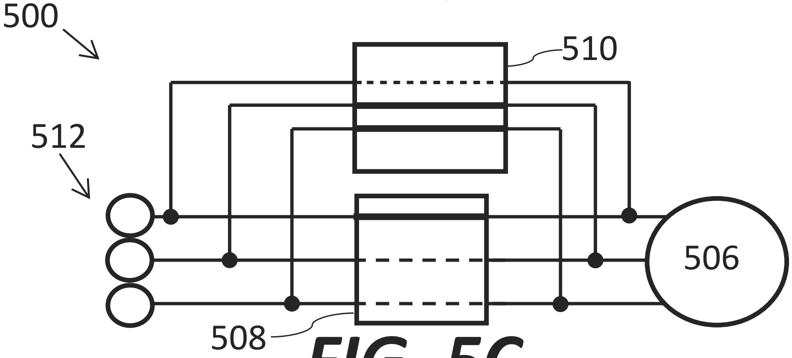


FIG. 5C

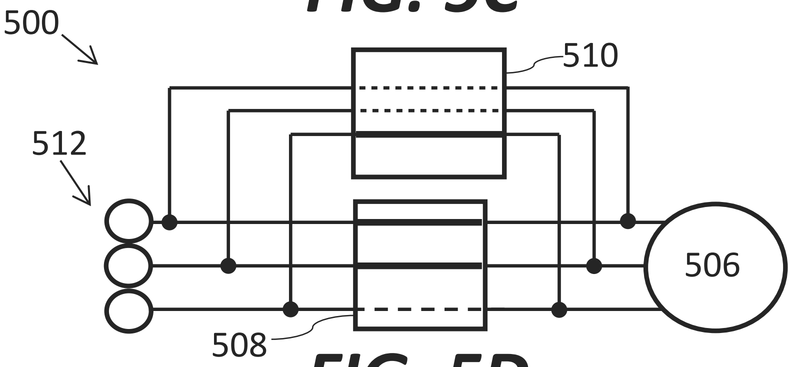


FIG. 5D

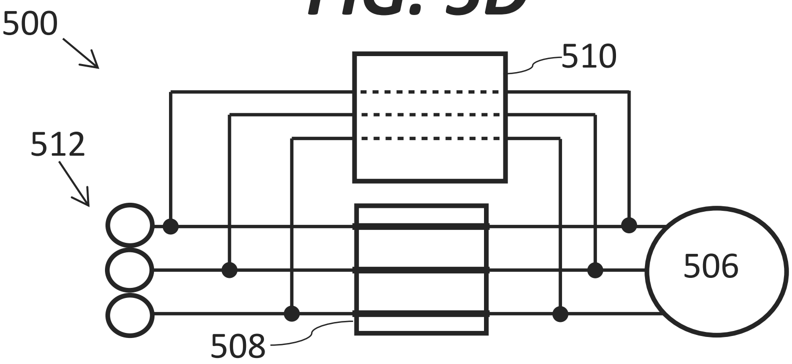


FIG. 5E

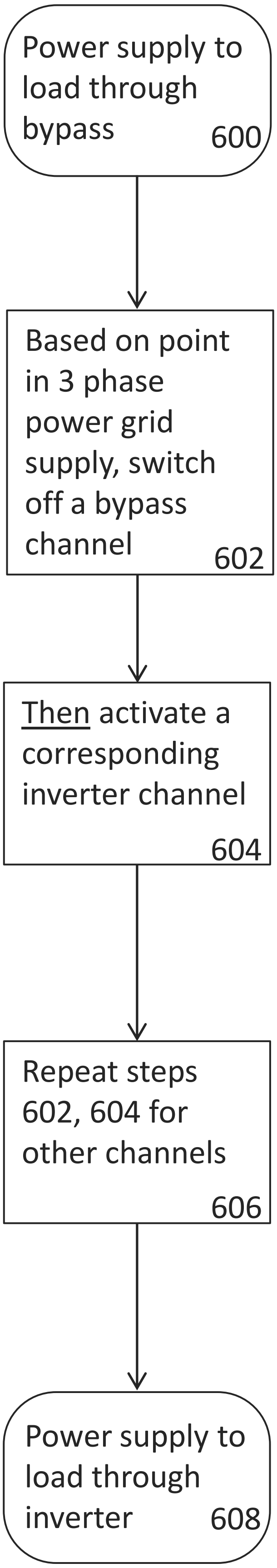


FIG. 6

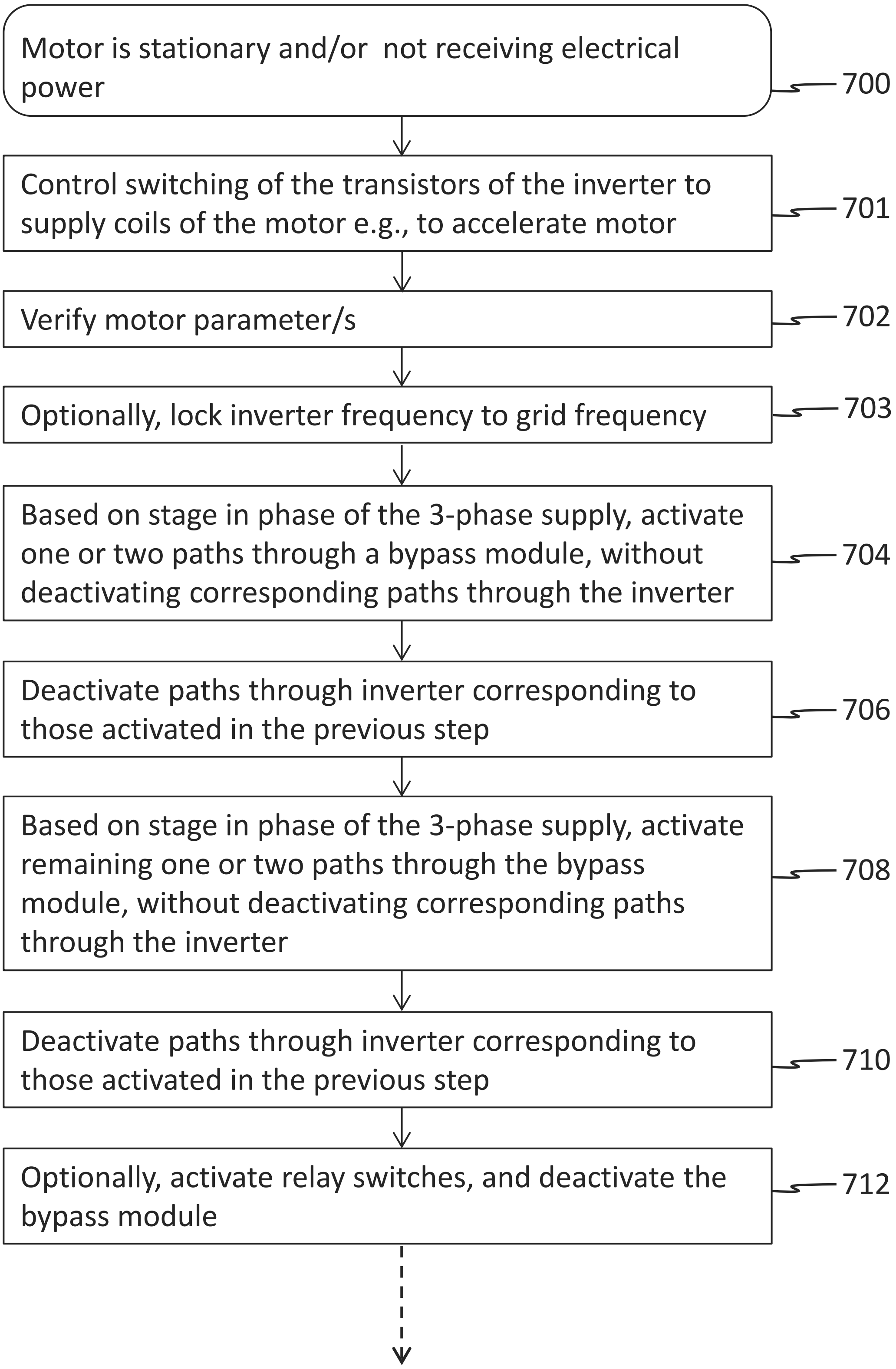

Motor is stationary and/or not receiving electrical power
700
Control switching of the transistors of the inverter to supply coils of the motor e.g., to accelerate motor
701
Verify motor parameter/s
702
Optionally, lock inverter frequency to grid frequency
703
Based on stage in phase of the 3-phase supply, activate one or two paths through a bypass module, without deactivating corresponding paths through the inverter
704
Deactivate paths through inverter corresponding to those activated in the previous step
706
Based on stage in phase of the 3-phase supply, activate remaining one or two paths through the bypass module, without deactivating corresponding paths through the inverter
708
Deactivate paths through inverter corresponding to those activated in the previous step
710
Optionally, activate relay switches, and deactivate the bypass module
712

FIG. 7A

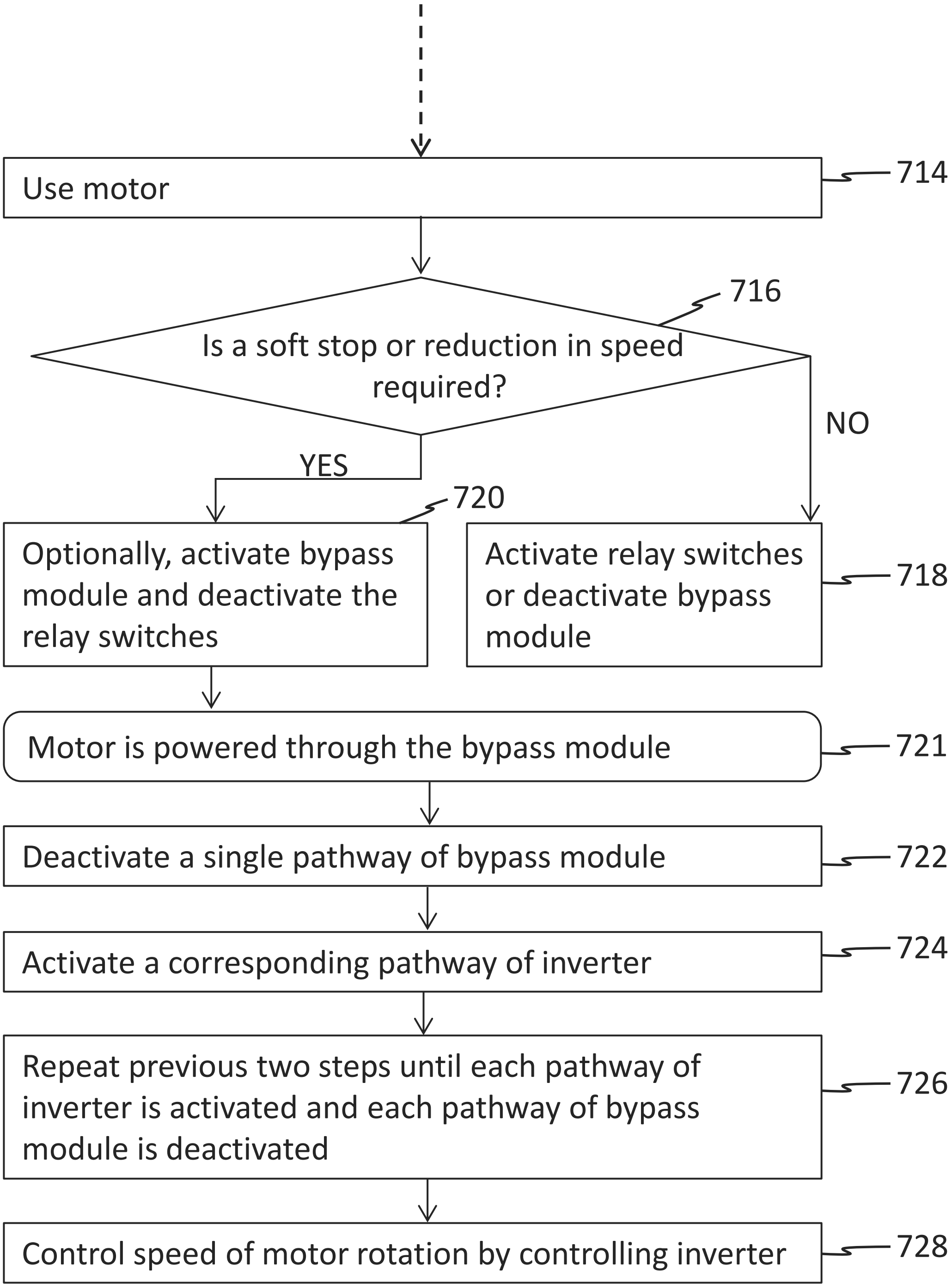

Use motor
714
Is a soft stop or reduction in speed required?
716
YES
NO
720
Optionally, activate bypass module and deactivate the relay switches
Activate relay switches or deactivate bypass module
718
Motor is powered through the bypass module
721
Deactivate a single pathway of bypass module
722
Activate a corresponding pathway of inverter
724
Repeat previous two steps until each pathway of inverter is activated and each pathway of bypass module is deactivated
726
Control speed of motor rotation by controlling inverter
728

FIG. 7B

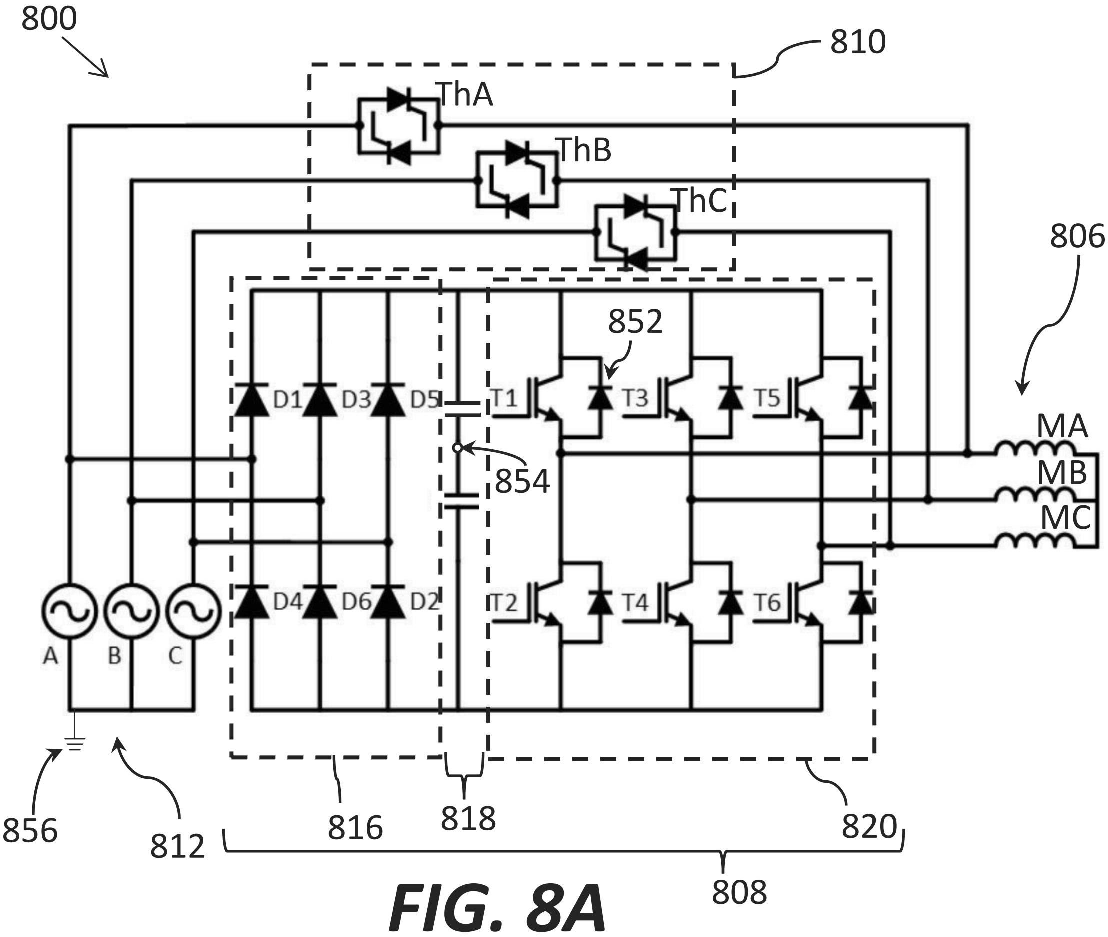

800
810
ThA
ThB
ThC
806
852
D1
D3
D5
T1
T3
T5
MA
854
MB
MC
D4
D6
D2
T2
T4
T6
A
B
C
856
812
816
818
820
808

FIG. 8A

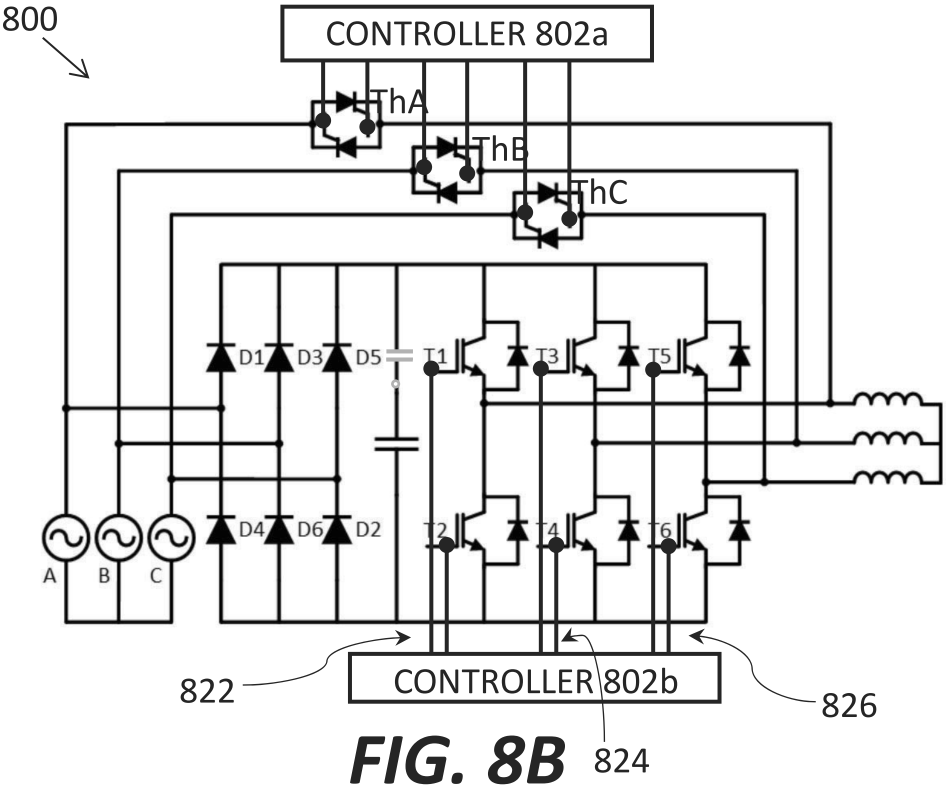

800
CONTROLLER 802a
ThA
ThB
ThC
D1
D3
D5
T1
T3
T5
D4
D6
D2
T2
T4
T6
A
B
C
822
CONTROLLER 802b
826
824

FIG. 8B

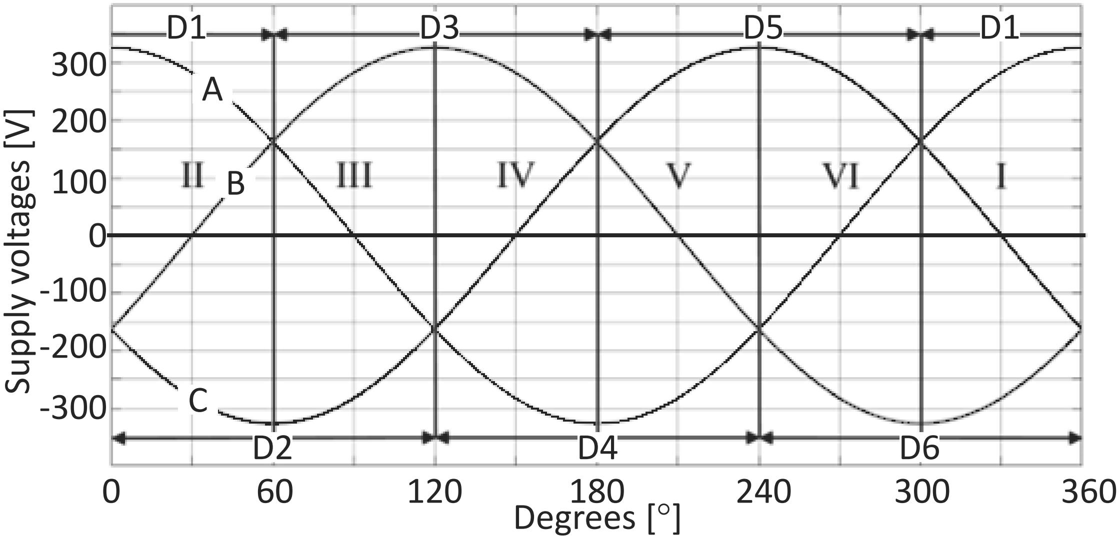

D1
D3
D5
D1
A
B
C
II
III
IV
V
VI
I
D2
D4
D6
Supply voltages [V]
300
200
100
0
-100
-200
-300
0
60
120
180
240
300
360
Degrees [°]

FIG. 9

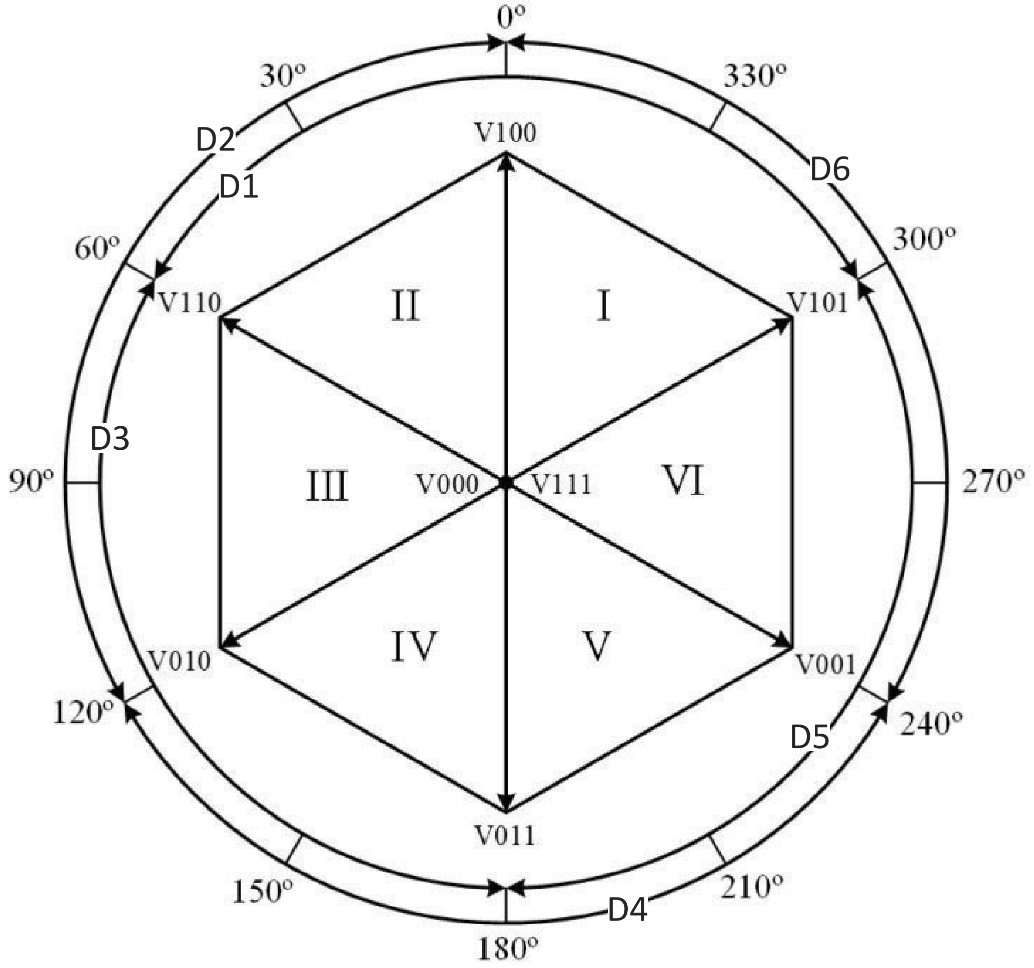

0°
30°
330°
D2
D1
D6
60°
300°
V100
V110
V101
II
I
D3
90°
III
V000
V111
VI
270°
IV
V
V010
V001
120°
240°
D5
V011
150°
210°
D4
180°

FIG. 10

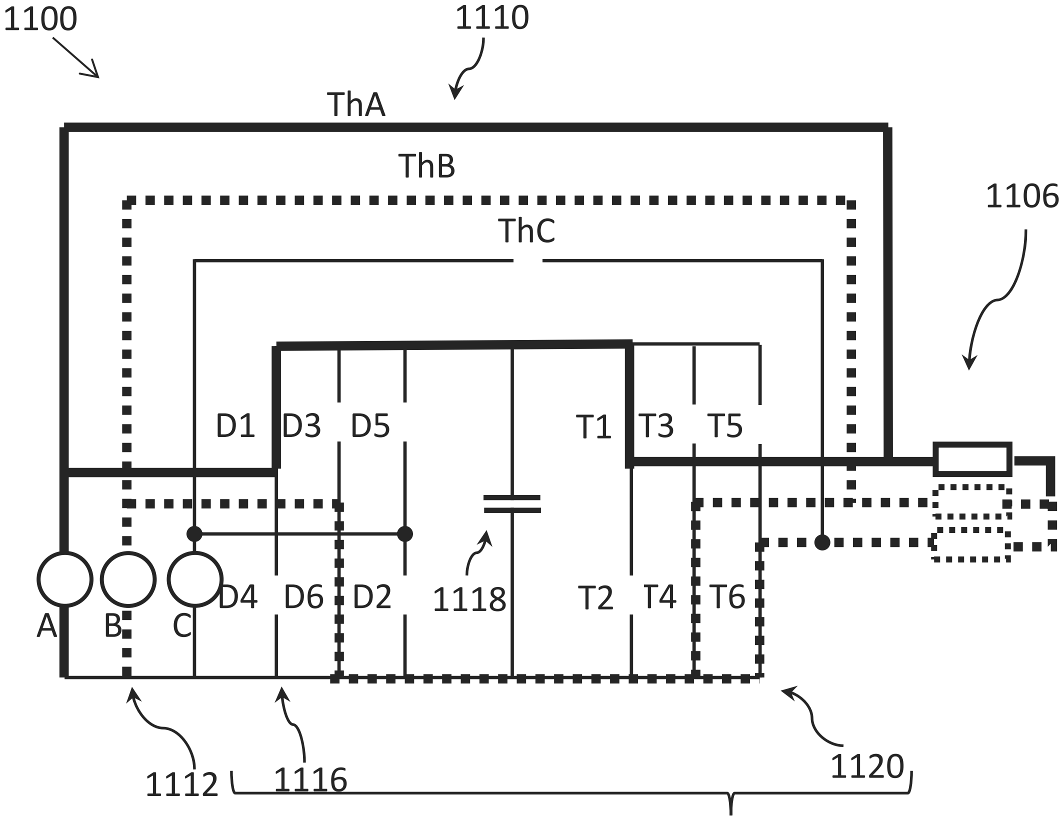


FIG. 11A

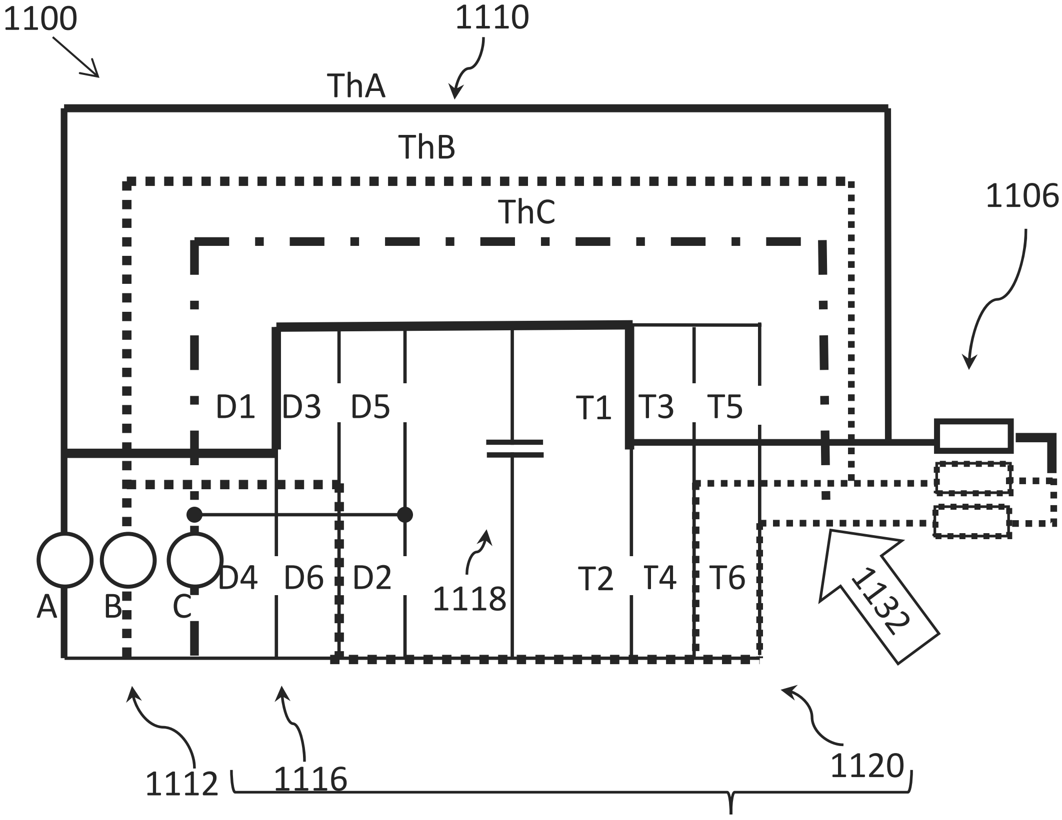


FIG. 11B

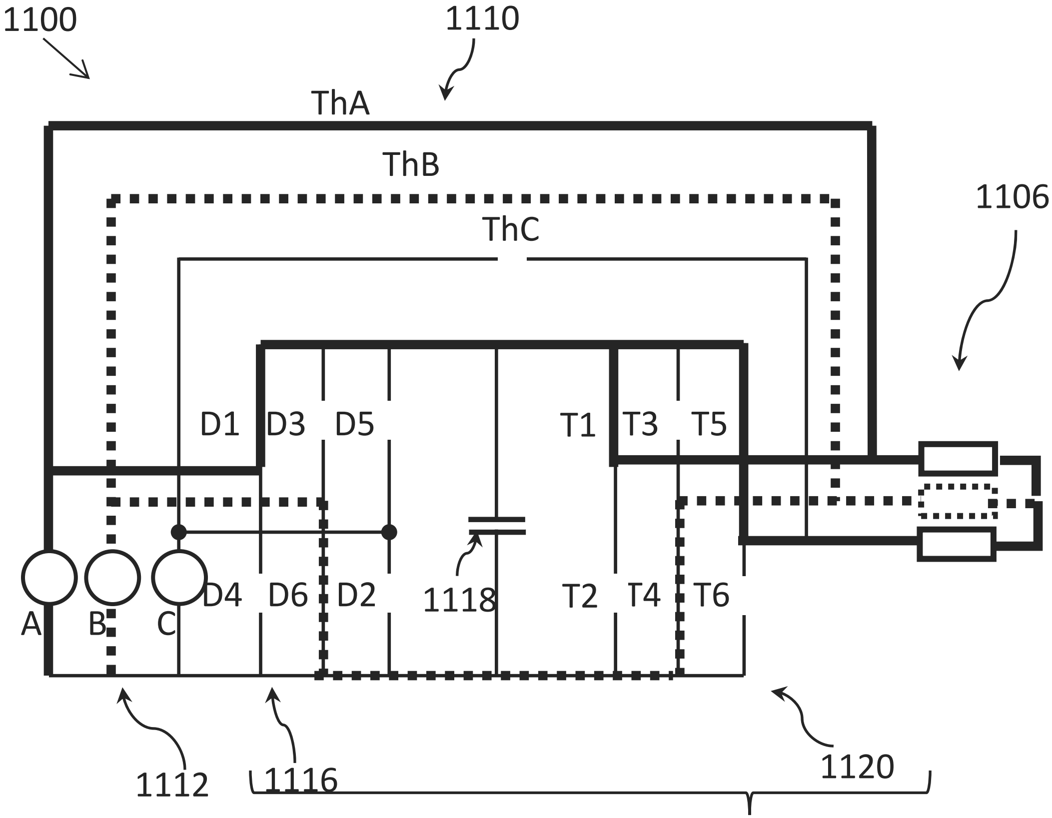


FIG. 11C

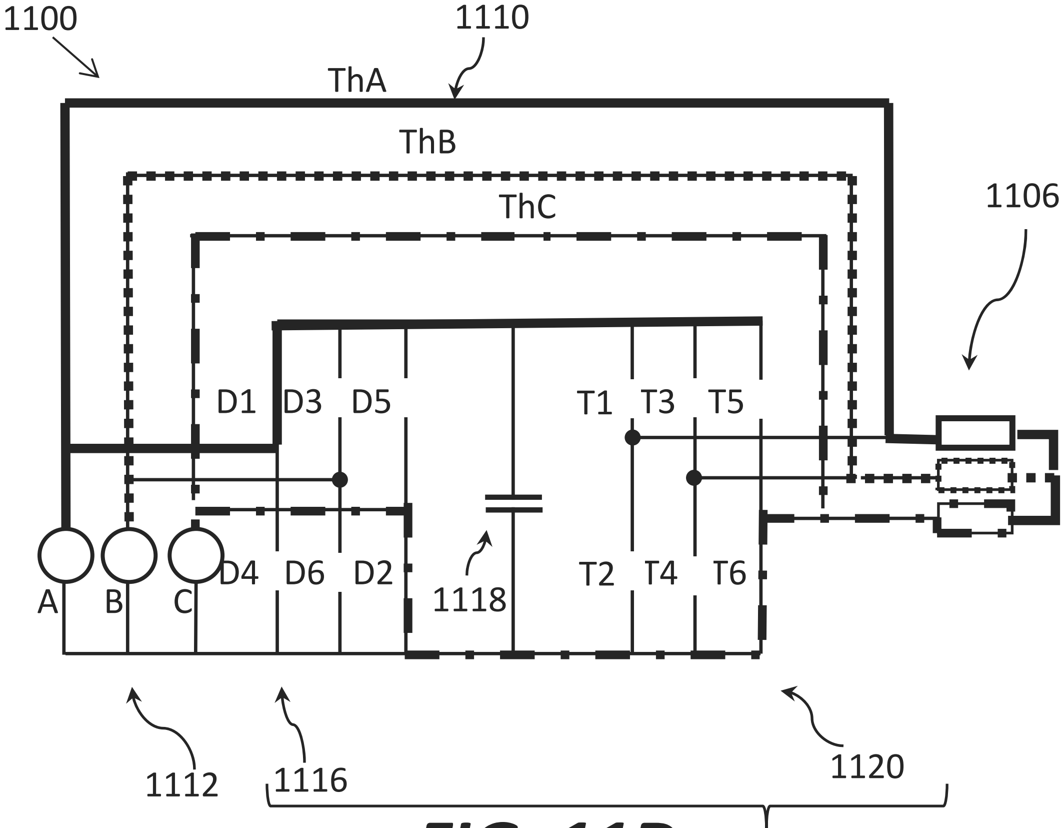


FIG. 11D

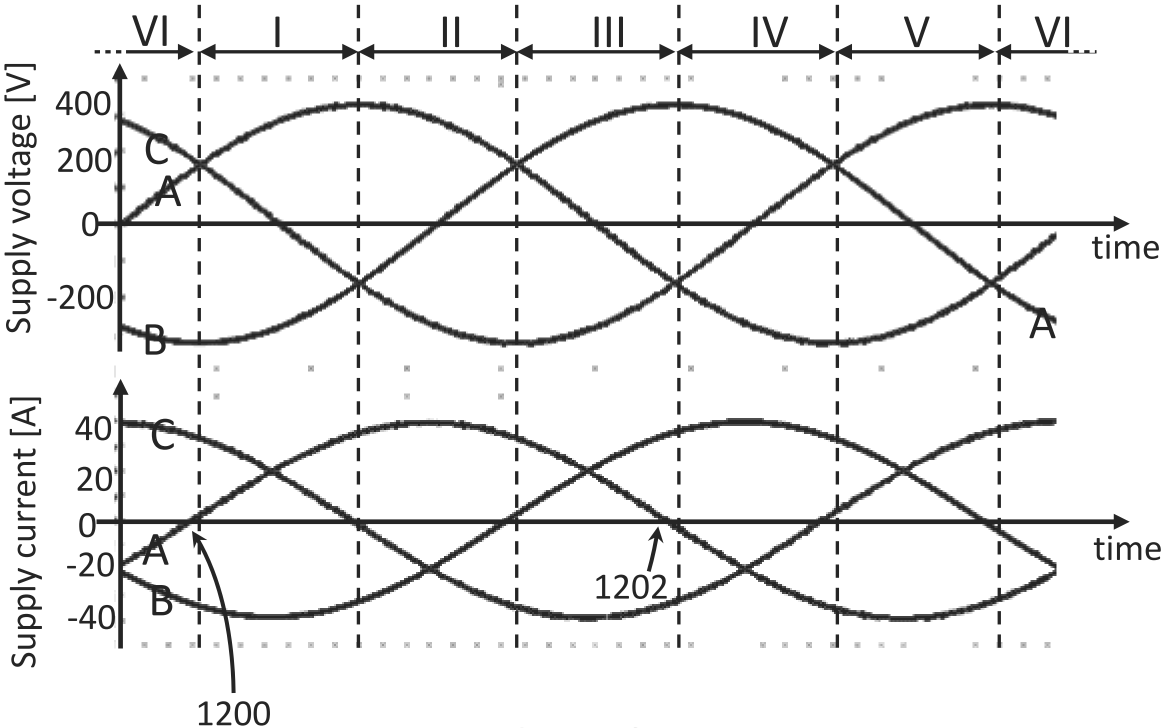


FIG. 12

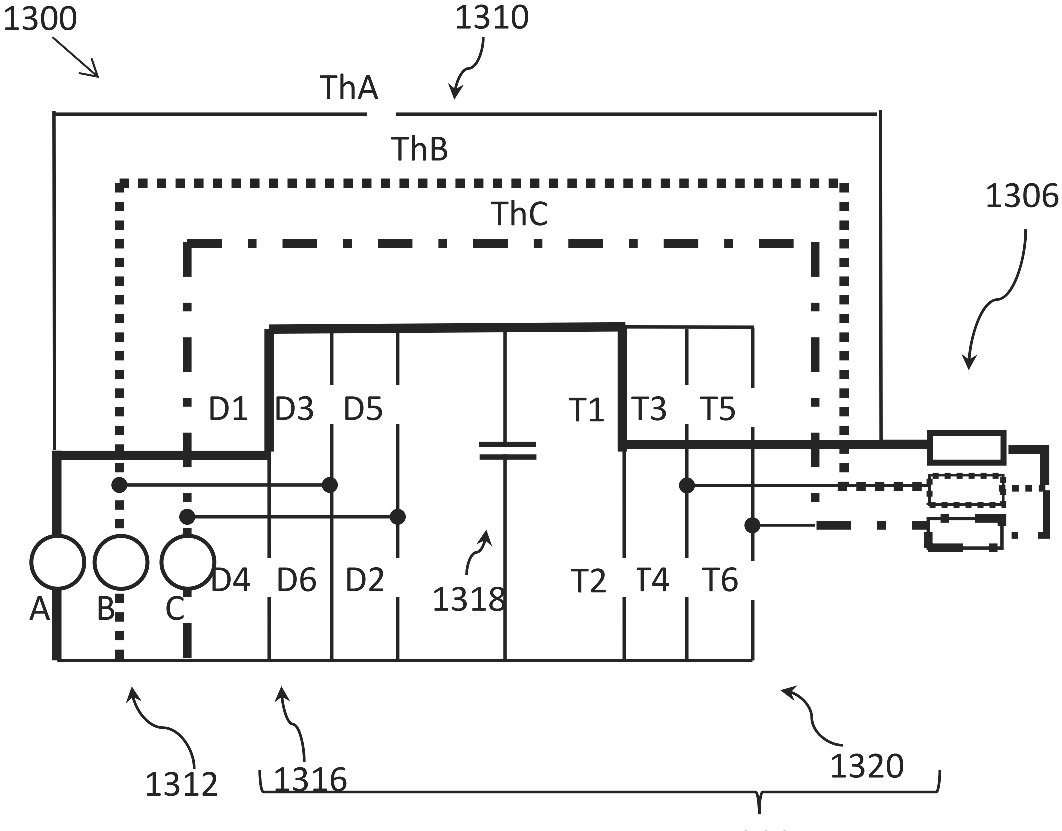


FIG. 13A

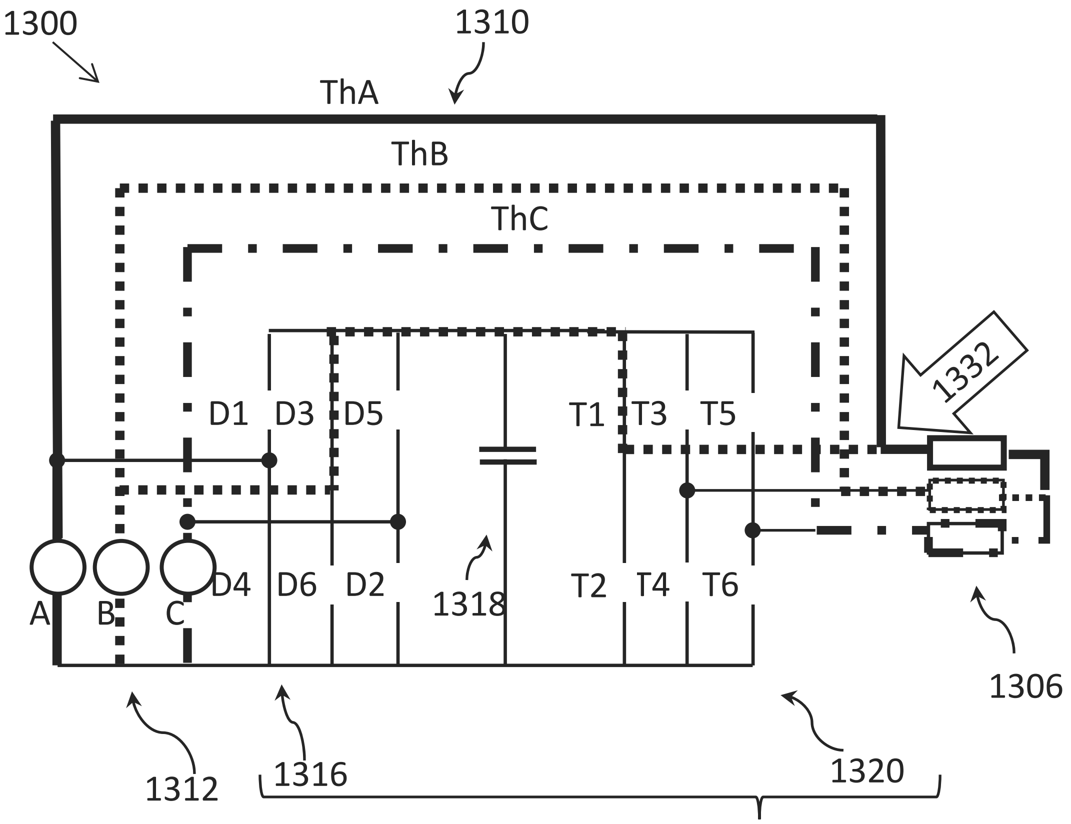


FIG. 13B

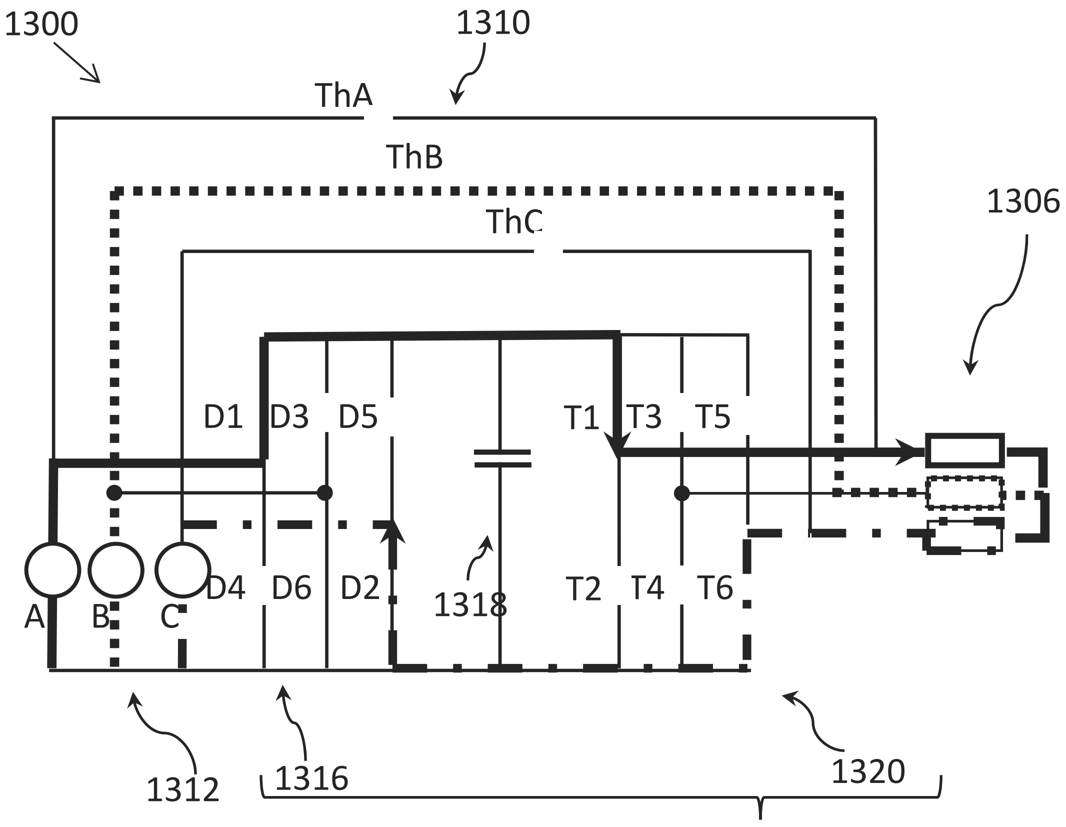


FIG. 13C

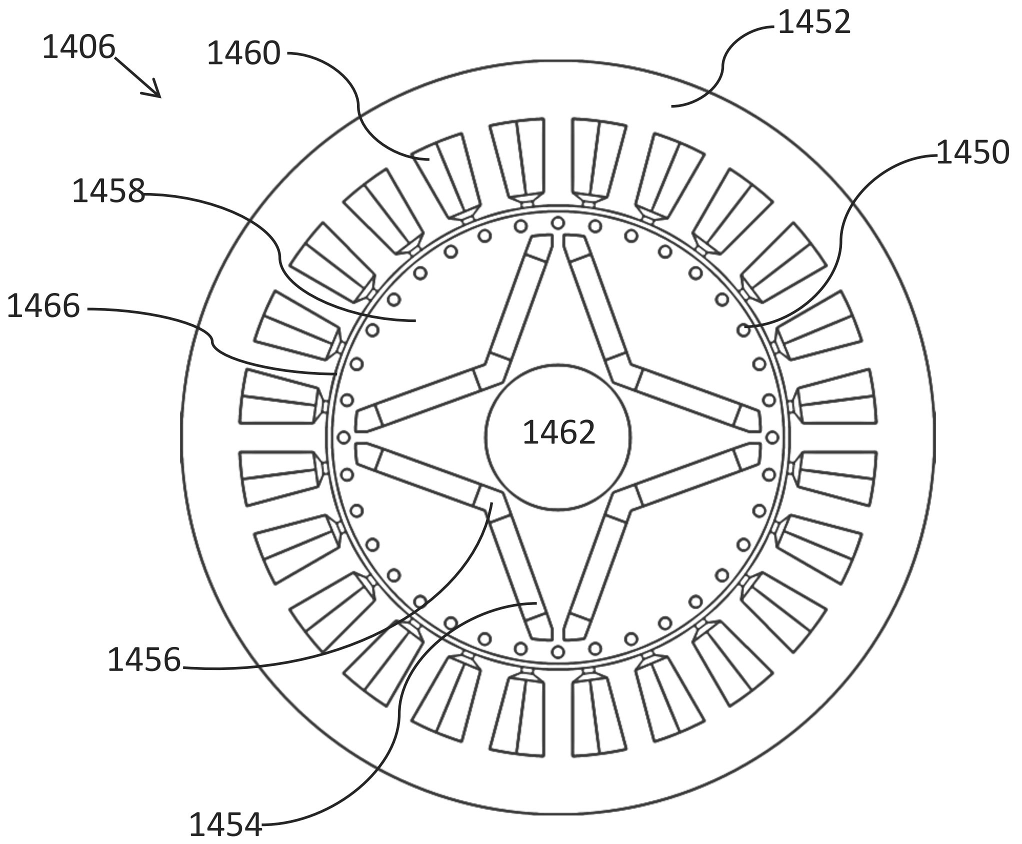

1406
1460
1452
1450
1458
1466
1462
1456
1454

FIG. 14

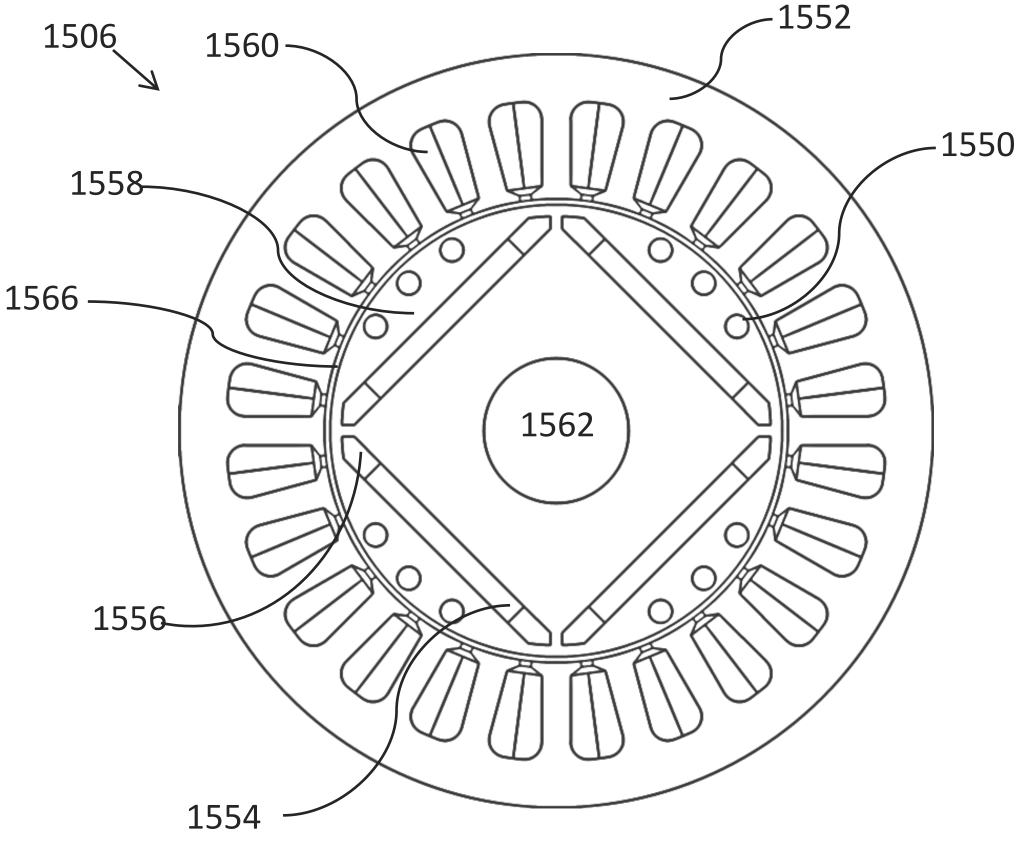

1506
1560
1552
1550
1558
1566
1562
1556
1554

FIG. 15

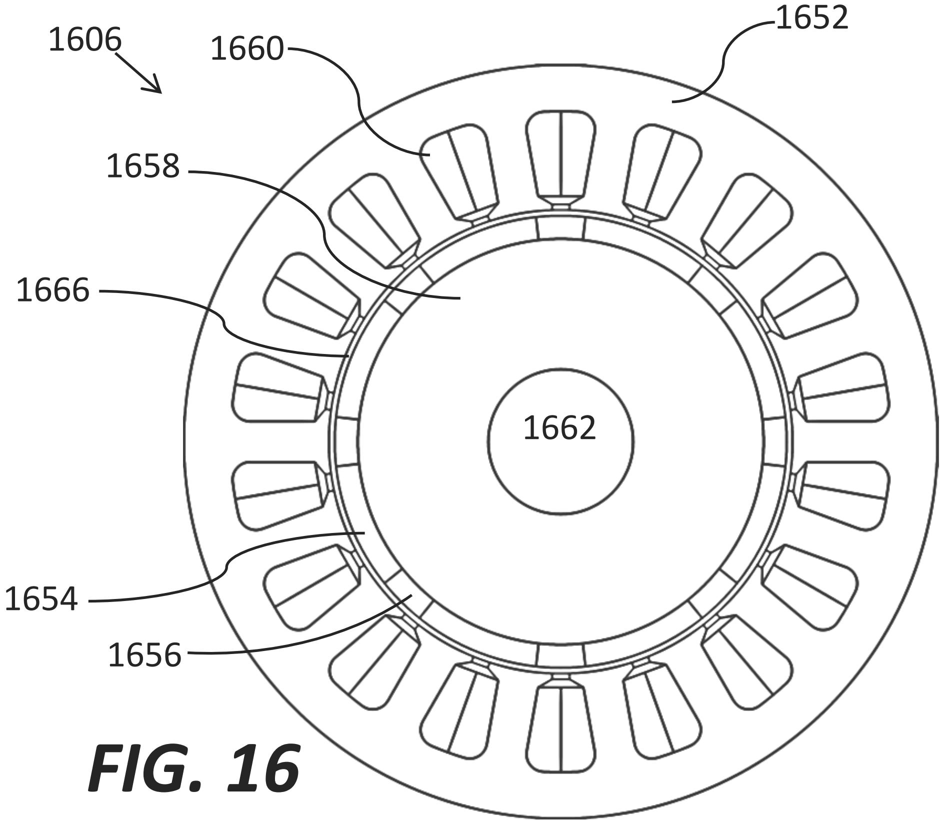

1606
1660
1652
1658
1666
1662
1654
1656

FIG. 16

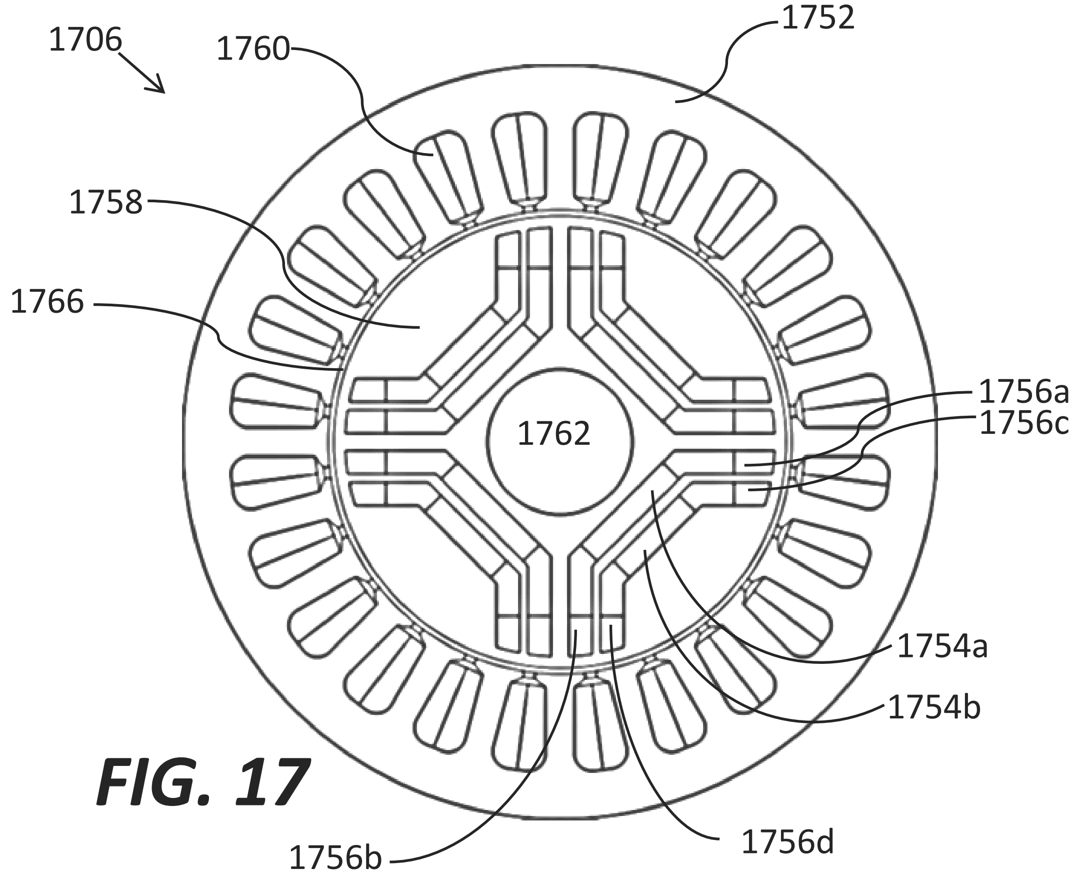

1706
1760
1752
1758
1766
1762
1756a
1756c
1754a
1754b
1756b
1756d

FIG. 17

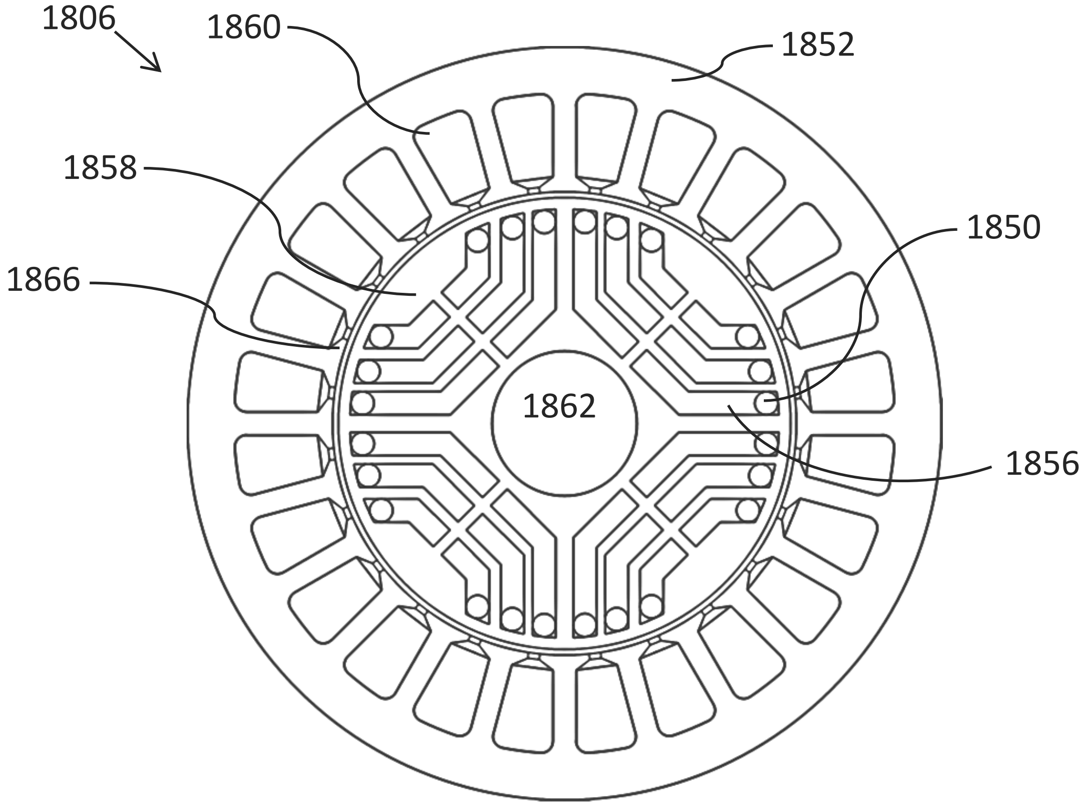

1806
1860
1852
1858
1850
1866
1862
1856

FIG. 18

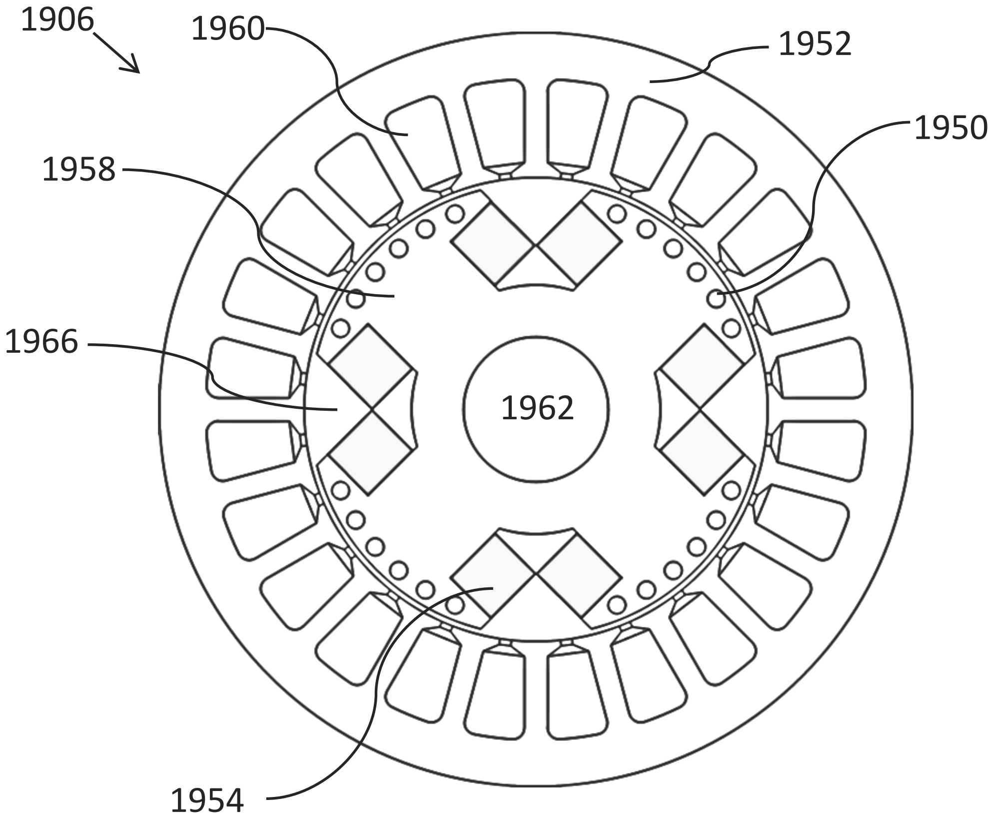

1906
1960
1952
1958
1950
1966
1962
1954

FIG. 19

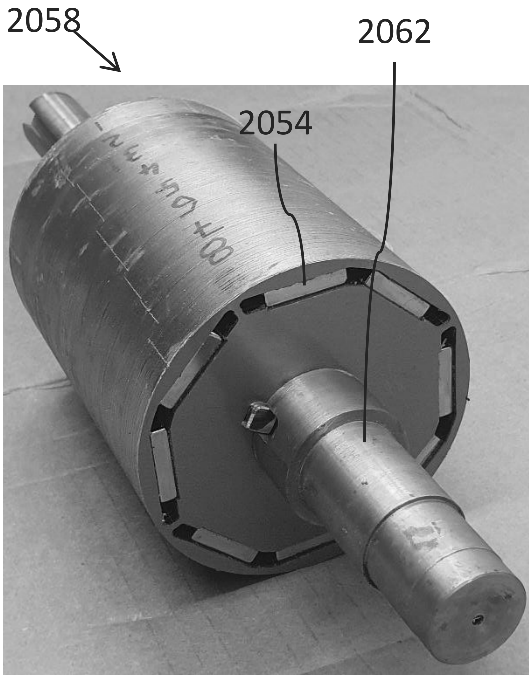


FIG. 20A

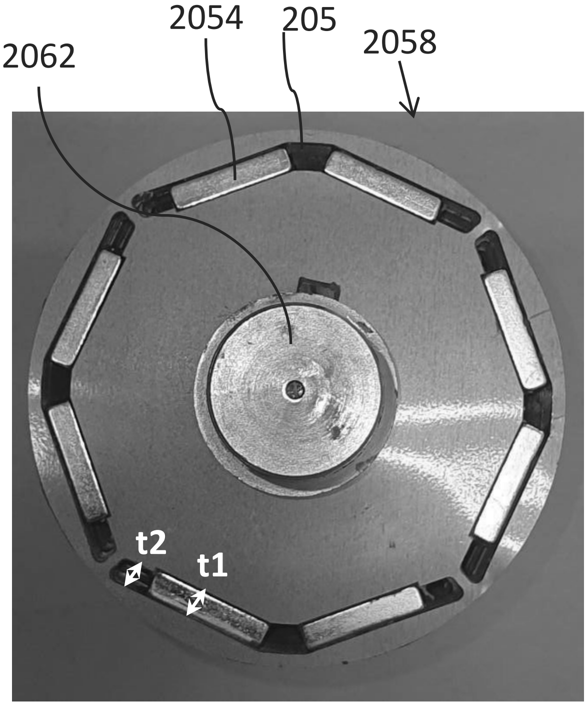


FIG. 20B

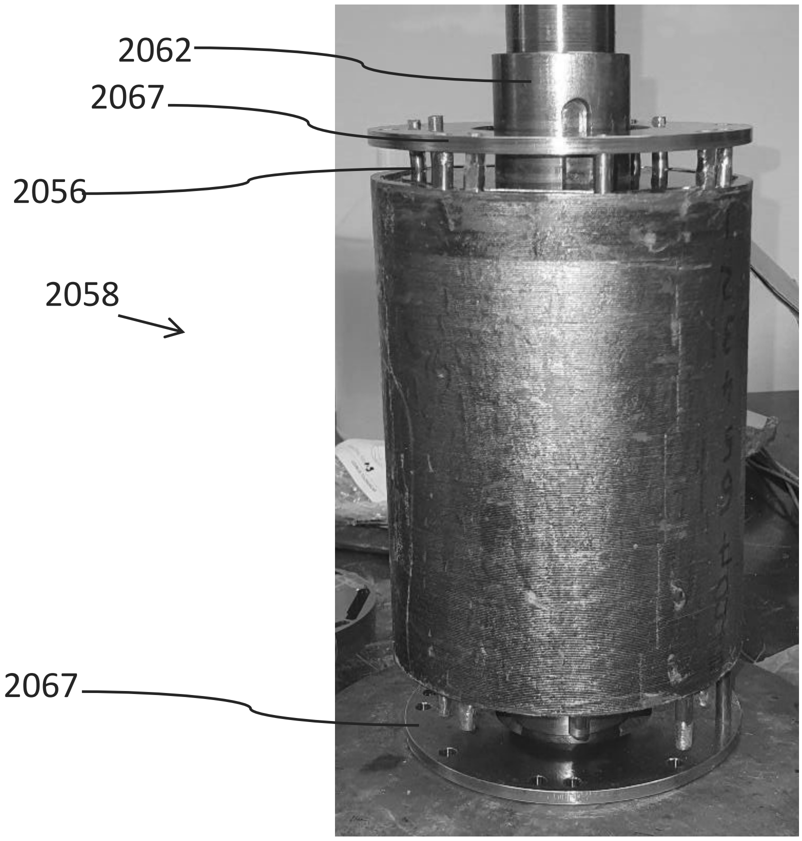


FIG. 20C

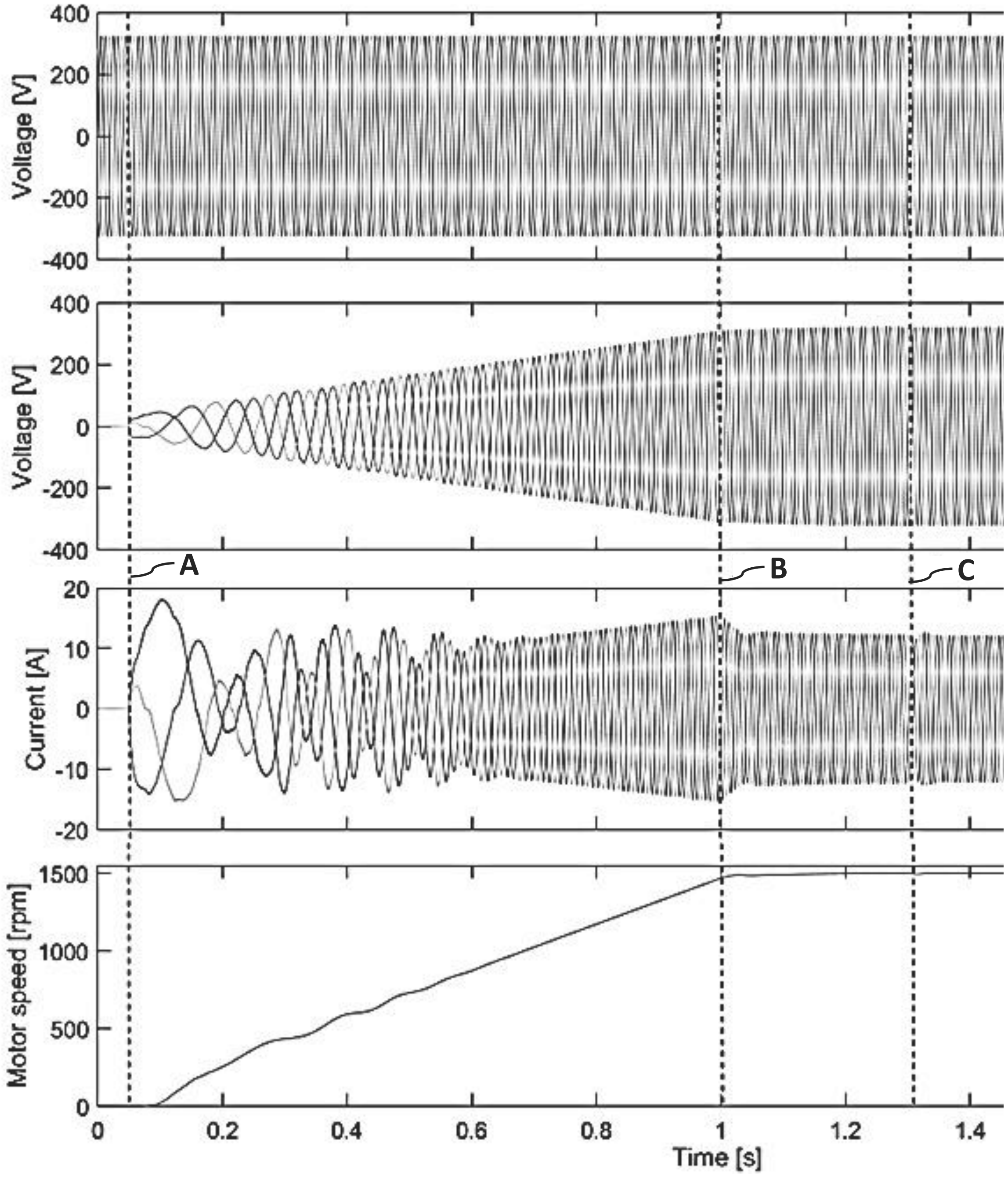

400
200
0
-200
-400
Voltage [V]
400
200
0
-200
-400
Voltage [V]
A
B
C
20
10
0
-10
-20
Current [A]
1500
1000
500
0
Motor speed [rpm]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Time [s]

FIG. 21

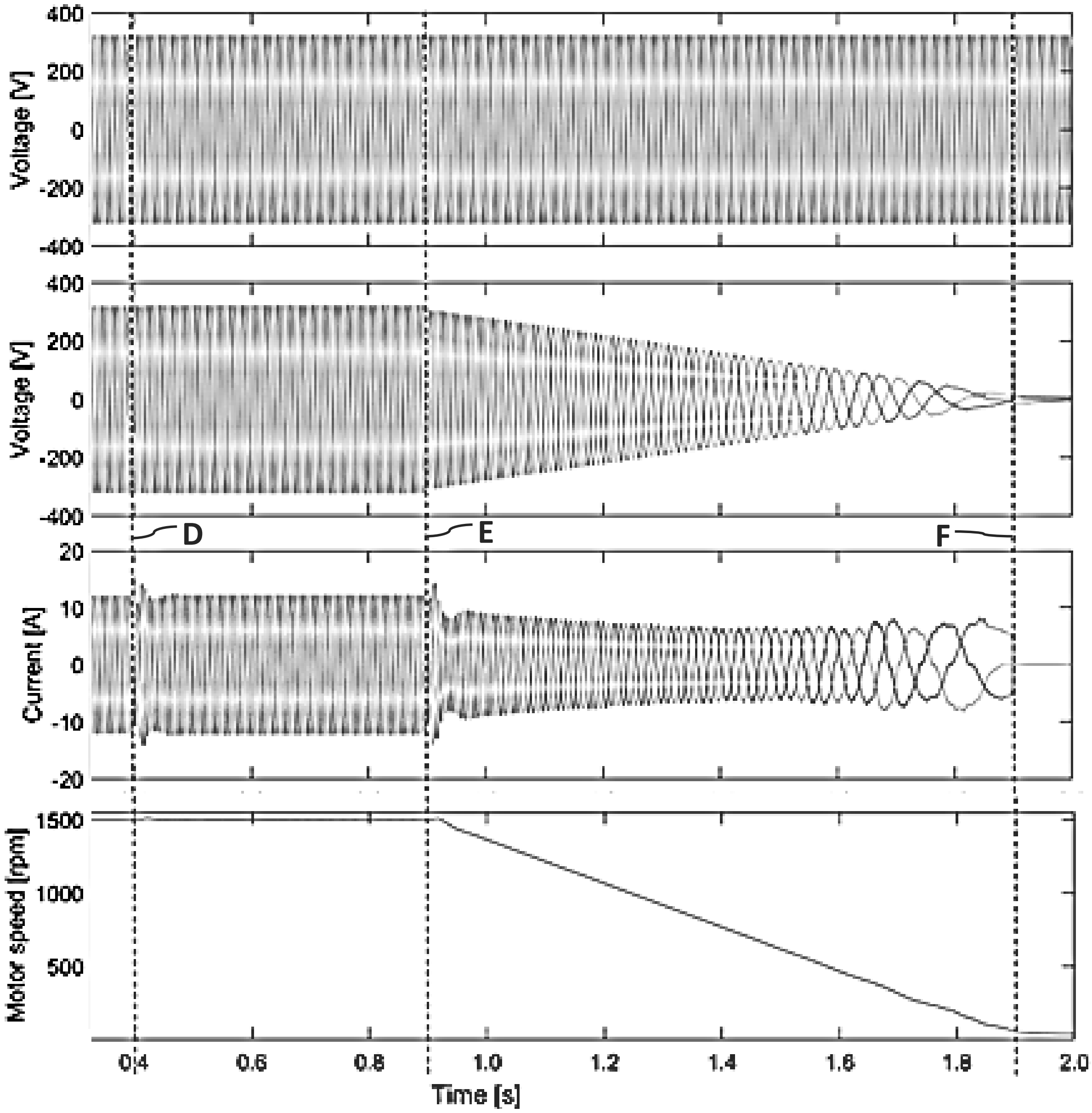

400
200
0
-200
-400
Voltage [V]
400
200
0
-200
-400
Voltage [V]
D
E
F
20
10
0
-10
-20
Current [A]
1500
1000
500
Motor speed [rpm]
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Time [s]

FIG. 22

ABSTRACT

A system comprising: a rotor comprising one or more elements providing a rotor magnetic field and an induction structure including at least one closed conduction loop, the rotor within a bore of a stator which provides a stator rotating magnetic field interacting with the rotor magnetic field to produce torque and crossing the at least one closed conduction loop; an inverter receiving a three phase supply and delivering a variable frequency three phase supply to the stator through a plurality of electrical pathways; a bypass module configured to selectively deliver the three phase supply directly to the stator through a plurality of bypass electrical pathways; a controller configured to: identify a phase state of the three phase supply; activate bypass pathways and deactivate inverter pathways, while continuously maintaining power through at least one pathway to the stator, timing of individual activations and deactivations based on the phase state.