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TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS,
ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

DOUBLY EXCITED SYNCHRONOUS MACHINE SYSTEM WITH VARIABLE TORQUE-SPEED-EFFICIENCY CHARACTERISTICS

FIELD

The present disclosure relates generally to synchronous machines with access to one or two types of excitations. More specifically, the present disclosure relates to wound rotor or stator synchronous machines configured for two or more operating modes to provide different operating characteristics. The present disclosure also relates to systems and methods for operating such current carrying conductor wound synchronous machines.

BACKGROUND

Electric vehicle drive systems, also called electric traction drive systems (ETDS), including an inverter and an electric motor with or without gear box, are typically optimized for performance under certain specific conditions, such as a specific drive cycle, peak power rating, continuous power rating, load profile, acceleration, mass of vehicle, etc. to provide maximum drive cycle efficiency within a cost and package target. However, there is no guarantee that a particular electric vehicle (EV) that is using such an ETDS will follow the assumed drive cycle. Several factors, such as driver acceleration behavior, road gradient and mass, may affect real-world driving performance. For example, most existing ETDS are optimized for WLTC (Worldwide harmonized Light vehicles Test Cycles). However, a drive cycle in New York City is different from a drive cycle in another location, such as Detroit, Michigan or Autobahn in Europe. The usage scenario from person to person is also different. Hence, maximum efficiency desired cannot be guaranteed for every driving profile. It would be beneficial

to change the e-drive based on every drive cycle, driver, mass, etc. However, this is not possible using conventional ETDS, as e-drive hardware is fixed when an EV is sold. Accordingly, there is a need to provide electric drive hardware that can employ varying operating characteristics to provide enhanced efficiency over different operating conditions.

SUMMARY

In accordance with an aspect of the disclosure, a system for a synchronous electric machine is provided. The system includes a motor. The motor includes a rotor and a stator. At least one of the rotor or the stator has a plurality of DC excitation conductors. At least one of the rotor or the stator has a plurality of AC windings. The system also includes an inverter configured to generate an AC power on a set of motor leads for application to the plurality of AC windings for providing power to the motor. The system also includes a DC power source configured to supply DC current to at least some of the plurality of DC excitation conductors. The system also includes at least one mode switch configured to change a configuration of at least one of the plurality of DC excitation conductors or the plurality of AC windings.

BRIEF DESCRIPTION OF THE DRAWINGS

Further details, features and advantages of designs of the invention result from the following description of embodiment examples in reference to the associated drawings. FIG. 1 shows a cut-away end view of a conductor wound synchronous machine; FIG. 2 shows a perspective view of a rotor of the conductor wound synchronous machine of FIG. 1;

FIG. 3 shows an efficiency map of the conductor wound synchronous machine of FIG. 1, with stator windings and rotor windings thereof having a first electrical connection;

FIG. 4 shows an efficiency map of the conductor wound synchronous machine of FIG. 1, with stator windings and rotor windings thereof having second electrical connections that are different from the first electrical connection;

FIG. 5 shows the achievable efficiency map of the conductor wound synchronous machine of FIG. 1, with stator windings and rotor windings reconfigured for different operating conditions, in accordance with an aspect of the present disclosure;

FIG. 6 shows a schematic block diagram of a system for a conductor wound synchronous machine, in accordance with an aspect of the present disclosure;

FIG. 7 shows a schematic diagram of a system that includes a first stator mode switch for changing a configuration of the stator windings between different wiring configurations;

FIG. 8 shows a schematic diagram of a system that includes a second stator mode switch for changing a configuration of the stator windings between different wiring configurations;

FIG. 9 shows a schematic diagram of a conventional circuit for exciting field windings of a rotor in a WFSM;

FIG. 10 shows a cross-sectional schematic of a WFSM with slip rings for supplying an excitation current to the field windings in the rotor thereof;

FIG. 11 shows a perspective schematic diagram of a rotor of a WFSM with two different sets of field windings and with slip rings arranged to provide the excitation current thereto;

FIG. 12 shows a schematic diagram of a first circuit for changing the excitation of the field windings for operating the WFSM in two or more different operating modes;

FIG. 13 shows a schematic diagram of a second circuit for changing the excitation of the field windings for operating the WFSM in two or more different operating modes;

FIG. 14 shows a plot illustrating efficiencies of the WFSM for different combinations of speed and torque;

FIG. 15 shows a plot illustrating efficiencies of the WFSM for different combinations of speed and torque and with at least one of the field windings of the rotor operating in a de-excited mode;

FIG. 16 shows a schematic diagram of a first inductive power transfer configuration for supplying an excitation power to the field windings of the WFSM;

FIG. 17 shows a schematic diagram of a second inductive power transfer configuration for supplying an excitation power to the field windings of the WFSM;

FIG. 18 shows a cross-sectional schematic of a WFSM with rotating transformers or multiple PCBs for supplying an excitation current to the field windings in the rotor thereof in accordance with a inductive power transfer system or a capacitive power transfer system;

FIG. 19 shows a flow chart illustrating a method for operating a system for a wound field synchronous machine, in accordance with an aspect of the present disclosure;

FIG. 20 shows a graph of torque vs. speed with plots representing overall operating characteristics of the WFSM with different stator and rotor configurations; and

FIG. 21 shows a plot illustrating efficiencies of the WFSM for different combinations of speed and torque with selective de-excitation of the field windings of the rotor, and with the stator windings being reconfigured for every load point.

DETAILED DESCRIPTION

Referring to the Figures, wherein like numerals indicate corresponding parts throughout the several views, systems and methods for a doubly-excited synchronous machine, such as a wound field synchronous machine (WFSM), that is configured to provide changing operational characteristics that determine its torque-speed curve.

The present disclosure provides a "Chameleon motor" that is capable of changing operational characteristics online (i.e. on-the-fly during operation). The operational characteristics may be changed based on one or more factors, such as the driving profile, load profile, mass etc. Such doubly-excited synchronous machines could be traditionally known as wound rotor/field synchronous machine (WFSM), a synchronous machine with alternating current (AC) and direct current (DC) excited stator, flux augmented machine, etc. The WFSM of the present disclosure may function as a motor, as a generator, and/or for other functions. The WFSM may be called an electric motor, conductor wound motor or simply a motor, for its primary purpose and operation of converting electrical energy to mechanical energy.

Such a WFSM may provide enhanced control opportunities when compared with a permanent magnet synchronous motor (PMSM). For example, a WFSM may provide access to control AC windings and the DC windings independently. The DC windings could be on a stator or rotor of the machine. The machine could have one or more rotors and one or more stators. Such a motor-based e-drive has been found to provide

higher drive cycle efficiency compared to a permanent magnet machine in certain mid to high-speed drive cycles with comparatively same or lower cost. Furthermore, the proposed approaches can further expand the torque-speed region of the same motor hardware and provide better efficiency at different operating points and conditions. The proposed techniques can be applied to stator only, rotor only and/or to both the rotor and the stator. Hence, this provides multiple torque speed maps beyond the conventional torque speed map of the machine.

Let us take WFSM as an example to implement and prove the proposed approach. Such a motor could have an n-phase, AC fed stator wound to provide m-poles and an m-pole rotor with copper wires wound across the rotor poles. The rotor/field windings are excited by DC. DC power to the rotor could be provided via number of techniques such as: 1) conductive power transfer system – Brushes and slip rings 2) wireless power transfer system: inductive or capacitive power transfer system 3) self-excited system: rotor excitation comes from the stator side employing different harmonic components and a rotating rectifier. Rotor could also have transformer windings in addition to field windings. Although a WFSM is used as an example, the principles of the present disclosure may be applied to other types of motors, such as motors having either or both of stator windings and/or permanent magnets disposed in the stator and/or motors having either or both of rotor windings and/or permanent magnets disposed in the rotor.

In accordance with an aspect of the disclosure, a system for a synchronous electric machine is provided. The system includes a motor including a stator having a plurality of stator windings and a rotor having a plurality of rotor windings. The system also includes

an inverter configured to generate an AC power on a set of motor leads for application to the plurality of stator windings for providing power to the motor. The system also includes number of switches configured to change a configuration of the plurality of stator windings between different coils. This may result in shifting between serial and parallel winding configurations, number of poles, star and delta winding arrangements, etc. For example, the system could change a configuration of the plurality of stator windings and/or a configuration of the plurality of rotor windings to optimize for both efficiency and for performance, on-the-fly during operation. The configurations of the plurality of stator windings and/or the plurality of rotor windings may be adjusted depending on requirements for the motor under a given set of conditions, such as motor speed and/or torque demand.

In accordance with another aspect of the disclosure, a system for a synchronous electric machine is provided. The system includes a motor including a stator having a plurality of stator windings and/or permanent magnets and a rotor having a plurality of rotor windings and/or permanent magnets. The system also includes an inverter configured to generate an AC power on a set of motor leads for application to the plurality of stator windings for providing power to the motor. The system also includes a DC power source configured to supply DC current to a DC excitation conductor. The system also includes an excitation supply including an excitation changing switch that selectively controls current flow between the DC excitation conductor and at least one rotor winding of the plurality of rotor windings.

In accordance with another aspect of the disclosure, a system for a synchronous electric machine is provided. The system includes a motor including a stator having a

plurality of stator windings and a rotor having a plurality of rotor windings. The system also includes an inverter configured to generate an AC power on a set of motor leads for application to the plurality of stator windings for providing power to the motor. The system also includes one or many switches configured to change a configuration of the plurality of stator windings between different coils. This may result in shifting between serial and parallel winding configurations, number of poles, star and delta winding arrangements, etc. The system also includes a DC power source configured to supply DC current to a DC excitation conductor. The system also includes an excitation supply including an excitation changing switch that selectively controls current flow between the DC excitation conductor and at least one DC winding of the plurality of DC windings. The principles of the present disclosure may be applied to various different types of synchronous machines having AC and DC windings. Either or both of the AC windings and/or the DC windings may be located on the stator and/or the rotor. A wound-field synchronous motor (WFSM) is used as an example to show results of the present invention. Windings in the stator and the rotor may each have configurations that are changed separately or in any combination to achieve optimal performance.

The system of the present disclosure may use a number of switches in the rotor or stator to configure different coil connections, which can provide different designs such as serial and parallel winding designs, change number of poles, star and delta winding arrangements, tap changing, etc.

FIG. 1 shows a cut-away end view of a WFSM 10. The WFSM 10 includes a rotor 20 and a stator 30. FIG. 2 shows a perspective view of the rotor 20 of the WFSM 10. The rotor 20 may be similar or identical to a rotor for a conventional salient pole wound-field

synchronous machine. Specifically, the rotor 20 is a salient pole type rotor having a rotor core 22 of electrical steel that includes a base 23 having a ring-shaped cross-section defining a bore that receives a motor shaft 28. The base 23 extends annularly about an axis of rotation of the rotor 20. The rotor 20 also includes a plurality of poles 24 extending radially outwardly from the base 23 of the core 22 at regular angular intervals thereabout. The rotor 20 shown in FIG. 1 has eight of the poles 24, each spaced apart by 45-degrees. However, the rotor 20 may include any number of the poles 24, such as four or six of the poles 24. Each of the poles 24 has a T-shape cross-section, with a body 25 extending radially outwardly from the base 23 and a head 27 extending perpendicularly to the body 25 and spaced away from the base 23.

A rotor winding 26 of conductive wire wraps around the body 25 of each of the poles 24 for carrying an electrical current and thus generating a magnetic field through each of the pole 24. The rotor winding 26 in adjacent ones of the poles 24 may carry different currents, such as currents in opposite directions, thereby causing adjacent ones of the poles 24 to have magnetic fields in opposite directions. The WFSM 10 shown in FIG. 1 is configured as an internal rotor motor, circumferentially surrounded by a stator 30 that remains stationary as the first rotor 10 rotates. However, the principles of the present disclosure may be applied to an external rotor motor configuration having an external rotor that surrounds the stator.

The stator 30 of the WFSM 10 includes a stator core 32 of electrical steel having a cylindrical shape. The stator 30 also includes a plurality of stator teeth 34 that protrude radially inwardly from the stator core 32 and which extend along an axial length of the stator 30. The stator 30 shown in FIG. 1 includes forty-eight of the stator teeth 34.

However, the stator 30 may include a different number of the stator teeth 34. A plurality of stator windings 36 of conductive wire wraps around each of the stator teeth 34 for selectively generating magnetic fields therein.

Reconfigurable stator winding approach to change the torque-speed-efficiency maps

Keeping a same stator core 32, the stator windings 36 can be wired differently to have different number of poles, star and delta configurations, have one serial path or multiple parallel paths etc. on the fly during motor operation. For example, having one serial path will provide a high torque and low base speed, will have a shorter constant torque region and extended constant power region compared to having multiple parallel paths. Torque speed map of the WFSM 10 can be expanded with the same stator and rotor hardware by changing sets of the stator windings 36 from serial to parallel winding configuration. For example, and with reference to FIG. 1, the forty-eight stator windings 36 may include sixteen of the stator windings 36 associated with each of three electrical phases, A, B, and C. The sixteen A-phase ones of the stator windings 36 may be electrically connected in serial. Alternatively, the A-phase ones of the stator windings 36 may be electrically connected in two or more parallel combinations. For example, the A-phase ones of the stator windings 36 may include eight sets of two parallel-connected stator windings 36. The eight sets that comprise the A-phase ones of the stator windings 36 may be connected in series. However, this is merely an example, and the WFSM 10 may include a different number and/or a different configuration of the stator windings 36.

Changes to the configuration of the stator and rotor windings 36 can affect properties of the WFSM 10. Multiple parallel paths will lead to reduction in overall peak torque capability, extended base speed, constant torque region and constant power region. Both the resultant torque speed maps due to series and parallel configurations of the stator and rotor windings 36 will have different efficiency contours as well. Hence, it would be beneficial to reconfigure the stator and rotor windings 36 during online operation of the machine depending on the load point and operating conditions. In one example, the stator windings 36 may be reconfigured from series to parallel wiring configurations, or vice versa. Depending on the number of parallel paths, the stator resistance and hence copper loss in the WFSM 10 can be reduced by a factor of four, leading to efficiency benefits in the overall torque speed envelop of the machine. Additionally or alternatively, other reconfiguration of the stator and rotor windings 36 may be performed during online operation of the machine, such as a number of poles that are energized.

FIG. 3 shows an efficiency map of the WFSM 10 with stator and rotor windings 36 having a first electrical connection, and FIG. 4 shows an efficiency map of the WFSM 10 with stator and rotor windings 36 having second electrical connections that are different from the first electrical connection. FIG. 5 shows an efficiency map of the WFSM 10 with stator and rotor windings 36 having different electrical connections (i.e., serial or parallel, pole changed, coil changed) for different operating conditions, such as different combinations of torque and speed, and to optimize for efficiency of the WFSM across the ranges of torques and speeds.

FIG. 6 shows a schematic block diagram of a system 40 for operating a WFSM 10, in accordance with an aspect of the present disclosure. The system 40 includes a direct current (DC) power supply 42, such as a battery pack or a DC bus transmitting DC power from a rectifier or another source. The system 40 also includes an inverter 44 including a plurality of power switches 46 (only one representative power switch 46 is shown) that generates, using power from the DC power supply, alternating current (AC) power on a set of motor leads 48 for application to the stator windings 36 of the WFSM 10.

The system 40 includes a controller 50 for controlling various functions. The controller 50 may control operation of the inverter 44. For example, the controller 50 may generate one or more control signal for controlling conductive states of the power switches 46 for generating the AC power. In some embodiments, the controller 50 may control may control other functions and/or components within the system 50, such as operation of a stator mode switch 60 and/or operation of a rotor mode switch 64. The controller 50 includes a processor 52 coupled to a storage memory 114. The storage memory 114 includes an instruction storage 56 storing instructions, such as program code for execution by the processor 52. The storage memory 54 also includes a data storage 56 for holding data for use by the processor 52. The data storage 56 may record, for example, values of the parameters measured by one or more sensors and/or the outcome of functions calculated by the processor 52.

The system 40 also includes a stator mode switch 60 configured to change wiring connections between the motor leads 48 and the stator windings 36. For example, the

stator mode switch 36 may change the stator windings 36 between a parallel configuration and a series configuration.

The system 40 also includes a rotor excitation supply 62, which supplies electrical power for energizing the rotor windings 26 of the WFSM 10. The system 40 also includes a rotor mode switch 64 configured to selectively change wiring connection between the rotor excitation supply 62 and the rotor windings 26 of the WFSM 10. For example, the rotor mode switch 64 may selectively de-energize some of the rotor windings 26 while maintaining supply of power to remaining ones of the rotor windings 26.

FIG. 7 shows a schematic diagram of a first stator mode control system 40a that includes a first stator mode switch 60a for changing a configuration of the stator windings 36 in the WFSM 10 between different wiring configurations. The first stator mode switch 60a functions as the stator mode switch 60 in the system 40 and includes eight mode switches P1, P2, P3, P4, P5, S1, S2, S3. Each of the mode switches P1, P2, P3, P4, P5, S1, S2, S3 may include one or more power electronic devices, such as transistors or other semiconductor switches, for selectively controlling electrical current therethrough. Each of the mode switches P1, P2, P3, P4, P5, S1, S2, S3 may be controlled by the controller 50.

For simplicity of illustration, only six of the stator windings 36 are shown on FIG. 7, including two of the stator windings 36 associated with each of the A, B, and C phases. However, the principle of FIG. 7 may be applied to any number of the stator windings, such as where there are four or more of the stator windings 36 associated with each of the phases, and/or where there are a different number of the phases, such as five, six,

nine, or twelve phases. To operate the WFSM 10 with the stator windings 36 in a series configuration, switches S1, S2, S3 are ON (i.e. in a conductive state); and switches P1, P2, P3, P4, P5 are OFF (i.e. in a non-conductive state). To operate the WFSM 10 with the stator windings 36 in a parallel configuration, switches P1, P2, P3, P4, P5 are ON; and switches S1, S2, S3 are OFF.

FIG. 8 shows a schematic diagram of a second stator mode control system 40b that includes a second stator mode switch 60b for changing a configuration of the stator windings 36 in the WFSM 10 between different wiring configurations. The second stator mode switch 60b functions as the stator mode switch 60 in the system 40 and includes five mode switches Ks1, Ks2, Ks3, Kp1, Kp2. Each of the mode switches Ks1, Ks2, Ks3, Kp1, Kp2 of the second stator mode switch 60b may include one or more power electronic devices, such as transistors or other semiconductor switches, for selectively controlling electrical current therethrough. Each of the mode switches Ks1, Ks2, Ks3, Kp1, Kp2 may be controlled by the controller 50.

For simplicity of illustration, only six of the stator windings 36 are shown on FIG. 8, including two of the stator windings 36 associated with each of the A, B, and C phases. However, the principle of FIG. 8 may be applied to any number of the stator windings, such as where there are four or more of the stator windings 36 associated with each of the phases, and/or where there are a different number of the phases, such as five, six, nine, or twelve phases. The second stator mode control system 40b includes two separate inverters 44a, 44b, with each of the inverters 44a, 44b supplying AC power to a corresponding set of motor leads 48a, 48b.

The stator windings 36 of the WFSM include a first set A1, B1, C1, and a second set A2, B2, C2, with each of the sets A1, B1, C1, A2, B2, C2, of the stator windings 36 being connected to a corresponding one of the inverters 44a, 44b via a corresponding set of the motor leads 48a, 48b.

To operate the WFSM 10 with the stator windings 36 in a first configuration, switches Ks1, Ks2, Ks3 are ON (i.e. in a conductive state); and switches Kp1, Kp2 are OFF (i.e. in a non-conductive state). In this first configuration, only a first inverter 44a may be active. A second inverter 44b of the inverters 44b may remain idle. To operate the WFSM 10 with the stator windings 36 in a second configuration, switches Kp1, Kp2 are ON; and switches Ks1, Ks2, Ks3 are OFF. In this second configuration, each of the sets A1, B1, C1, A2, B2, C2 of the stator windings 36 may be independently supplied with power from a corresponding one of the inverters 44a, 44b. This second configuration is not a true parallel connection, since each of the sets A1, B1, C1, A2, B2, C2 of the stator windings 36 are electrically isolated from one another. However, the separate inverters 44a, 44b may enable the sets A1, B1, C1, A2, B2, C2 of the stator windings 36 to be operated similar to a parallel configuration.

FIG. 9 shows a schematic diagram of a conventional circuit for exciting rotor windings 26 in the WFSM 10. The rotor windings 26 may also be called field windings. The circuit of FIG. 9 includes a first excitation supply 62a which functions as the rotor excitation supply 62 of the system 40. The first excitation supply 62a includes a DC power source 68 and a first field regulator switch 70 configured to selectively conduct current for generating a regulated DC voltage on a first field excitation conductor 72+. The first field regulator switch 70 is shown on FIG. 9 as an insulated gate bipolar transistor (IGBT).

However, other types of devices, such as a field effect transistor or another type of junction device. The controller 50 may control operation of the first field regulator switch 70, such as by using pulse width modulation (PWM) to control the regulated DC voltage for application to the rotor windings 26. A first slip ring 66a and a second slip ring 66b provide electrical connections between the first excitation supply 62a and the rotor windings 26 that rotate with the rotor 20. The first slip ring 66a provides a connection between the first field excitation conductor 72+ and a first end of the rotor windings 26, and the second slip ring 66b provides a connection between a reference conductor 72- and a second end of the rotor windings 26 opposite from the first end thereof.

A first diode 74 includes an anode terminal and a cathode terminal. The anode terminal is connected to a negative terminal of the DC power source 68 and to the reference conductor 72-. The cathode terminal of the first diode 74 is connected to the first field excitation conductor 72+. The first diode 74 may protect the DC power source 68 from a short circuit when the first field regulator switch 70 is switched on. The first diode 74 may also provide a discharge path for de-energizing an inductance L of the rotor winding 26 when the first field regulator switch 70 is off (i.e. in a non-conductive state).

By-product of such an inverter architecture

The WFSM 10 can be used towards integrated charging of a battery pack in an EV, as well. Three terminals of the 3-phase stator/motor can be connected to the grid to get 3-phase supply and the other 3 terminals are connected to the output of the inverter. The rotor windings 26 are de-excited. The stator windings 36 act as a line inductor in the charging circuit. By having the option of changing between series and parallel configurations of the stator windings 36, the value of the line inductor can be varied.

This helps the battery charging operation. Moreover, the additional switches in the inverter 40a, 40b can also be used for mode switching between charging and propulsion.

FIG. 10 shows a cross-sectional schematic of a first WFSM 10a with slip rings 66a, 66b for supplying an excitation current to the field windings in the rotor thereof. The first WFSM 10a shows brushes 67 that slide along the slip rings 66a, 66b for transferring current between the rotor windings 26 and non-rotating external circuitry, such as the rotor excitation supply 62.

Rotor de-excitation approach to change the torque-speed-efficiency maps

Keeping the stator and stator side inverter fixed, rotor could be excited and de-excited in a conventional WFSM by changing the DC field current fed to the rotor between zero and maximum. The rotor poles are serially wound. This application proposes a novel rotor excitation system which can control every pole pair independently and reduce the flux/pole during online operation of the machine. Instead of having one set of conductive or self-excited or wire power transfer system as conventionally used, the proposed concept will have two or more modular excitation systems that can be paralleled and connected to each pole pair or a set of pole pairs. In case we want to operate the motor in its baseline condition to provide maximum torque until base speed all the poles in the rotor will be excited. This will enable operation of the motor that is similar to a conventional WFSM. In case we want to change the torque speed curve of the motor, one or multiple set of brushes can be de-excited, and the stator would see a reduced flux/pole.

This will reduce torque rating of the machine configuration and shift the efficiency contour. It will also improve the core losses due to reduced flux/pole. The field winding resistance will also decrease based on the number of poles excited. This will influence or decrease the rotor copper losses. For example, in an 8 pole rotor, all 8 poles will be excited to deliver maximum performance and only 2 poles will be excited to produce limited torque or power rating performance. Biggest benefit here is that, even though, only 2 poles/one pole pair of the rotor are excited, flux lines still flows through each pole, and hence, the stator sees an 8-pole rotor which keeps the stator and rotor in synchronism.

In a conductive power transfer system, 2 or more brushes can be used with multiple slip rings, where each unit is connected to a specific number of poles. This means a specific set of poles can be excited or de-excited by powering or switching off supply to the corresponding brush-slip ring systems. Two or more brushes may be used for each of the slip rings.

FIG. 11 shows a perspective schematic diagram of a first rotor 20a of a WFSM with a first field winding set 26a and a second field winding set 26b, and with corresponding slip rings 66a, 66b, 66c. The first field winding set 26a is connected to the first slip ring 66a and the second slip ring 66b. The second field winding set 26b is also connected to the second slip ring 66b, which is connected to a common or shared conductor. An end of each winding comprising the second field winding set 26b opposite from the second slip ring 66b is connected to a third slip ring 66c. This third slip ring 66c enables the second field winding set 26b to be energized selectively and separately from the excitation applied to the first field winding set 26a via the first slip ring 66a.

FIG. 12 shows a schematic diagram of a first adjustable excitation circuit 80a for changing the excitation of the field winding sets 26a, 26b for operating the WFSM 10 in two or more different operating modes. The first adjustable excitation circuit 80a includes a second excitation supply 62b that is similar to the first excitation supply 62a, and which may also function as the rotor excitation supply 62 of the system 40. The second excitation supply 62b includes all of the components of the first excitation supply 62a with the addition of an excitation changing switch 82 that selectively controls current flow between the first field excitation conductor 72+ and the second field winding set 26b via a second field excitation conductor 73+ and the third slip ring 66c. The excitation changing switch 82 may include a field effect transistor, such as a MOSFET, that is controlled by the controller 50 for selectively energizing the second field winding set 26b. However, other types of devices, such as a junction transistor may be used for the excitation changing switch 82.

As shown in FIG. 12, each of the first field winding set 26a and the second field winding set 26b may have a resistance value R and an inductance value L that is one-half of a corresponding value of a rotor winding 26 in the rotor 20 shown in FIG. 9.

FIG. 13 shows a schematic diagram of a second adjustable excitation circuit 80b for changing the excitation of the field winding sets 26a, 26b for operating the WFSM 10 in two or more different operating modes. The second adjustable excitation circuit 80b includes a third excitation supply 62c that is similar to the first excitation supply 62a, and which may also function as the rotor excitation supply 62 of the system 40. The third excitation supply 62c includes all of the components of the first excitation supply 62a with the addition of a second field regulator switch 71 and a second diode 75 connected

to the second field winding set 26b via the third slip ring 66c. The second field regulator switch 71 selectively controls current from the DC power source 68 to the second field winding set 26b via the second field excitation conductor 73+ and the third slip ring 66c. The second field regulator switch 71 may be controlled by the controller 50 similarly to the first field regulator switch 70. The field regulator switches 70, 71 may be independently controlled for selectively controlling excitation voltage applied to each of the field winding sets 26a, 26b. The second field regulator switch 71 is shown as an IGBT. However, other types of devices, such as a FET, may be used. The third excitation supply 62c also includes a second diode 75 having an anode terminal and a cathode terminal. The anode terminal of the second diode 75 is connected to a negative terminal of DC power source 68 and to the reference conductor 72-. The cathode terminal of the second diode 75 is connected to the second field excitation conductor 73+. The second diode 75 may protect the DC power source 68 from a short circuit when the second field regulator switch 71 is switched on. The second diode 75 may also provide a discharge path for de-energizing an inductance L of the second field winding set 26b when the second field regulator switch 71 is off (i.e. in a non-conductive state).

As shown in FIG. 13, each of the first field winding set 26a and the second field winding set 26b may have a resistance value R and an inductance value L that is less than corresponding values of a rotor winding 26 in the rotor 20 shown in FIG. 9. For example, each of the first field winding set 26a and the second field winding set 26b may have a resistance value that is one-half of the resistance value of a conventional field winding, and each of the first field winding set 26a and the second field winding set

26b may have an inductance value that is one-half of the inductance value of the conventional field winding.

FIG. 14 shows a plot illustrating efficiencies of the WFSM 10 for different combinations of speed and torque and with a baseline configuration, including all of the field winding sets 26a, 26b being energized. FIG. 15 shows a plot illustrating efficiencies of the WFSM 10 for different combinations of speed and torque and with at least one of the field winding sets 26a, 26b of the rotor 20 operating in a de-excited mode under certain conditions to provide increased efficiency in certain regions.

In a wireless power transfer system, multiple rectifiers exciting specific set of poles or windings can be built on PCBs. Each of these rectifiers will convert AC coming from the receiver compensation network (consisting of stationary and rotating PCBs or transformers) and supply to corresponding poles they are connected to. Capacitive coupling wireless power transfer system can also be used. Multiple PCB can be used and connected to specific set of poles.

In a self-excited system, AC is induced in receiving PCBs or transformer windings. Specific receiving PCBs or transformer windings can be de-excited or excited based on which turns or poles we want in the equivalent circuit of the motor.

FIG. 16 shows a schematic diagram of a first inductive power transfer circuit 100 for supplying an excitation power to the field winding sets 26a, 26b of a second rotor 20b of a WFSM. The second rotor 20b may be similar or identical to the first rotor 20a, with the addition of one or more rectifiers 112, 114 for generating the DC power for application to the field winding sets 26a, 26b.

The first inductive power transfer circuit 100 includes a first stator converter 102 that receives power from the DC power supply 42 and which includes a first switch set 104 having four switching devices configured to generate an AC power having a first resonant frequency on a first set of output conductors 108a. The first stator converter 102 also includes a second switch set 106 having four switching transistors configured to generate an AC power having a second resonant frequency, different than the first resonant frequency, on a second set of output conductors 108b. Each of the first switch set 104 and the second switch set 106 are shown having IGBT transistors for each of the switching devices. However, either or both of the first switch set 104 and the second switch set 106 may use a different number of switching devices and/or a different type of switching devices, such as FETs or a different type of junction switch devices. The controller 50 may command operation of each of the switches of the first stator converter 102.

The first inductive power transfer circuit 100 also includes a first rotating transformer 110 with primary windings coupled to the first set of output conductors 108a and the second set of output conductors 108b. The first rotating transformer 110 also has a set of secondary windings that rotate with the second rotor 20b and which supply AC power from the first stator converter 102 to each of the one or more rectifiers 112, 114 via a first set of rotating conductors 108c. The first rotating transformer 110 may be electrically and/or mechanically configured to direct the AC power from the first switch set 104 to the first rectifier 112 for energizing the first field winding set 26a. The first rotating transformer 110 may be electrically and/or mechanically configured to direct the AC power from the second switch set 106 to the second rectifier 114 for energizing the

second field winding set 26b. Thus, the controller 50 may independently control excitation of each of the 26a, 26b by independently controlling the first switch set 104 and the second switch set 106.

FIG. 17 shows a schematic diagram of a second inductive power transfer circuit 140 for supplying an excitation power to the field winding sets 26a, 26b of a second rotor 20b of a WFSM. The second inductive power transfer circuit 140 may use the same or a similar second rotor 20b as the first inductive power transfer circuit 100.

The second inductive power transfer circuit 140 includes a second stator converter 142 that receives power from the DC power supply 42 and which includes a third switch set 144 having four switching devices configured to generate AC power on a third set of output conductors 148. The second stator converter 142 also includes a fourth switch set 146 having four switching transistors configured to generate AC power on a fourth set of output conductors 154. Each of the third switch set 144 and the fourth switch set 146 are shown having IGBT transistors for each of the switching devices. However, either or both of the third switch set 144 and the fourth switch set 146 may use a different number of switching devices and/or a different type of switching devices, such as FETs or a different type of junction switch devices. The controller 50 may command operation of each of the switches of the second stator converter 142.

The second inductive power transfer circuit 140 also includes a second rotating transformer 150 with primary windings coupled to the third set of output conductors 148. The second rotating transformer 150 also has a set of second secondary windings 152 that rotate with the second rotor 20b and which supply AC power from the third switch set 144 to the first rectifier 112 for energizing the first field winding set 26a. The second

inductive power transfer circuit 140 also includes a third rotating transformer 156 with primary windings coupled to the fourth set of output conductors 154. The third rotating transformer 156 also has a set of third secondary windings 158 that rotate with the second rotor 20b and which supply AC power from the fourth switch set 146 to the second rectifier 112 for energizing the second field winding set 26b.

FIG. 18 shows a cross-sectional schematic of a WFSM 160 with rotating transformers 150, 156 and multiple printed circuit boards (PCBs) 162 for supplying an excitation current to the field windings 26a, 26b in the second rotor 20b. The PCBs 162 may contain electric circuitry of the rectifiers 112, 114.

Rotor and stator combined approach to change the torque-speed-efficiency maps

This will be the 3rd approach. Here we could change the series and parallel configuration of the stator windings 36 as well as de-excite one or more field winding sets 26a, 26b in the rotor 20a, 20b, 20c of a WFSM to obtain additional torque speed curves. This gives another degree of controllability to choose optimal currents and voltages to obtain maximum efficiency in a specific load point and operating condition.

FIG. 19 shows a flow chart illustrating a method 200 for operating a system for a wound field synchronous machine. Some or all steps of the method 200 can be performed by the controller 50, in accordance with some embodiments of the present disclosure. As can be appreciated in light of the disclosure, the order of operation within the method is not limited to the sequential execution as illustrated in FIG. 19, but may be performed in one or more varying orders as applicable and in accordance with the present disclosure. The method 200 starts at 202 and includes initializing motor parameters at step 204. Step 204 may include receiving or inputting device-specific parameters, such as a

number of poles, resistances, and inductances of the stator windings 36 and/or the field windings 26a, 26b.

The method 200 proceeds with offline finite element analysis (FEA) and generation of efficiency maps at step 206. Step 206 may be performed during or prior to initial construction and/or installation of the WFSM in a vehicle. In some embodiments, step 206 may be performed for a specific WFSM device to take into account characteristics of the specific WFSM device. Alternatively or additionally, step 206 may be performed once for a general design of the WFSM, with the efficiency maps used for multiple EVs and/or multiple different individual WFSM devices.

The method 200 includes a first loop 210, which may be called a torque-speed envelope improvement loop. The first loop 210 includes a first decision block 212 that chooses, based on a torque command T^* and a speed command ω^* for the WFSM, an operating mode for the stator windings 36. The first decision block 212 may use a truth table, which may include a lookup table and/or one or more logical operations, such as numerical comparisons, to determine the operating mode for the stator windings 36 based on the torque command T^* and the speed command ω^* and based on predetermined conditions. The predetermined conditions may be set forth in the efficiency maps generated at step 206.

The method 200 includes operating the stator windings 36 in a series wiring configuration at step 214. The method 200 also includes operating the stator windings 36 in a parallel wiring configuration at step 216. The method 200 may implement a given one of steps 214 or 216 at any given time based on the determination of the first decision block 212.

The method 200 includes a second loop 220, which may be called an efficiency improvement loop. The second loop 220 includes a second decision block 222 that chooses, based on the torque command T^* and the speed command ω^* for the WFSM, an operating mode for one or more field winding sets 26a, 26b in the rotor 20a, 20b, 20c of the WFSM. The second decision block 222 may use a truth table, which may include a lookup table and/or one or more logical operations, such as numerical comparisons, to determine the operating mode for the one or more field winding sets 26a, 26b based on the torque command T^* and the speed command ω^* and based on predetermined conditions. The predetermined conditions may be set forth in the efficiency maps generated at step 206.

The method 200 includes operating the one or more field winding sets 26a, 26b in a de-excited configuration at step 224. The method 200 also includes operating the one or more field winding sets 26a, 26b in an excited configuration at step 226. The method 200 may implement a given one of steps 224 or 226 at any given time based on the determination of the second decision block 222.

FIG. 20 shows a graph of torque vs. speed with plots representing operating characteristics of the WFSM with stator windings 36 thereof in each of a series configuration and in a parallel configuration. The graph of FIG. 20 includes labels 1-8 representing different operating regions that may correspond to decisions of the first decision block 212 and the second decision block 222.

FIG. 21 shows a plot illustrating efficiencies of the WFSM for different combinations of speed and torque with selective de-excitation of the field winding sets 26a, 26b of the rotor 20a, 20b, 20c.

The foregoing description is not intended to be exhaustive or to limit the disclosure.

Individual elements or features of a particular embodiment are generally not limited to that particular embodiment, but, where applicable, are interchangeable and can be used in a selected embodiment, even if not specifically shown or described. The same may also be varied in many ways. Such variations are not to be regarded as a departure from the disclosure, and all such modifications are intended to be included within the scope of the disclosure.

REFERENCE LIST

- 10 wound filed synchronous motor (WFSM)
- 20 rotor
- 20a first rotor
- 20b second rotor
- 22 rotor core
- 23 base
- 24 poles
- 25 body
- 26 rotor winding
- 26a first field winding set
- 26b second field winding set
- 27 head
- 28 motor shaft
- 30 stator
- 32 stator core
- 34 stator teeth
- 36 stator windings
- 40 system
- 40a first stator mode control system
- 40b second stator mode control system
- 42 direct current (DC) power supply
- 44 inverter
- 44a inverter
- 44b inverter
- 46 power switch
- 48 motor leads
- 48a motor leads
- 48b motor leads
- 50 controller

52	processor
56	data storage
60	stator mode switch
60a	first stator mode switch
60b	second stator mode switch
62	rotor excitation supply
62a	first excitation supply
62b	second excitation supply
62c	third excitation supply
64	rotor mode switch
66a	first slip ring
66b	second slip ring
66c	third slip ring
68	DC power source
70	first field regulator switch
71	second field regulator switch
72-	reference conductor
72+	first field excitation conductor
74	first diode
75	second diode
80a	first adjustable excitation circuit
80b	second adjustable excitation circuit
82	excitation changing switch
100	power transfer circuit
102	first stator converter
104	first switch set
106	second switch set
108a	first set of output conductors
108b	second set of output conductors
110	first rotating transformer
112	first rectifier

114	second rectifier
114	storage memory
140	second inductive power transfer circuit
142	second stator converter
144	third switch set
146	fourth switch set
148	third set of output conductors
150	second rotating transformer
152	second secondary windings
154	fourth set of output conductors
156	third rotating transformer
158	third secondary windings
160	WFSM
162	printed circuit boards (PCBs)
200	method
202	start
204	step
206	step
210	first loop
212	first decision block
214	step
216	step
220	second loop
222	second decision block
224	step
226	step

CLAIMS

What is claimed is:

1. A system (40) for a synchronous electric machine, comprising:
 - a motor including a rotor (20) and a stator (30), at least one of the rotor (20) or the stator (30) having a plurality of DC excitation conductors, and at least one of the rotor (20) or the stator (30) having a plurality of AC windings;
 - an inverter (44, 44a, 44b) configured to generate an AC power on a set of motor leads (48, 48a, 48b) for application to the plurality of AC windings for providing power to the motor;
 - a DC power source (68) configured to supply DC current to at least some of the plurality of DC excitation conductors; and
 - at least one mode switch configured to change a configuration of at least one of the plurality of DC excitation conductors or the plurality of AC windings.
2. The system (40) of Claim 1, wherein the at least one mode switch is configured to selectively control a flow of the DC current between the DC power source (68) and at least one of the plurality of DC excitation conductors.
3. The system (40) of Claim 1, wherein the at least one mode switch is configured to change the configuration of the plurality of DC excitation conductors.
4. The system (40) of Claim 3, wherein the at least one mode switch is configured to change the configuration of the plurality of DC excitation conductors

between an excited configuration and a de-excited configuration with the DC current being supplied to fewer than all of the plurality of DC excitation conductors.

5. The system (40) of Claim 1, wherein the motor is a wound-field motor (10) including the plurality of DC excitation conductors being disposed on the rotor (20).

6. The system (40) of Claim 5, wherein the plurality of DC excitation conductors include a first field winding set (26a) and a second field winding set (26b); and wherein the first field winding set (26a) is configured to always be energized by the DC power source (68), and the second field winding set (26b) is configured to be selectively energized by the at least one mode switch.

7. The system (40) of Claim 6, wherein the rotor (20) includes a plurality of poles (24) and the first field winding set (26a) and the second field winding set (26b) are each located on one or more separate poles (24) of the rotor (20).

8. The system (40) of Claim 6, further comprising: a plurality of slip rings for transmitting electrical current between the DC power source (68) and the plurality of DC excitation conductors disposed on the rotor (20).

9. The system (40) of Claim 6, further comprising: a rotating transformer and a rectifier configured to transmit electrical current between the DC power source (68) and the plurality of DC excitation conductors disposed on the rotor (20).

10. The system (40) of Claim 6, further comprising: a capacitor power transfer system including a plurality of printed circuit boards (162) and a rectifier configured to transmit electrical current between the DC power source (68) and the plurality of DC excitation conductors disposed on the rotor (20).

11. The system (40) of Claim 6, wherein the DC power source (68) includes a first field regulator switch (70) configured to generate a first regulated DC voltage for application to the first field winding set (26a) and a second field regulator switch (71) configured to generate a second regulated DC voltage for application to the second field winding set (26b); and

wherein the first field regulator switch (70) and the second field regulator switch (71) are separately controllable for selectively changing the excitation of one of the first field winding set (26a) and the second field winding set (26b) while maintaining an excitation of the other one of the first field winding set (26a) and the second field winding set (26b).

12. The system (40) of Claim 1, further comprising: a controller (50) in functional communication with the at least one mode switch and configured to change the configuration of the at least one of the plurality of DC excitation conductors or the plurality of AC windings based on at least one of a speed command and a torque command.

13. The system (40) of Claim 1, wherein the at least one mode switch is configured to change the configuration of both of the at least one of the plurality of DC excitation conductors and the plurality of AC windings.

14. The system (40) of Claim 1, wherein the plurality of DC excitation conductors are disposed on the stator (30).

15. The system (40) of Claim 1, wherein the at least one mode switch is configured to change the configuration of the plurality of AC windings.

16. The system (40) of Claim 15, wherein the at least one mode switch is configured to change the configuration of the plurality of AC windings between a serial configuration and a parallel configuration.

17. The system (40) of Claim 15, wherein the at least one mode switch is configured to change the configuration of the plurality of AC windings between star and delta winding arrangements.

18. The system (40) of Claim 15, wherein the at least one mode switch is configured to change a number of poles (24) energized by the plurality of stator and rotor windings (36/ 26).

19. The system (40) of Claim 15, wherein the system (40) includes the first stator mode control system (40a) of the present disclosure.

20. The system (40) of Claim 15, wherein the system (40) includes the second stator mode control system (40b) of the present disclosure.

21. The system (40) of Claim 1, wherein the system (40) is operable in a charging mode to change an inductance of the plurality of AC windings, with the plurality of AC windings connected between an AC charging source and a rectifier configured to charge a battery.

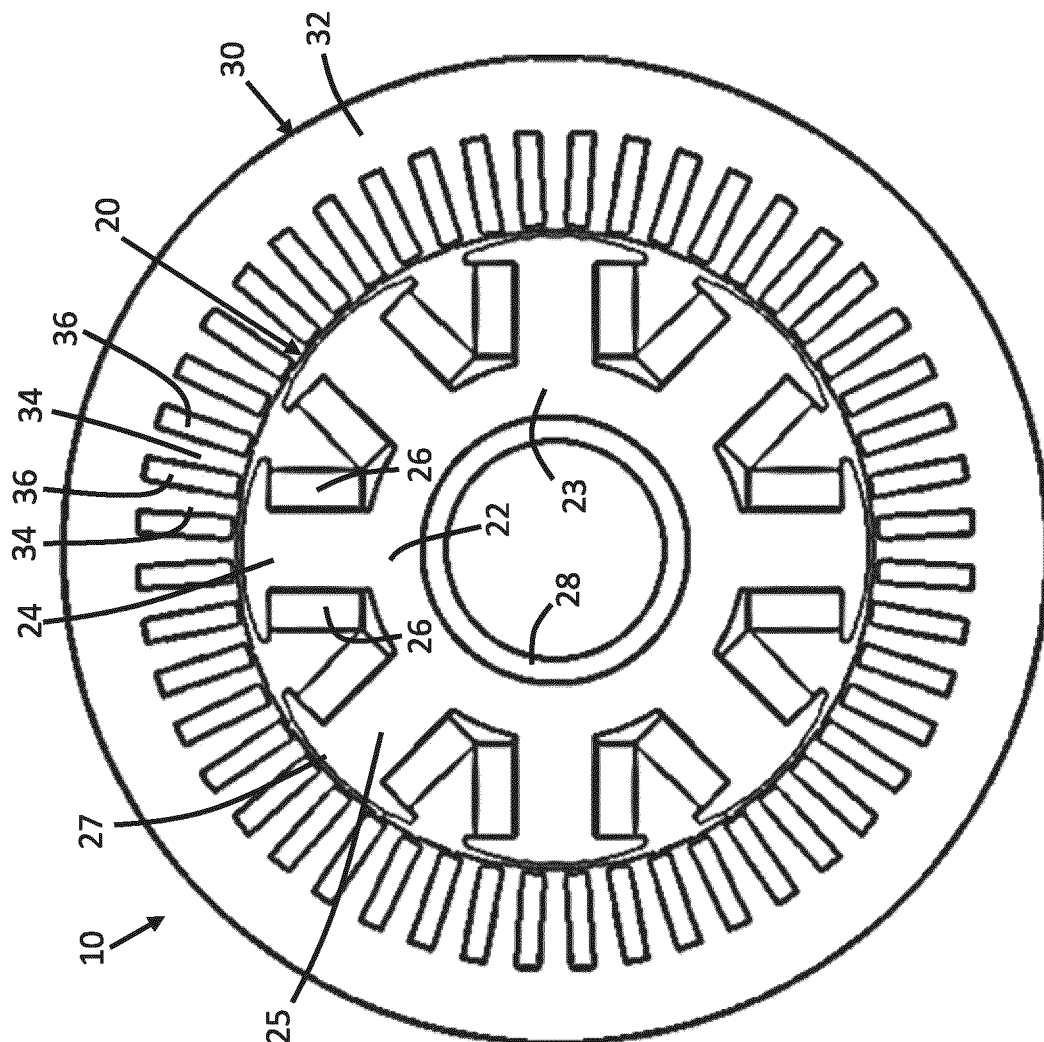


Fig. 1

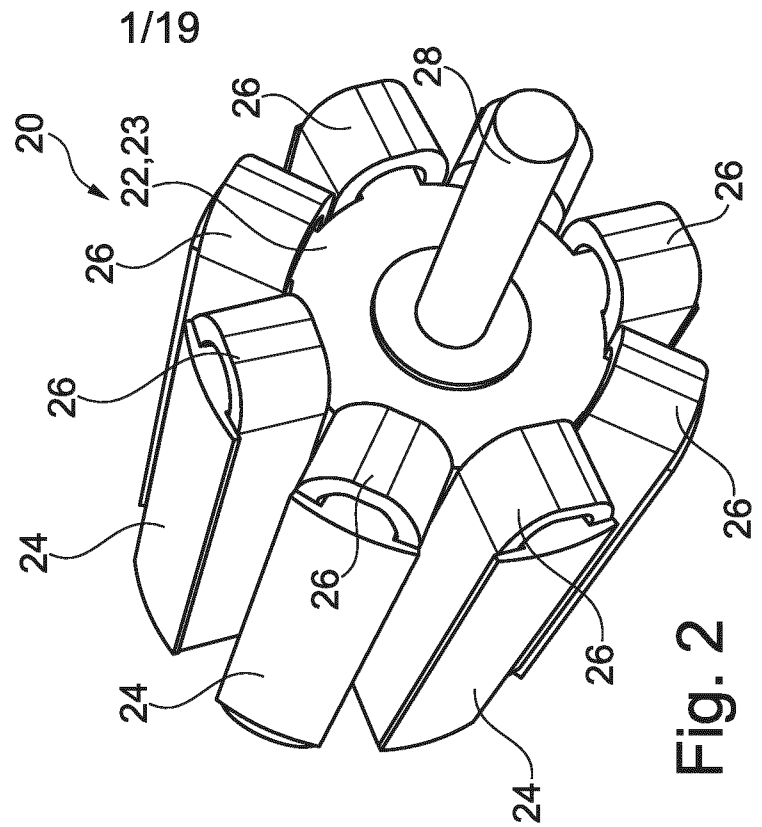


Fig. 2

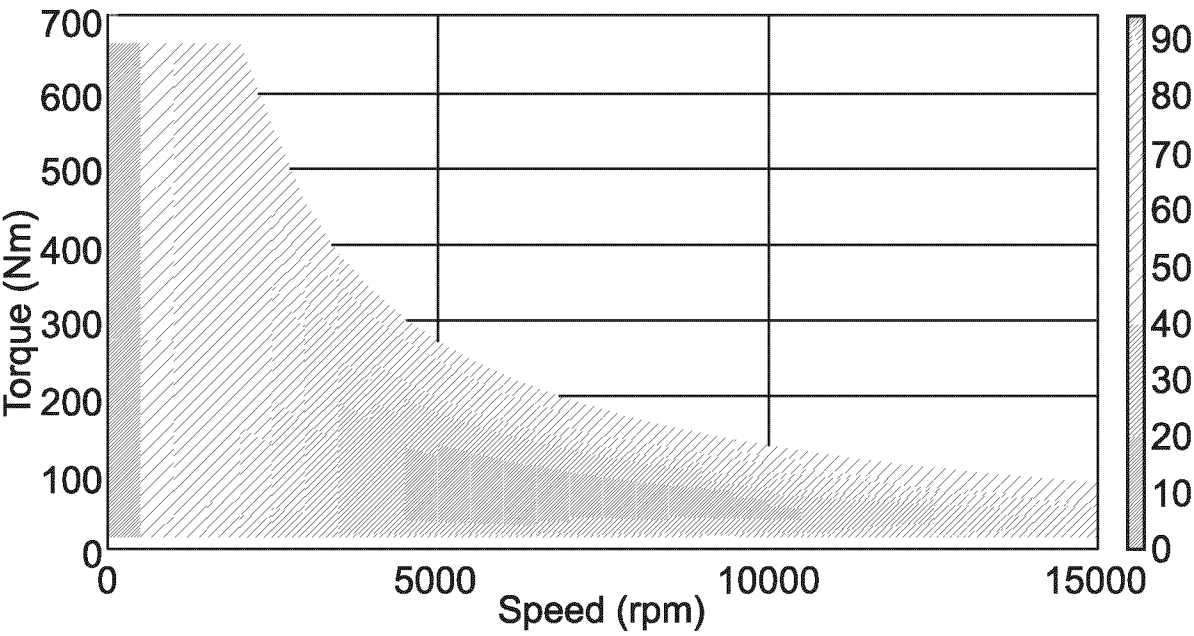


Fig. 3

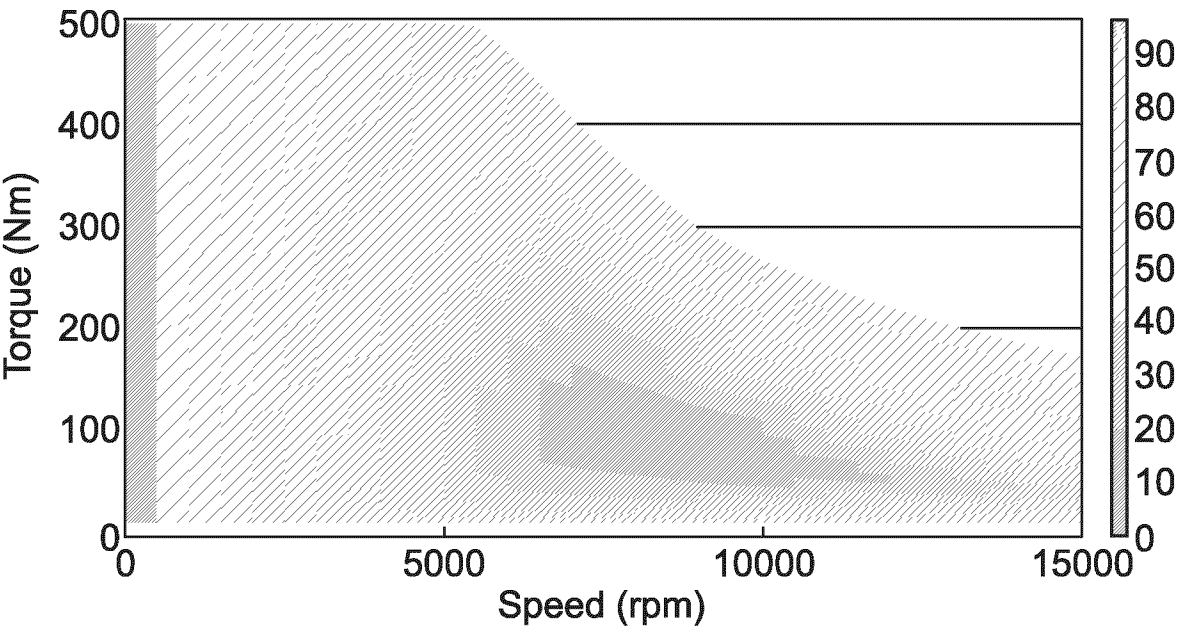


Fig. 4

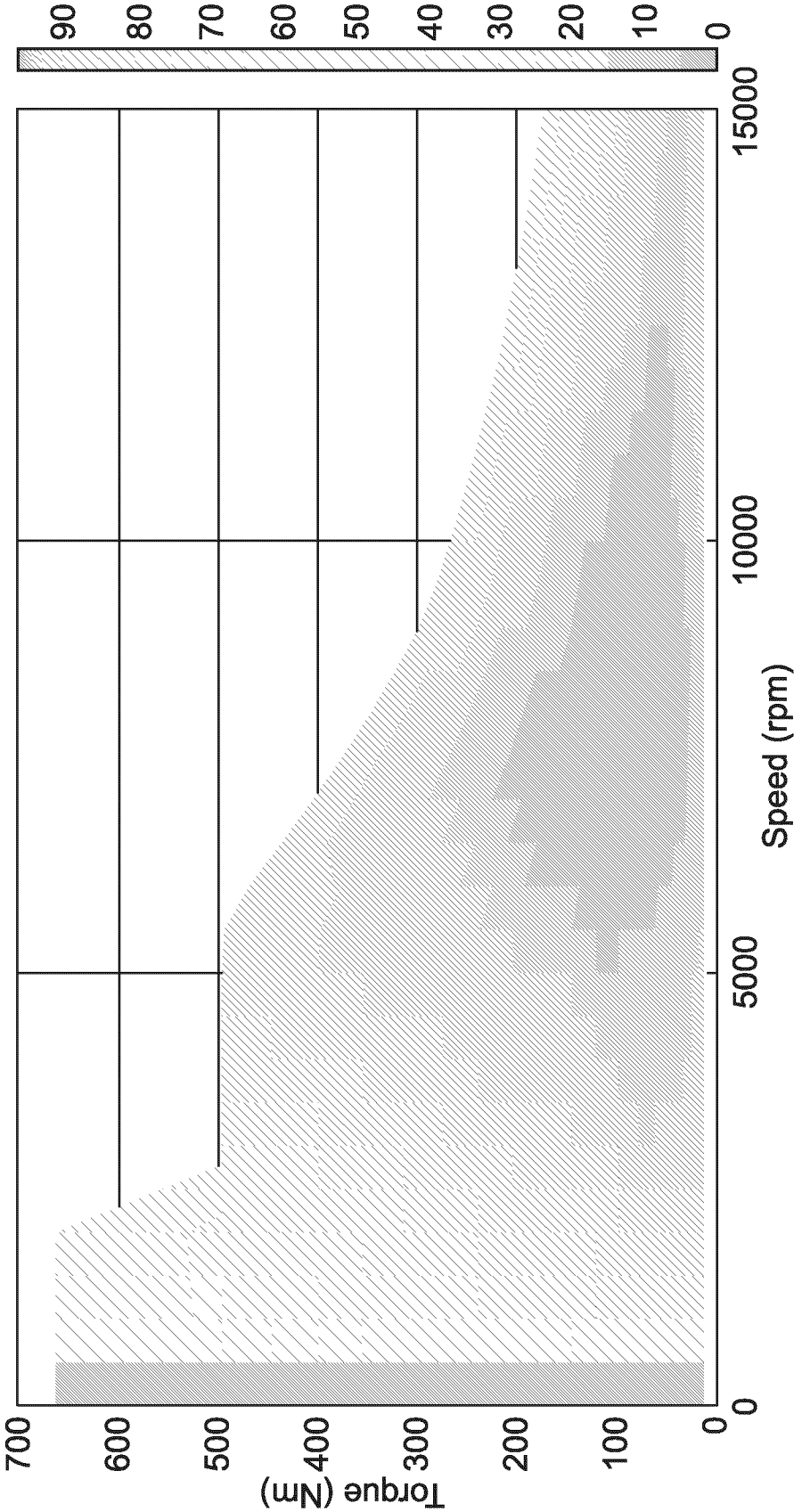


Fig. 5

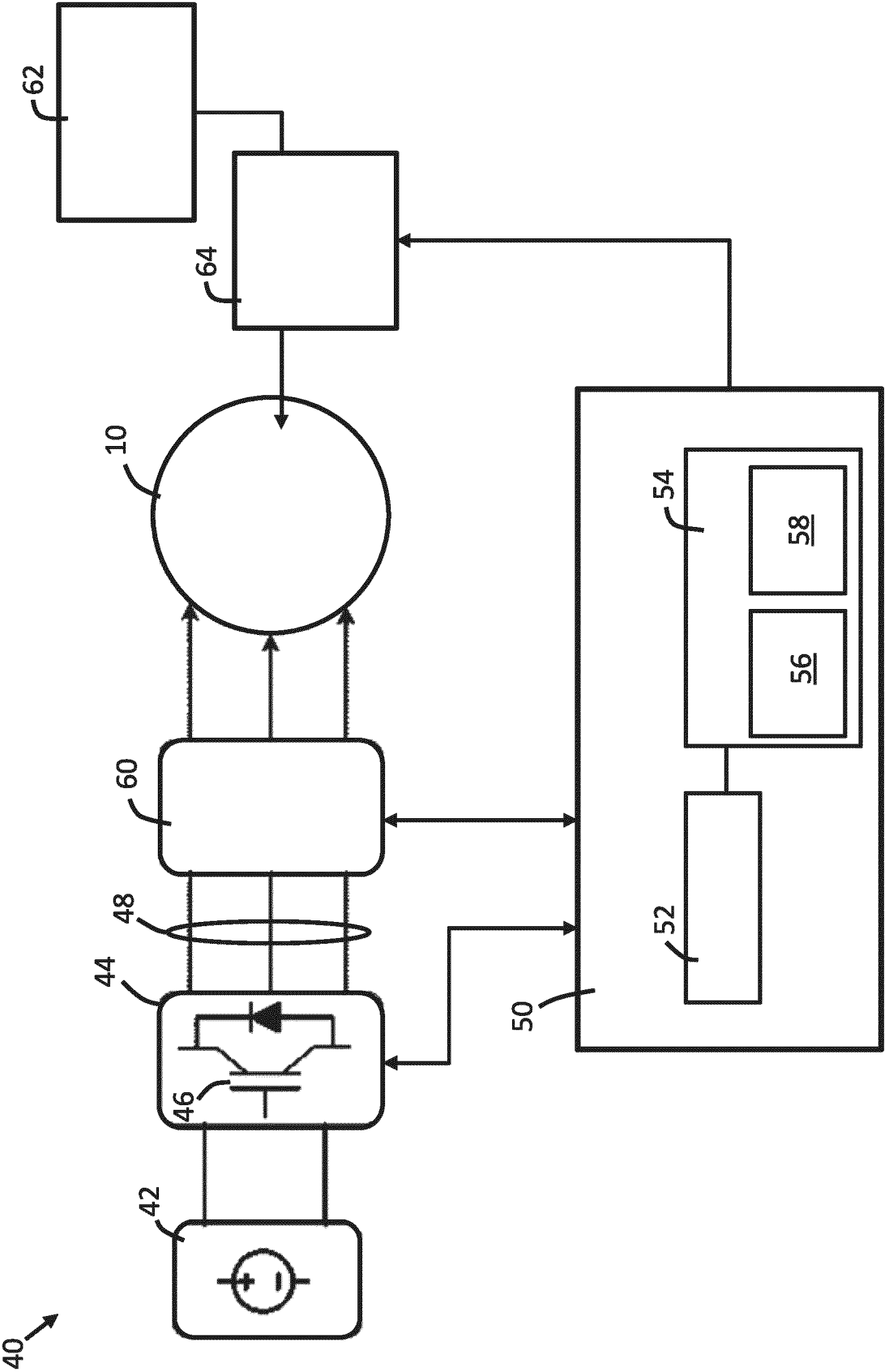
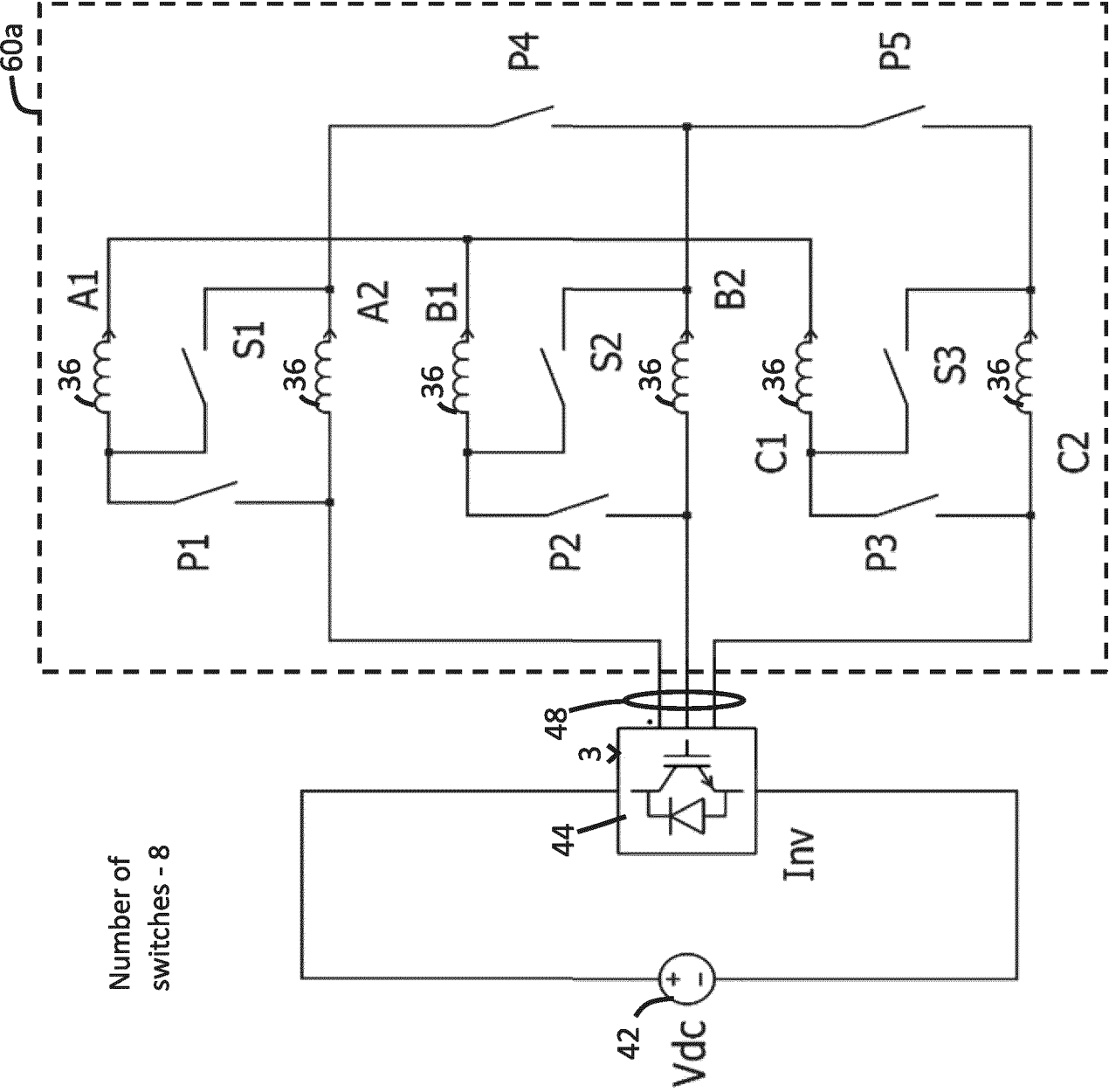


Fig. 6



Number of
switches - 8

Fig. 7

Series – S1, S2, S3 are ON; P1, P2, P3, P4, P5 are OFF
Parallel – P1, P2, P3, P4, P5 are ON; S1, S2, S3 are OFF

40b →

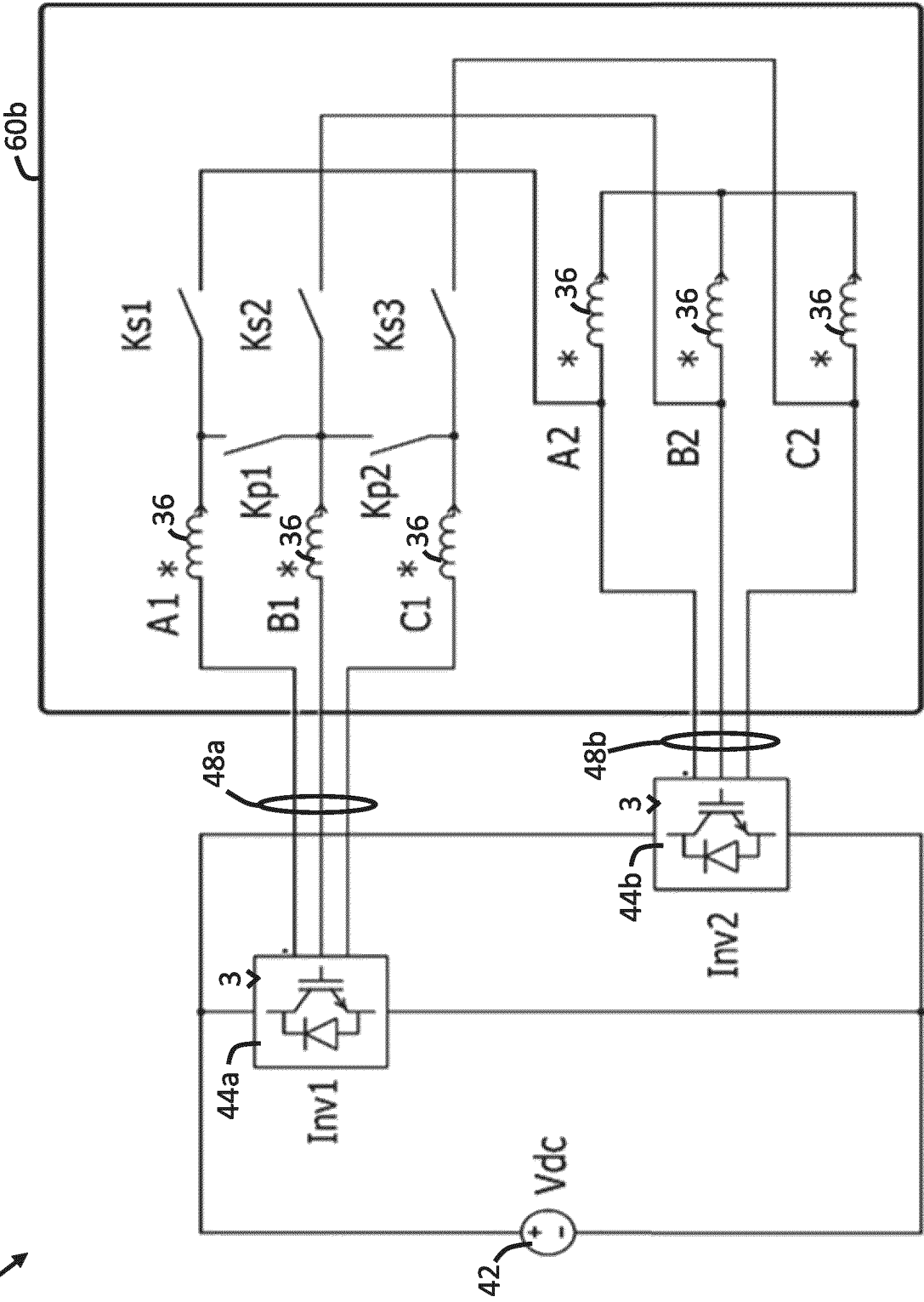


Fig. 8

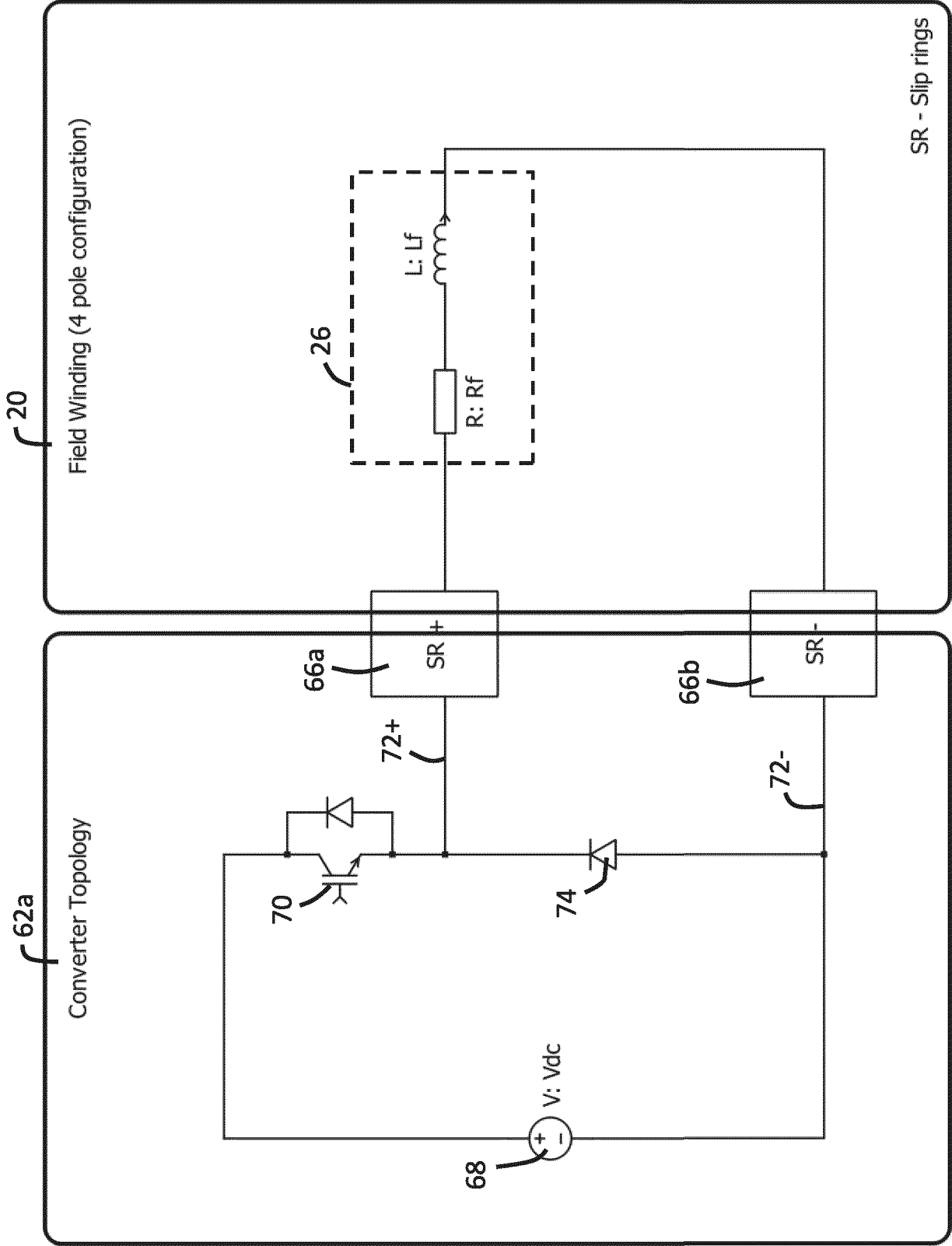


Fig. 9

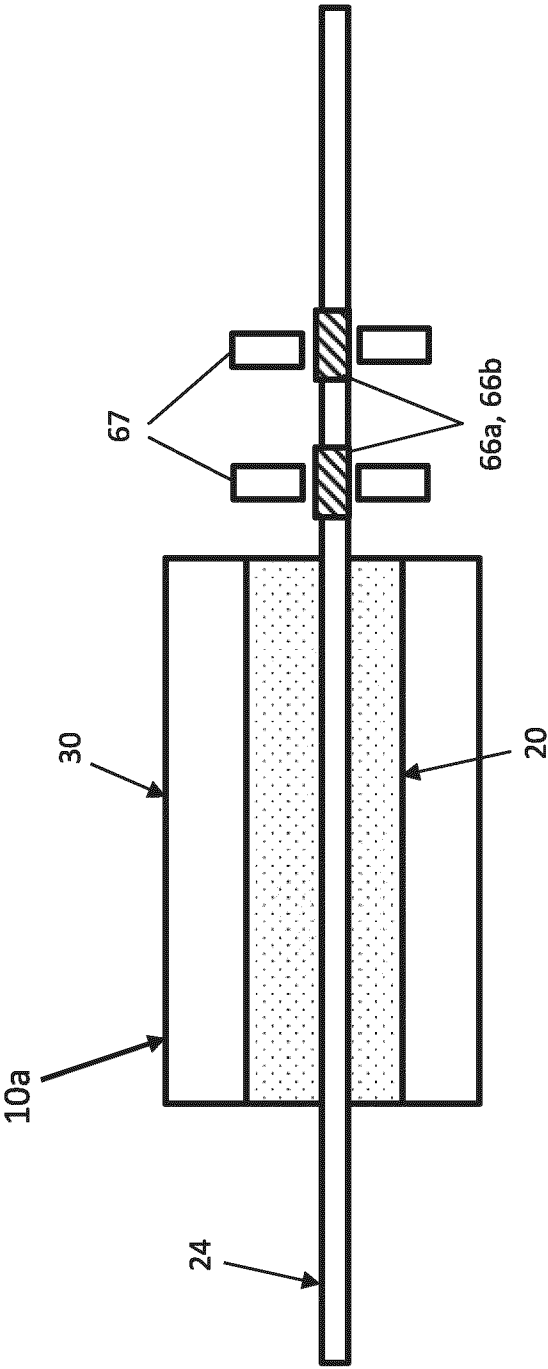


Fig. 10

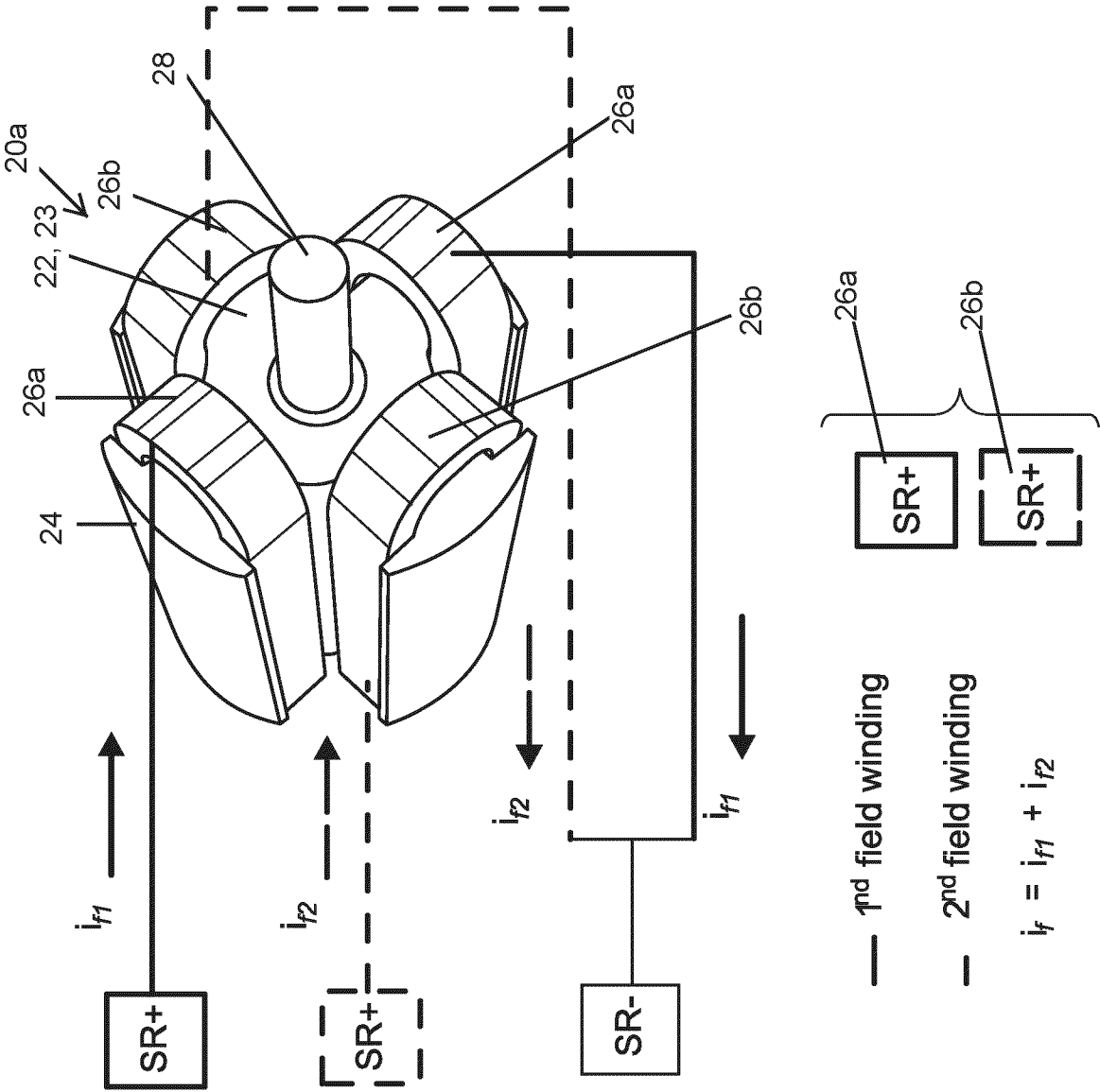


Fig. 11

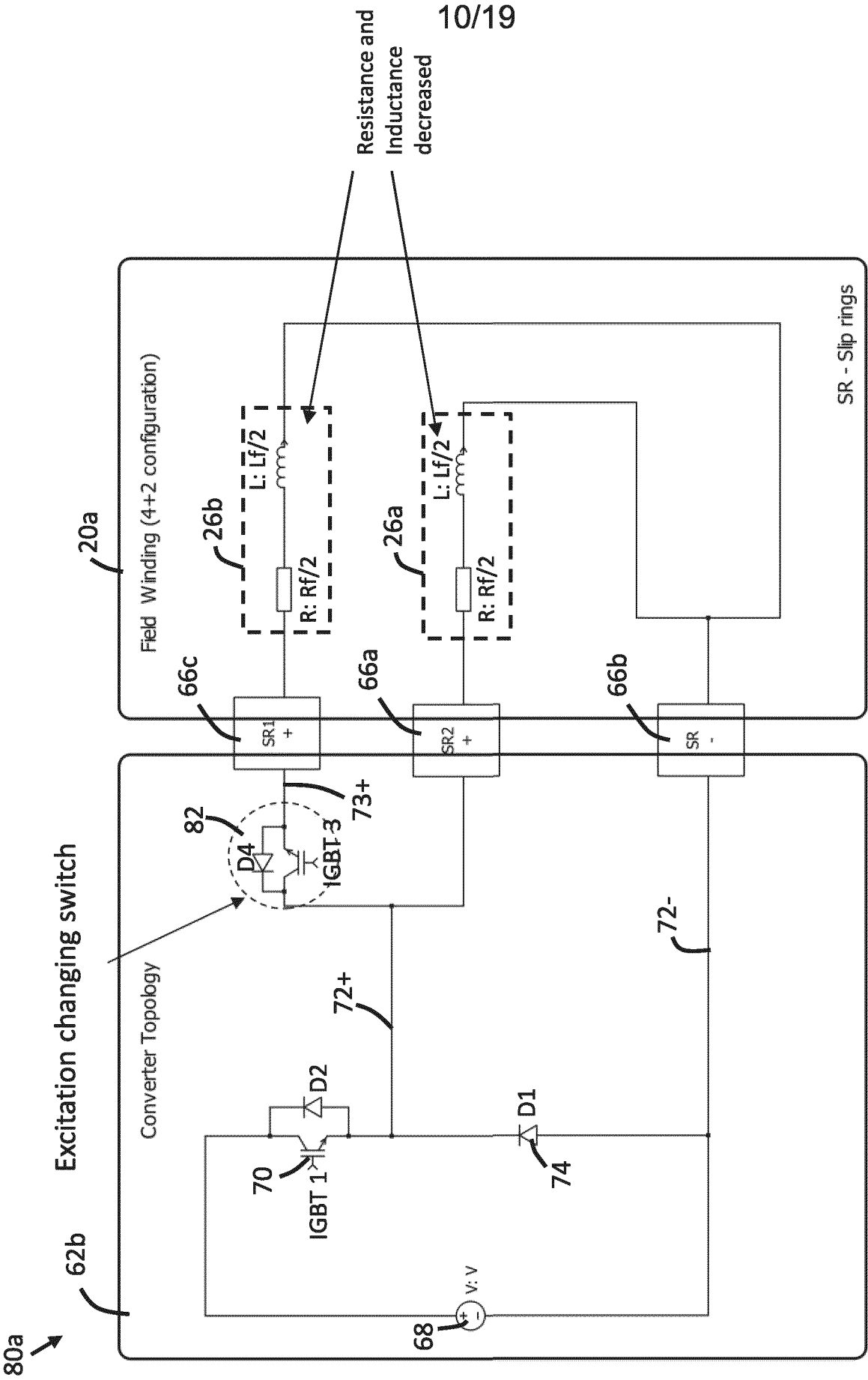
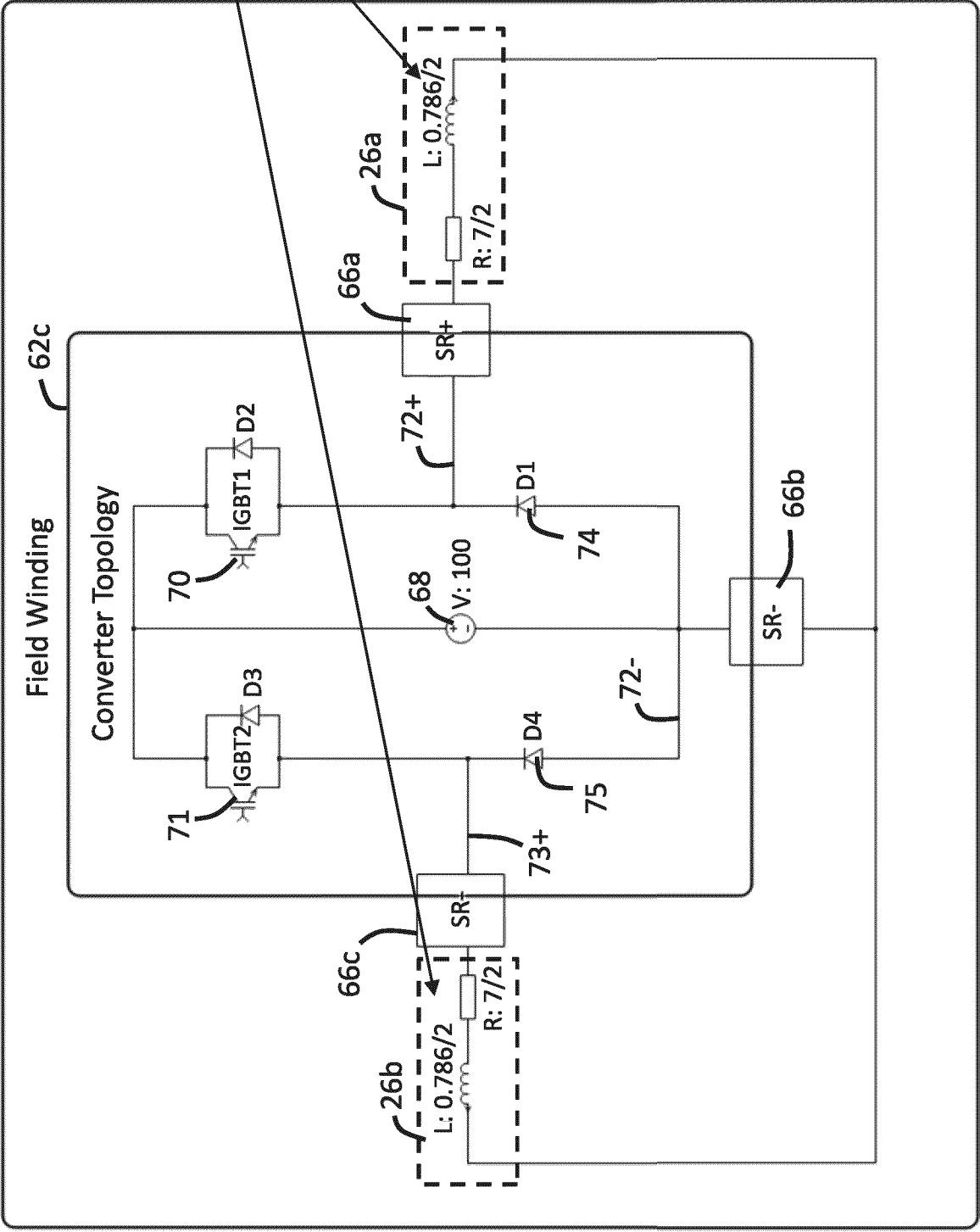


Fig. 12

De-exciter switch and diode

80b



Resistance and inductance decreased

Fig. 13

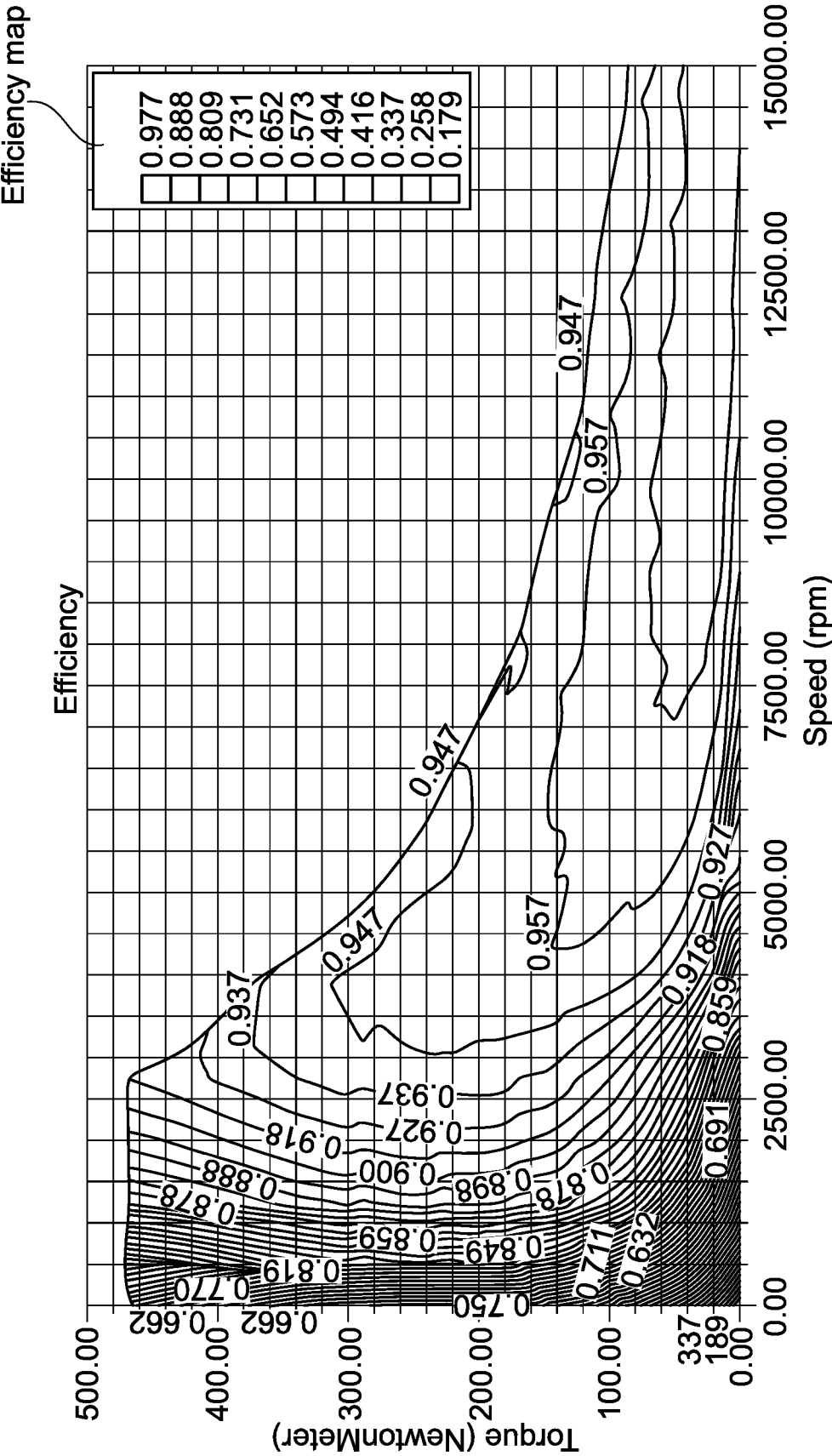


Fig. 14

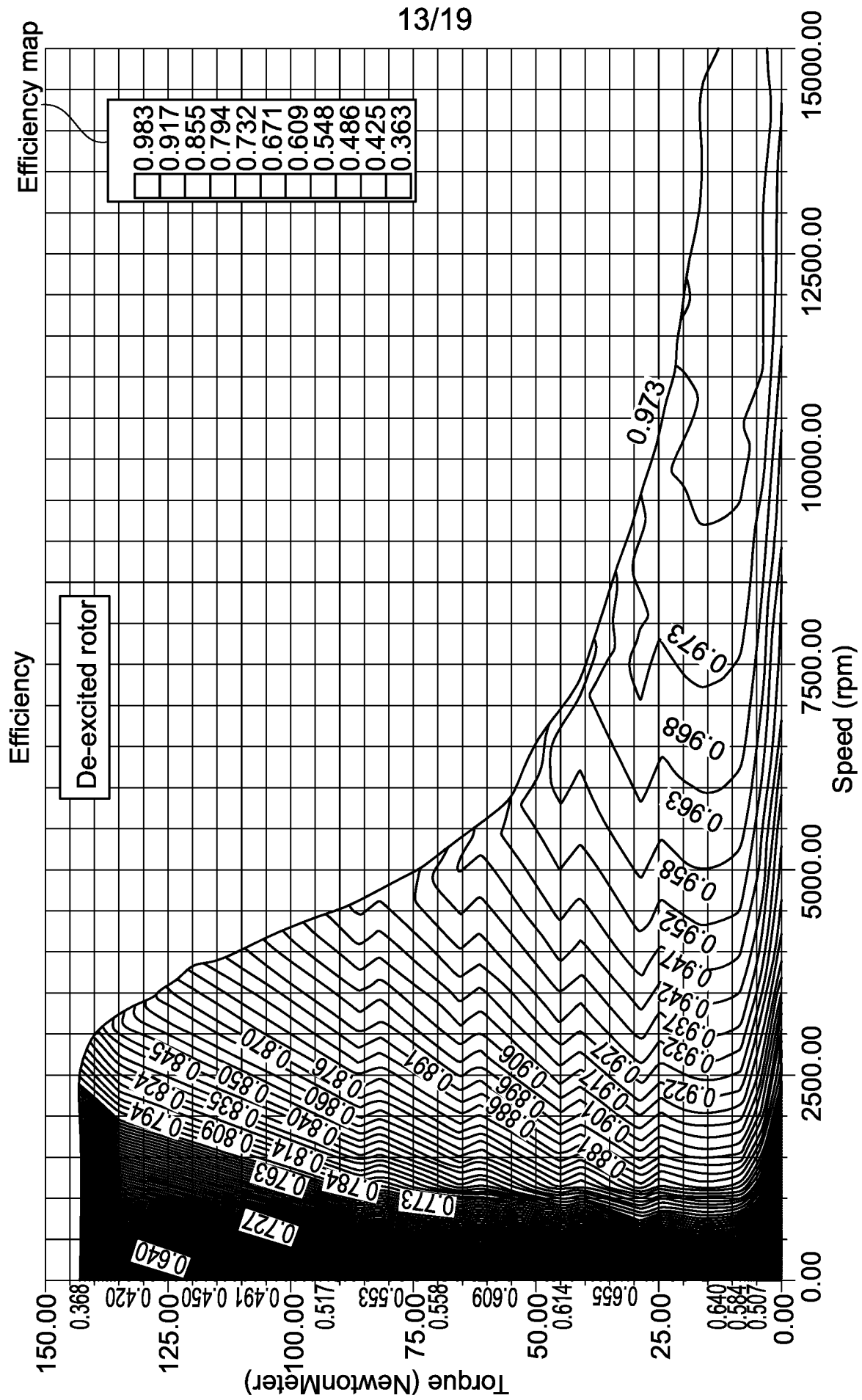


Fig. 15

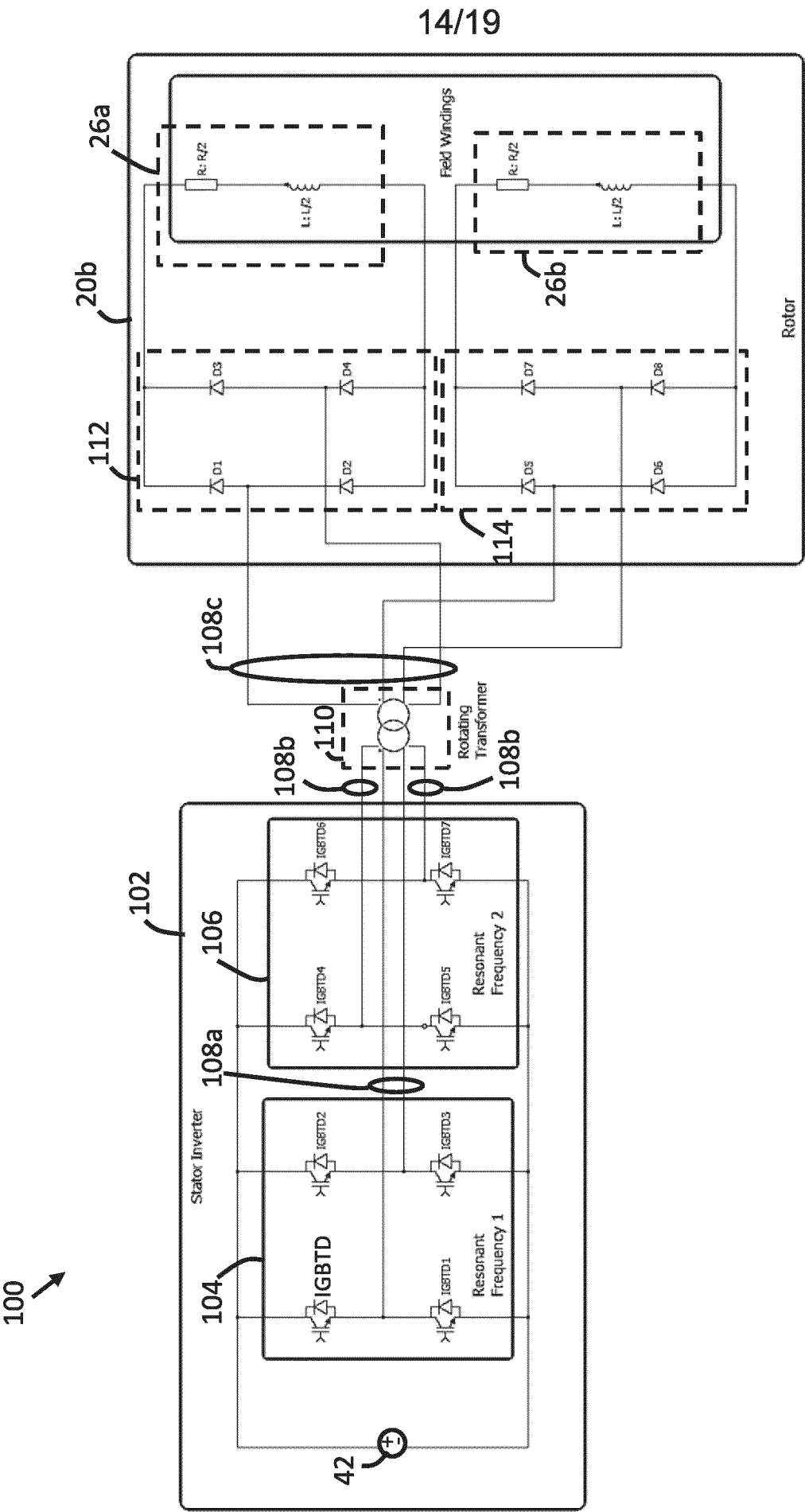


Fig. 16

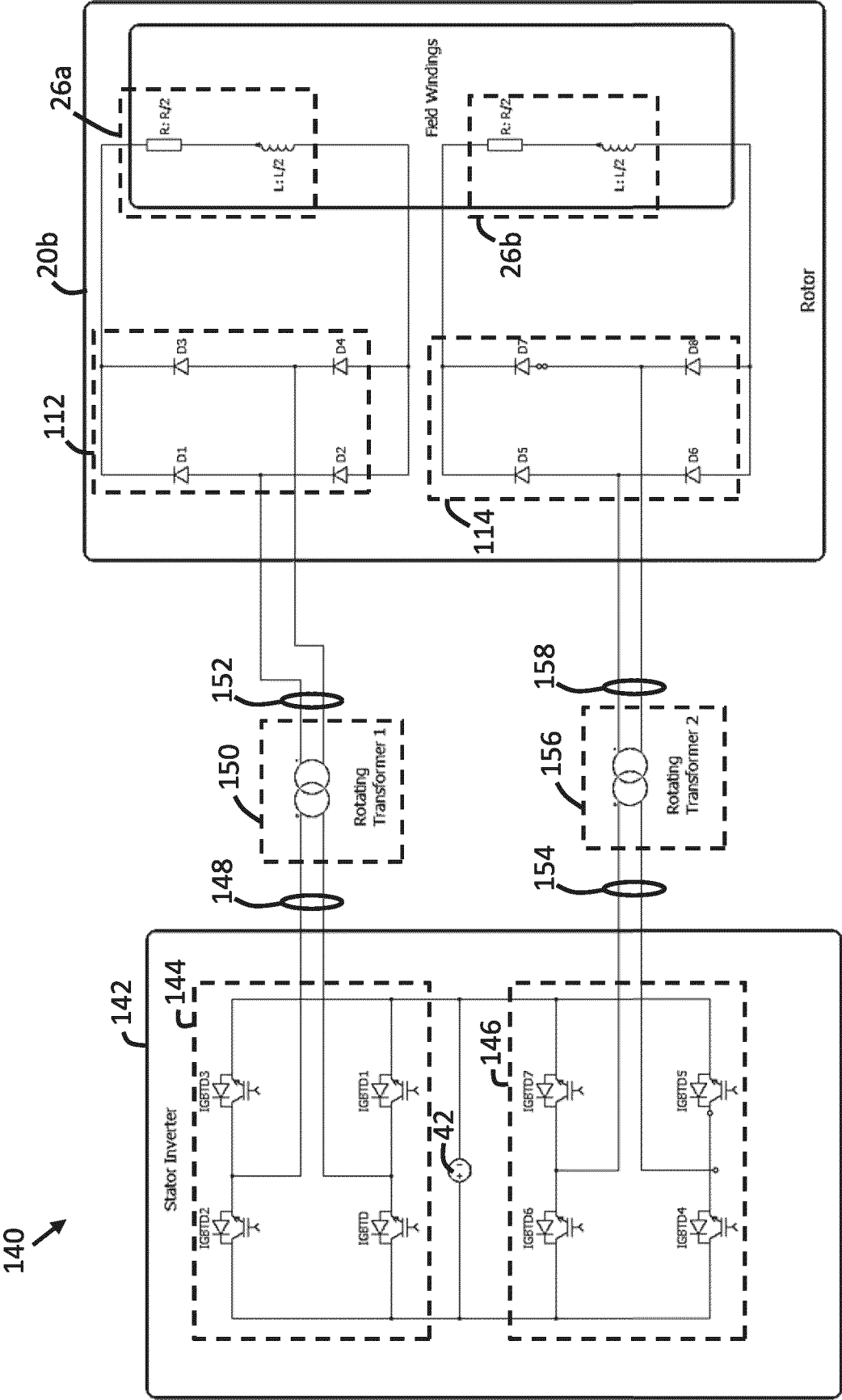


Fig. 17

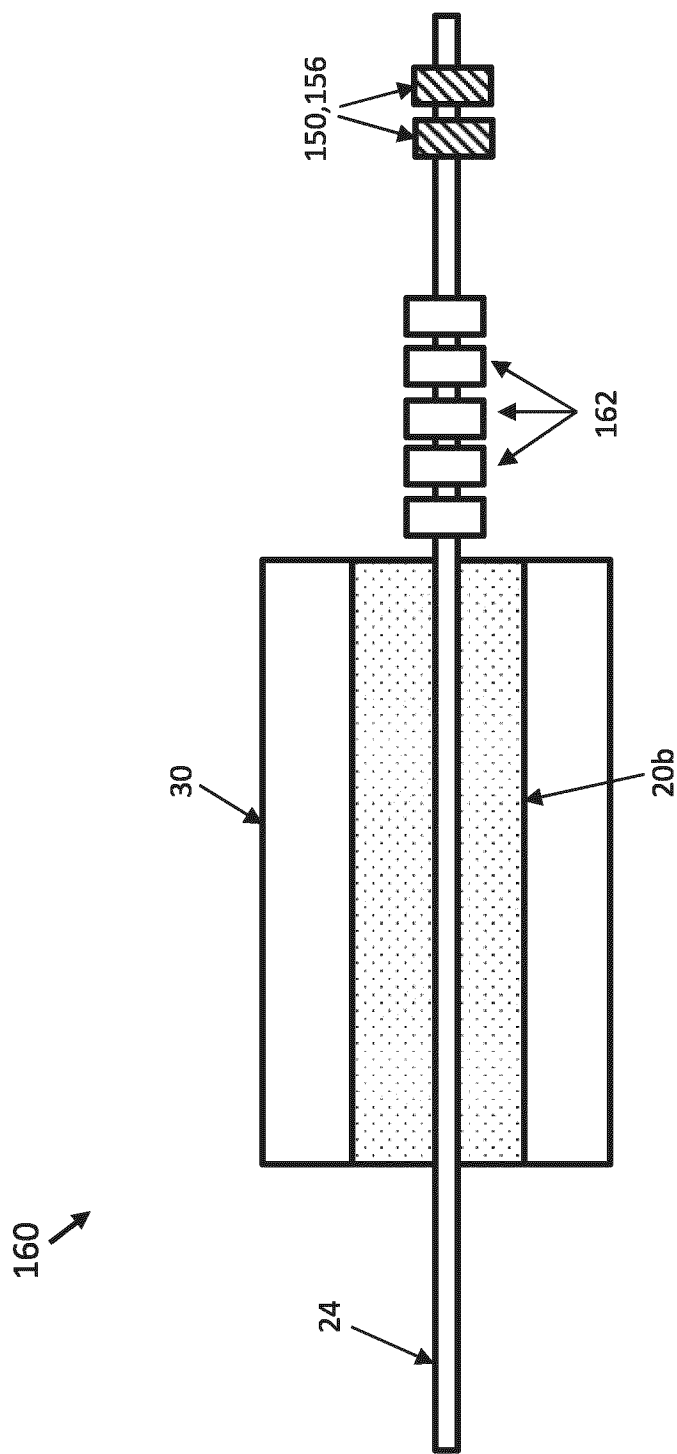


Fig. 18

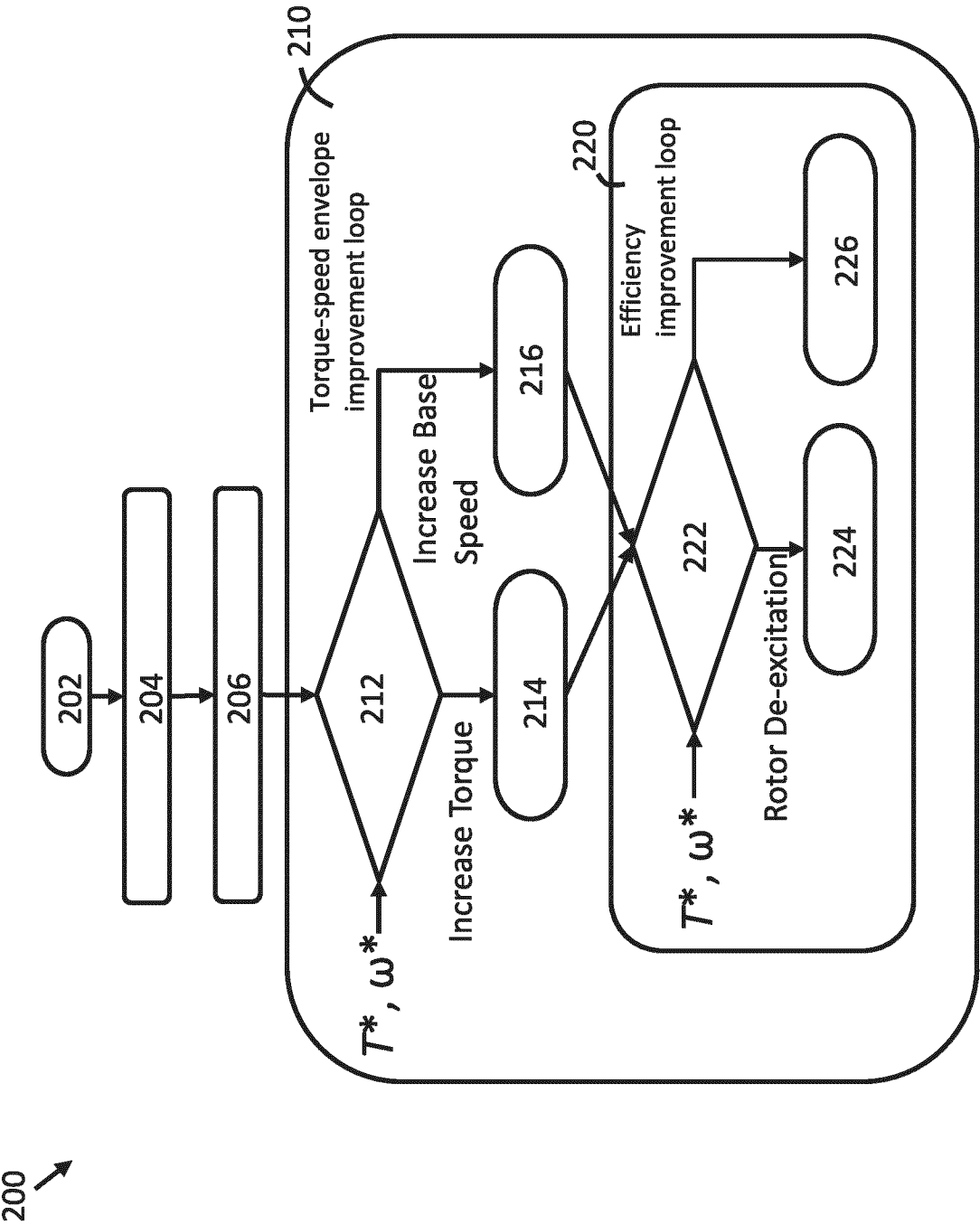


Fig. 19

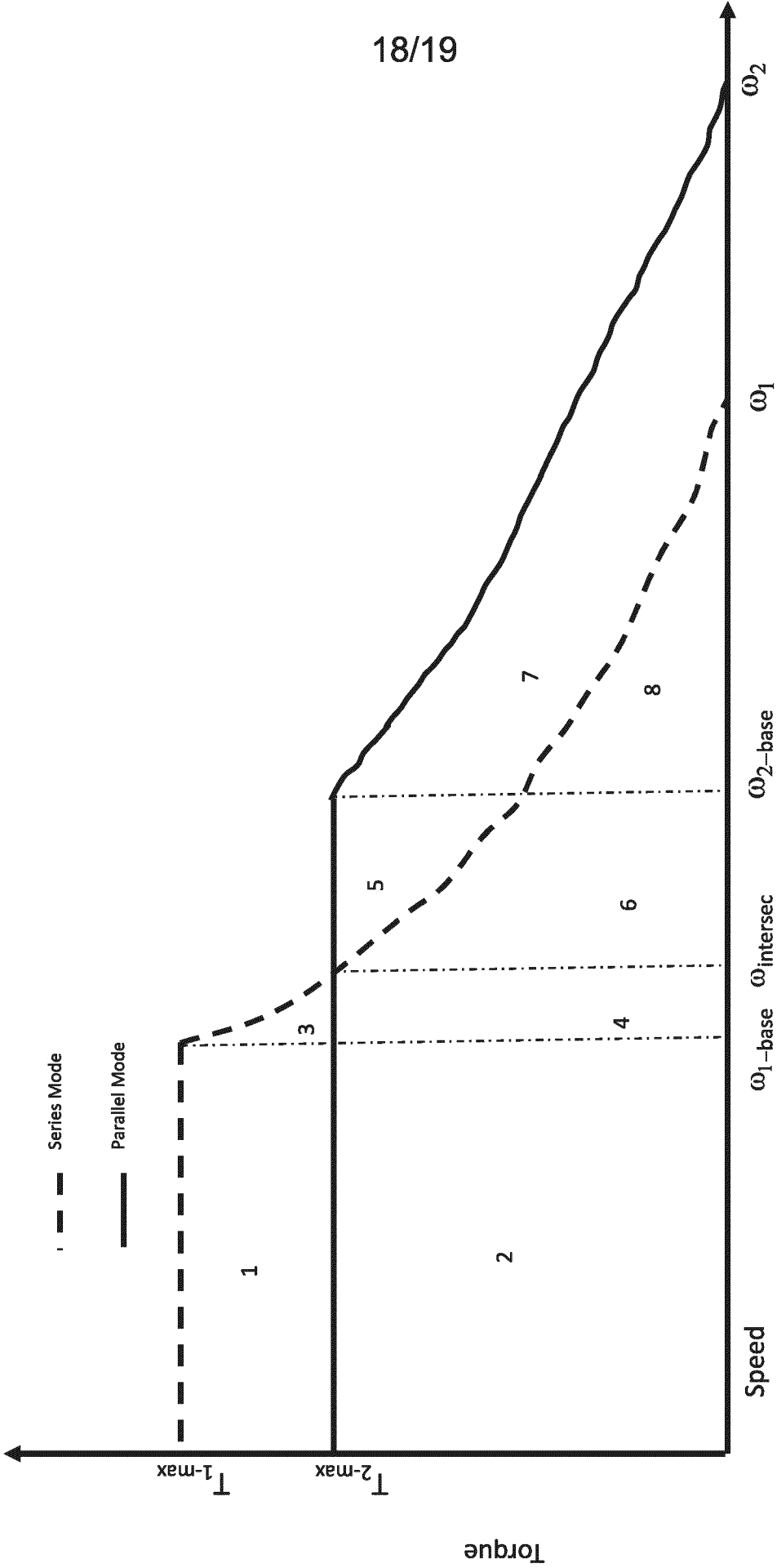
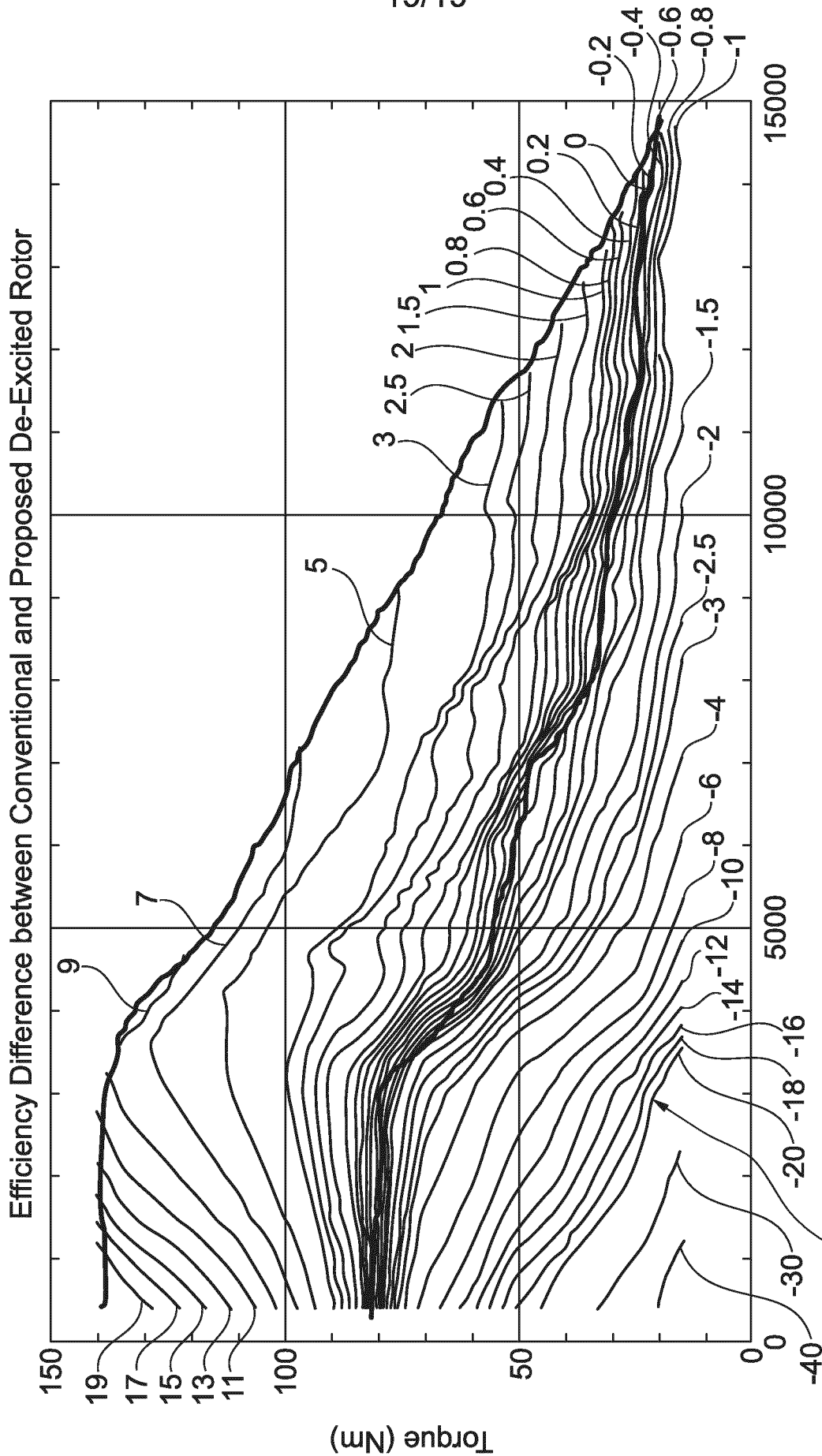


Fig. 20



Speed (rpm)

Fig. 21

De-excited rotor operation
for improved efficiency

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2023/079482

A. CLASSIFICATION OF SUBJECT MATTER INV. H02P6/00 H02P23/14 H02P25/18 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H02P		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 110 669 A (AKAMATSU MASAHIKO) 29 August 1978 (1978-08-29)	1-7, 9-11, 13-15, 17-21
Y	column 2, line 57 - column 3, line 1; figures 1, 5a, 5b column 4, line 52 - column 5, line 8 -----	8, 12, 16
Y	WO 2022/126193 A1 (RAPID POWER IND [AU]) 23 June 2022 (2022-06-23) paragraph [0007] - paragraph [0008]; figure 12 -----	8
Y	US 2017/133968 A1 (TAKAHASHI YUKI [JP]) 11 May 2017 (2017-05-11) paragraph [0006] - paragraph [0009]; figure 1 -----	12, 16
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search		Date of mailing of the international search report
12 January 2024		22/01/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Hascher, Thierry

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2023/079482

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