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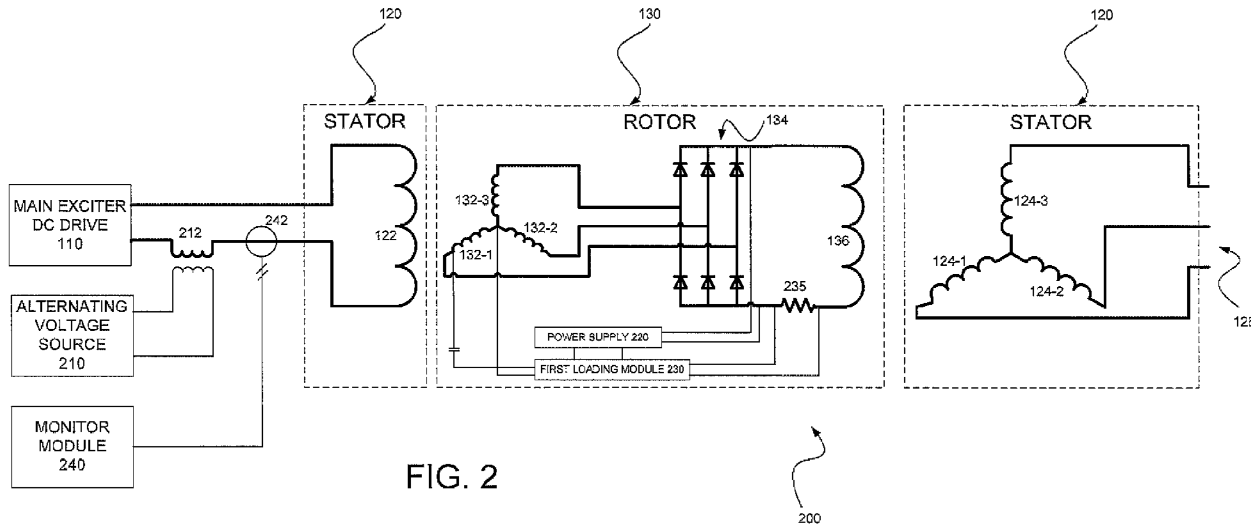

FIG. 2

(57) Abstract: The present disclosure relates to an electrical machine, a rotor for use in an electrical machine, a monitor module for use with an electrical machine and a method a method of determining a first machine characteristic of an electrical machine. The electrical machine comprises a rotor comprising one or more rotor exciter windings and a stator exciter winding for receiving a stator current to establish a magnetic field for causing electrical induction in the one or more rotor exciter windings. The electrical machine also comprises a first loading module mounted on the rotor and configured to receive a first input indicative of a first machine characteristic and apply a first load to a first rotor exciter winding of the one or more rotor exciter windings based at least in part on the received first input. The electrical machine also comprises a monitor module coupled to the exciter stator and configured to detect an effect of the applied first load on the stator current and determine the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current.

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An electrical machine

Technical Field

The present disclosure relates to an electrical machine, a rotor for an electrical machine, a monitor module for use with an electrical machine and a method of determining a first machine characteristic of an electrical machine during operation of the electrical machine.

Background

Electrical machines are electromechanical energy converters that convert electricity to mechanical power or vice-versa. One example of an electrical machine is an electric motor that converts electricity to mechanical power. Another example of an electrical machine is an electric generator that converts mechanical power to electricity. The construction and operation of the various different typical electrical machines will be well understood by the skilled person.

Electrical machines may be used in aviation for a number of different purposes. For example, electric generators may be fitted to aircraft to convert mechanical power from the aircraft engines to electrical power. Electrical machines, particularly electric generators, that are suitable for use in aviation need to be able to operate at speeds relatively high speeds. Typically, electrical machines that are suitable for use in aviation current need to operate at speeds of up to 24,000rpm, although there is a general trend for increasing the maximum speed, such that electrical machines suitable for use in aviation may need to be able to operate at speeds of up to around 28,000rpm, or higher, in the future. Therefore, any equipment operating on the rotor of an aviation electrical machine must be capable of withstanding high centrifugal acceleration levels. The equipment operating on the rotor of the aviation electrical machine should also be capable of withstanding wide temperature ranges, high levels of vibration and immersion in turbine oil. Furthermore, the electrical machine as a whole, including any equipment operating on the rotor of the electrical machine, should also be as small and/or as light as possible, and have long service intervals.

For a number of reasons, it may be useful to measure characteristics relating to the rotor of an electrical machine during the operation of the electrical. Those reasons may include one or more of the following:

- To validate a theoretical model of an electrical machine during development of a new electrical machine, for example by comparing the actual measurements of one or more machine characteristics with values that are predicted by the theoretical model. In this way, the theoretical model may be improved and/or the design of the electrical machine may be improved.
- To provide performance feedback that can be used to enhance the control and operation of the electrical machine.
- To monitor the performance of the electrical machine over time for servicing purposes.
- For use in failure diagnostics, for example to detect a failed rotor diode.
- Where electrical machine protection systems are in place, they may use primary measurements from the rotor, rather than analysing secondary effects.

However, because the rotor of an electrical machine is a moving part (most commonly rotating about an axis), it can be difficult to reliably communicate signals from the rotor, and therefore to reliably obtain measurements relating to the rotor.

Brushed electrical machines comprise brushes and a slip ring on the rotor. The slip ring rotates with the rotor and interfaces with the stationary brushes. Electrical signals may be communicated to and/or from the rotor through the slip ring and brushes. Thus, signals (such as measurements taken on the rotor, or rotor currents to be measured) may be communicated from the rotor to some external entity (for example, to a failure diagnostics module). However, brushed electrical machines tend to have problems with reliability and require regular servicing. Furthermore, they tend to be large, heavy and have a large overhung moment. Therefore, for many applications, particularly where reliability, weight and size are important (such as in aviation), it is preferable to use brushless electrical machines. Brushless electrical machines do not have a slip ring and brushes, therefore signals cannot be communicated from the rotor in this way.

US 2007/0014374 A1 describes an isolation device comprising a pulse transformer isolation barrier. The device is configured to perform time division multiplexed transmission of power and data from a primary coil of the transformer to a secondary coil of the transformer. As such, during power frames of time, power is transmitted from the primary coil to the secondary coil and during data frames of time, data is transmitted from the primary coil to the secondary coil. Data is transmitted across the transformer digitally during the data frames, for example using Manchester Coded Data. Duplex communication (i.e., communication from the primary coil to the secondary coil and communication from the secondary coil to the primary coil) can also be achieved by load impedance switching on the secondary side of the transformer during the data frames. For load impedance switching, a load presented across the secondary coil can be switched between two different values. By changing the load across the secondary coil, the load current on the primary coil of the digital signal to be transmitted from the primary coil to the secondary coil will change. This change in primary load current caused by a change in load on the secondary coil may be detected by isolating the component of primary side current that is caused by load impedance from the component of primary side current that is caused by magnetising inductance. This may be achieved by using a transmit data encoding scheme for the digital communication from primary to secondary that is double DC balanced (i.e., DC balanced in both current and voltage) and then measuring primary side current at the specific times magnetizing inductance current is known to be close to zero, or by generating a compensating current which acts to cancel the magnetizing inductance current.

However, operation of such a signal isolation device on an electrical machine may be extremely complex, as one of the transformer coils (the primary coil or the secondary coil) would be mounted on the rotor and therefore moving relative to the other coil, which would be off the rotor. This could make the isolation of the magnetizing inductance current very challenging. Furthermore, even if such challenges could be overcome, it may not be desirable to add such an isolation device to an electrical machine, as it may significantly increase the weight and size of the machine, which may be unacceptable in a number of different applications, for example in aviation.

Summary

In a first aspect of the present disclosure, there is provided an electrical machine comprising: a rotor comprising one or more rotor exciter windings; a stator exciter winding for receiving a stator current to establish a magnetic field for causing electrical induction in the one or more rotor exciter windings; a first loading module mounted on the rotor and configured to: receive a first input indicative of a first machine characteristic; and apply a first load to a first rotor exciter winding of the one or more rotor exciter windings based at least in part on the received first input; and a monitor module coupled to the exciter stator and configured to: detect an effect of the applied first load on the stator current; and determine the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current.

The effect of the applied first load on the stator current may comprise a first pulse in the stator current corresponding to the first rotor exciter winding passing the stator exciter winding.

The monitor module may be further configured to: detect a synchronisation pulse in the stator current; and detect the first pulse in the stator current using at least the synchronisation pulse.

The synchronisation pulse may be generated by a synchronisation rotor exciter winding of the one or more rotor windings passing the stator exciter winding.

The synchronisation pulse may be a pulse in the stator current with a peak value that is outside of an allowable operating range of the first pulse in the stator current.

Preferably, the electrical machine further comprises a power supply module mounted on the rotor, wherein the power supply module is coupled to the first loading module to provide electrical power to the first loading module. The power supply module may be coupled to the synchronisation rotor exciter winding to draw electrical power from the synchronisation rotor exciter winding, or coupled to a rotor generator winding to draw electrical power from the rotor generator winding.

The electrical machine may further comprise: a second loading module mounted on the rotor and configured to: receive a second input indicative of a second machine characteristic; and apply a second load to a second rotor exciter winding of the one or more rotor exciter windings based at least in part on the received second input; and wherein the monitor module is further configured to: detect an effect of the applied second load on the stator current; and determine the second machine characteristic based at least in part on the detected effect of the applied second load on the stator current.

The effect of the applied second load on the stator current may comprise a second pulse in the stator current corresponding to the second rotor exciter winding passing the stator exciter winding.

Preferably, the electrical machine further comprises a first alternating voltage source coupled to the stator exciter winding and configured and to apply a first alternating voltage to the stator exciter winding at a first frequency.

Preferably, the monitor module is tuneable to the first frequency to detect the effect of the applied first load on the stator current at the first frequency and determine the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current at the first frequency.

Preferably, the first loading module is tuned to the first frequency so that the applied first load is presented to an electrical signal induced in the first rotor exciter winding and alternating at the first frequency.

The electrical machine may be further configured to communicate the first machine characteristic and a further machine characteristic from the rotor to the monitor module using frequency division multiplexing. To achieve frequency division multiplexing, the electrical machine may further comprise: a multiplexing loading module mounted on the rotor, wherein the multiplexing loading module is tuned to a second frequency and is configured to: receive an input indicative of the further machine characteristic; and apply a multiplexing load to any of the one or more rotor exciter windings based at least in part on the received first input so that the applied multiplexing load is presented to an electrical signal induced in the rotor exciter winding and alternating at the second frequency; and the monitor module is further tuneable to the second frequency to detect the effect of the applied multiplexing load on the stator current at the second frequency and determine the further machine characteristic based at least in part on the detected effect of the applied multiplexing load on the stator current at the second frequency.

The electrical machine may further comprise a second alternating voltage source coupled to the stator exciter winding and configured to apply a second alternating voltage to the stator exciter winding at the second frequency.

The rotor exciter winding to which the multiplexing load is applied may be the first rotor exciter winding.

The first machine characteristic may comprise any of: a rotor temperature; an air gap temperature; an electrical machine temperature; a rotor diode current; a rotor diode voltage; a rotor generator winding current; a rotor generator winding voltage; a mechanical strain on the rotor; an oil pressure; an oil flow; or any other measurable feature, characteristic or parameter relating to the electrical machine.

The first loading module is configured to apply the first load to at least one further rotor exciter winding of the one or more rotor exciter windings based at least in part on the received first input. In this way, the first loading module may apply the first load to two or more rotor exciter windings (for example, some or all of the rotor exciter windings)

In a second aspect of the present disclosure, there is provided a rotor for use in the electrical machine provided above, the rotor comprising: one or more rotor exciter windings; and a first loading module configured to: receive a first input indicative of a first machine characteristic; and apply a first load to a first rotor exciter winding of the one or more rotor exciter windings based at least in part on the received first input.

In a third aspect of the present disclosure, there is provided a monitor module for coupling to the stator exciter winding of the electrical machine provided above, the monitor module being configured to: detect an effect on the stator current caused by a first load applied to a first rotor winding of the rotor of the electrical machine, wherein the first load is applied by a first loading module based at least in part on a first input that is indicative of a first machine characteristic; and determine the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current.

In a fourth aspect of the present disclosure, there is provided a method of determining a first machine characteristic of an electrical machine during operation of the electrical machine, the method comprising: applying a voltage across a stator exciter winding of the electrical machine; applying a first load to a first rotor exciter winding of the rotor based at least in part on a signal indicative of the first machine characteristic; detecting an effect of the applied first load on a stator current through the stator exciter winding; and determining the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current.

In a further aspect of the present disclosure, there is provided a rotor for use in the electrical machine provided above, the rotor comprising: one or more rotor exciter windings; one or more loads; and a first loading module configured to: receive a first input indicative of a first machine characteristic; and apply a first load of the one or more loads to a first rotor exciter winding of the one or more rotor exciter windings based at least in part on the received first input.

Drawings

Aspects of the present disclosure are described below, by way of example only, with reference to the following drawings, in which:

Figure 1 shows an example prior art three-phase brushless electrical machine;

Figure 2 shows an electrical machine in accordance with an aspect of the present disclosure;

Figure 3 shows an example waveform representing changes in the stator exciter winding alternating current of the electrical machine of Figure 2;

Figure 4 shows an electrical machine in accordance with a further aspect of the present disclosure;

Figure 5 shows an example waveform representing changes in the stator exciter winding alternating current of the electrical machine of Figure 5;

Figure 6 shows a further example waveform representing a stator exciter winding alternating current of the electrical machine of Figure 5; and

Figure 7 shows an example configuration of some of the modules of the electrical machines represented in Figure 2 and 4.

Detailed description

The present disclosure relates to an electrical machine that is configured to communicate at least one machine characteristic from a rotor of the electrical machine to an off-rotor monitor module whilst the electrical machine is operating. The characteristic is communicated by applying a load to at least one of the rotor exciter windings based at least in part on the machine characteristic and the monitor module detecting the effect that causes on the stator exciter winding current. By communicating the at least one machine characteristic in this way, there is minimal impact on the design of a standard electrical machine, such that the electrical machine can be made light weight and small, and also operate at relatively high speeds, such that the electrical machine is suitable for use in aviation. Furthermore, the at least one electrical characteristic can be communicated without requiring any physical connection, such as brushes and slip-rings, between the rotor and the monitor module.

Figure 1 of the drawings shows an example prior art, three-phase brushless electrical machine 100. The operation of the brushless electrical machine 100 will be well understood by the person skilled in the art. Nevertheless, a brief description of the brushless electrical machine 100 operating as an electrical generator is given below.

The electrical machine 100 comprises a stator 120 and a rotor 130. The stator 120 comprises a stator exciter winding 122 and a main exciter DC drive 110 is configured to apply a DC voltage across the stator exciter winding 122. This causes the stator exciter winding 122 to establish a magnetic field. The rotor 130 comprises three rotor exciter windings 132-1, 132-2, 132-3 that are configured for three-phase electrical generation. The rotor 130 is configured to rotate about its axis, such that as the rotor 130 rotates, each of the three rotor exciter windings 132-1, 132-2, 132-3 pass in turn through the magnetic field established by the stator exciter winding 122. For example, the first rotor exciter winding 132-1 may pass through the magnetic field established by the stator exciter winding 122 as the rotor 130 rotates, thereby causing a peak in electrical induction in the first rotor exciter winding 132-1. As the rotor 130 rotates through about 120° rotation, the second rotor exciter winding 132-2 may pass through the magnetic field established by the stator exciter winding 122, thereby causing a peak in electrical induction in the second rotor exciter winding 132-2. As the rotor 130 rotates through about 240° rotation, the third rotor exciter winding 132-3 may pass through the magnetic field established by the stator exciter winding 122, thereby causing a peak in electrical induction in the third rotor exciter winding 132-3. As the rotor 130 rotates through about 360°

rotation, the first rotor exciter winding 132-1 may again pass through the magnetic field established by the stator exciter winding 122, thereby again causing a peak in electrical induction in the first rotor exciter winding 132-1, and so on.

The rotor diodes 134 are configured as a three-phase bridge rectifier to rectify the induced 3-phase, AC voltage generated by the rotor exciter windings 132-1, 132-2, 132-3. The rectified voltage is applied across the rotor generator winding 136 to establish a magnetic field.

The stator 120 further comprises three stator generator windings 124-1, 124-2, 124-3, that are configured for three-phase electrical generation. The stator generator windings 124-1, 124-2, 124-3 are arranged such that as the rotor 130 rotates, the magnetic field established by the rotor generator winding 136 passes through each of the three stator generator windings 132-1, 132-2, 132-3 in turn. For example, the magnetic field established by the rotor generator winding 136 may pass through the first stator generator winding 124-1, thereby causing a peak in electrical induction in the first stator generator winding 124-1. As the rotor 130 rotates through about 120° rotation, the magnetic field established by the rotor generator winding 136 may pass through the second stator generator winding 124-2, thereby causing a peak in electrical induction in the second stator generator winding 124-2. As the rotor 130 rotates through about 240° rotation, the magnetic field established by the rotor generator winding 136 may pass through the third stator generator winding 124-3, thereby causing a peak in electrical induction in the third stator generator winding 124-3. As the rotor 130 rotates through about 360° rotation, the magnetic field established by the rotor generator winding 136 may again pass through the first stator generator winding 124-1, thereby causing a peak in electrical induction in the first stator generator winding 124-1, and so on. Thus, the electrical machine 100 generates a three-phase AC voltage at the generator output terminals 126.

As explained in the 'background' section, it may be desirable to measure machine characteristics on the rotor of an electrical machine such as that represented in Figure 1. To do this, taking measurements on the rotor and then communicating them off the rotor using a radiofrequency (RF) telemetry link has been considered. In particular, the measurements could be communicated from the rotor to some external entity (for example, to a failure diagnostics module) using an RF telemetry link between a rotor mounted RF telemetry transceiver and a stationary RF telemetry transceiver that interfaces with the external entity. However, for electrical machines that are designed to operate at relatively high speeds, such as those used in aviation, it has been determined that RF telemetry may not be very reliable, due to centrifugal forces on the rotor. Furthermore, the radiofrequency used must be one that is allocated by the relevant authorities (for example, governmental agencies, such as Ofcom in the UK, or the FCC in the US) for use for this purpose (i.e., the radiofrequency used should be within a part of the frequency spectrum that is allocated for such purposes). Because different countries allocate the parts of their radiofrequency spectrum differently, the radiofrequency to be used may be different depending on the country in which the electrical machine is operating. This would cause particularly significant problems when the electrical machine is operating on an international form of transport, for example on an aircraft that may fly between different countries, and through the airspace of numerous different countries during the journey. Choosing a radiofrequency for world-wide operation may be very difficult, if not impossible. Therefore, using a RF telemetry link may not be a viable solution for a number of types of electrical machine, particularly those designed to be used in aviation.

Figure 2 show an example representation of an electrical machine 200 in accordance with an aspect of the present disclosure. The electrical machine 200 is similar to that described in respect of Figure 1 and the process of generating a three-phase AC voltage at the output terminals 126 is the same as that described in respect of Figure 1. However, the electrical machine 200 represented in Figure 2 also includes some additional components to enable measurements, or other signals or values indicative of a characteristic of the electrical machine 200, to be communicated from the rotor 130 to a monitor module 240 that is off the rotor 130. The electrical machine 200 comprises a first alternating voltage source 210, which is coupled to the stator exciter winding 122 in order to apply a first alternating voltage to the stator exciter winding 122. In the example configuration represented in Figure 1, the first alternating voltage source 210 is coupled to the stator exciter winding 122 using a voltage transformer 212, although it will be appreciated that they may be coupled in any other suitable way. Consequently, an alternating current is superimposed on the direct current of the main exciter DC drive 110.

The first alternating voltage may alternate at any suitable frequency and at any suitable voltage level. For example, it may be at any frequency between about 100Hz to 10kHz, such as 800Hz, or 4kHz, or 9kHz, or at a frequency between about 500Hz to 5kHz, such as 1.2kHz, or 3.5kHz, or at a frequency between about 1kHz to 2kHz, such as 1.1kHz, or 1.87kHz, etc. The voltage level may be any suitable voltage which may, for example, be chosen in consideration of the voltage level of the DC exciter drive 110. For example, it may have a peak-to-peak voltage of between 0.2V to 100V, such as 0.6V, or 35V, or 90V, or a peak-to-peak voltage of between about 0.5V to 40V, such as 4V, or 26V, or a peak-to-peak voltage of between about 1V to 3V, such as 1.5V, or 2.45V, etc.

The alternating current superimposed on the direct current supplied to the stator exciter winding 122 causes an alternating magnetic field to be established by the stator exciter winding 122 at the frequency of the alternating voltage supplied by the first alternating voltage source 210. This, in turn, will induce an alternating current in each of the rotor exciter windings 132-1, 132-2, 132-3 as they each pass the stator exciter winding 122 as the rotor 130 rotates. The frequency of the induced current will alternate with a frequency that is the same as, or similar to, the frequency of the alternating voltage supplied by the first alternating voltage source 210.

A first loading module 230 is mounted on the rotor 130 at any convenient location. In the example arrangement represented in Figure 2, the first loading module 230 is coupled across a resistor 235 that is in series with the rotor generator winding 136. Thus, the first loading module 230 receives an input signal that is indicative of the current through the rotor generator winding 136 (i.e., the rotor generator winding current). Thus, the first loading module 230 can measure the rotor generator winding current.

A power supply module 220 is also mounted on the rotor 130 at any convenient location. The power supply module 220 is coupled to the rotor generator winding 136 in order to draw power from the rotor generator winding 136 (i.e., it is coupled across the rotor generator winding 136). The power supply module 220 is also coupled to the first loading module 230 in order to provide electrical power to the first loading module 230, so that the first loading module 230 can perform the functionality described below. The power supply module 220 may optionally comprise a smoothing capacitor and regulator to supply consistent DC power to the first loading module 230.

The first loading module 230 is coupled to the first rotor exciter winding 132-1 and is configured to apply a load to the first rotor exciter winding 132-1 based at least in part on its received input that is indicative of the rotor generator winding current. The load applied to the first rotor exciter winding 132-1 will affect the electrical induction of the first rotor exciter winding 132-1 as it passes the stator exciter winding 122. For example, depending on the type of load (for example, resistive, reactive, etc) an increase in the load applied may increase the level of electrical induction in the first rotor exciter winding 132-1, and a decrease in the load applied may decrease the level of electrical induction in the first rotor exciter winding 132-1. The load may be an ohmic resistive load, or a reactive load, or an impedance with ohmic resistance and also reactance. For example, the load may comprise at least one of a resistor(s), a capacitor(s), an inductor(s) and/or an active element(s), such as a semiconductor device.

The level of electrical induction that takes place in the first rotor exciter winding 132-1 as it passes the stator exciter winding 122 affects the amount of current drawn by the stator exciter winding 122 as the first rotor exciter winding 132-1 passes. For example, if the level of electrical induction in the first rotor exciter winding 132-1 increases, the amount of current drawn by the stator exciter winding 122 as the first rotor exciter winding 132-1 passes the stator exciter winding 122 will increase, and if the level of electrical induction in the first rotor exciter winding 132-1 decreases, the amount of current drawn by the stator exciter winding 122 as the first rotor exciter winding 132-1 passes the stator exciter winding 122 will decrease.

The monitor module 240 is coupled to the stator exciter winding 122 via a current transformer 242 and is configured to detect an effect of the load applied to the first rotor exciter winding 132-1 on the stator exciter winding alternating current. Thus, the monitor module 240 can detect a change (an increase or a decrease) in the level of stator exciter winding alternating current, and optionally a magnitude of that change. It will be appreciated that whilst the monitor module 240 detects changes in the stator exciter winding alternating current with use of a current transformer 242 in this particular example, it may alternatively be coupled to the stator exciter winding 122 and detect changes in the stator exciter winding alternating current by any other suitable means.

Figure 3 shows a simplified example waveform representing changes in the level of alternating current in the stator exciter winding (for example, changes in the peak-to-peak current, or changes in the rms current, etc). The x-axis represents time and the y-axis represents the change in current. In order to simplify the representation and make clear the effect that the monitor module 240 is configured to detect, only the peaks in the alternating current in the stator exciter winding 122 are shown and all noise and other signals are excluded.

At time t_1, the first rotor exciter winding 132-1 passes the stator exciter winding 122 and causes a peak of I_1 in the alternating current in the stator exciter winding 122. At this point, the rotor 130 may be considered to have rotated by 0°. At time t_2, the second rotor exciter winding 132-2 passes the stator exciter winding 122 and causes a peak of I_2 in the alternating current in the stator exciter winding 122. At this point, the rotor 130 may be considered to have rotated by 120°. At time t_3, the third rotor exciter winding 132-3 passes the stator exciter winding 122 and causes a peak of I_3 in the alternating current in the stator exciter winding 122. At this point, the rotor 130 may be considered to have rotated by 240°. At time t_4, the first rotor exciter winding 132-1 once again passes the stator exciter winding 122 and causes a peak of about I_1 in the alternating current in the stator exciter winding 122. At this point, the rotor 130 has made a complete rotation and may therefore be considered to have rotated by 0°. The time T between t_1 and t_4 represents the time for a complete rotation of the rotor 130, and is therefore the period of rotation of the rotor 130.

The load on the second rotor exciter winding 132-2 is not changed, so the peak in the alternating current in the stator exciter winding 122 as the second rotor exciter winding 132-2 passes the stator exciter winding 122 (at times t_2, t_5, t_8 and t_{11}) stays substantially constant at I_2 (for example, constant within reasonable operating thresholds). Likewise, the load on the third rotor exciter winding 132-3 is not changed, so the peak in the alternating current in the stator exciter winding 122 as the first rotor exciter winding 132-3 passes the stator exciter winding 122 (at times t_3, t_6, t_9 and t_{12}) stays substantially constant at I_3 (for example, constant within reasonable operating thresholds). At times t_1 and t_4 the load applied to the first rotor exciter winding 132-1 by the first loading module 230 is the same, such that as the first rotor exciter winding 132-1 passes the stator exciter winding 122, the peak in the alternating current in the stator exciter winding 122 stays substantially constant at I_1 (for example, constant within reasonable operating thresholds). Sometime after t_4, but before t_7, the first loading module 230 changes the load applied to the first rotor exciter winding 132-1 because a change in the rotor generator current has been measured by the first loading module 230. When the first rotor exciter winding 132-1 next passes the stator exciter winding 122 at time t_7, this change in loading is detected by the increase in the peak of alternating current in the stator exciter winding 122 to I_4.

If the monitor module 240 is configured not only to detect a change in the alternating current in the stator exciter winding 122, but also to measure the alternating current in the stator exciter winding 122 (for example, measure the peak value in alternating current, or the peak value in the rms of the alternating current), it may be calibrated to determine the load applied by the first loading module 230 based on that measure of alternating current. Because the first loading module 230 may be configured to apply particular sizes of load (for example, a particular magnitude or value of load) to represent particular values of measured rotor generator current (for example, the applied load may change proportionally with measured rotor generator current), the machine characteristic may be communicated to the monitor module 240 in an analogue fashion (for example, an analogue measurement or signal may be communicated from the rotor 130 to the monitor module 240 in an analogue way). Thus, the measured value of the rotor generator current may be communicated quickly and straightforwardly to the monitor module 240 by the first loading module 230 applying a load to the first rotor exciter winding 132-1 that is based at least in part on the measured value of the rotor generator current.

It will be appreciated that in an alternative configuration, rather than receiving an input indicative of rotor generator current, the first loading module 230 may receive an input indicative of some other machine characteristic. For example, it may receive an input indicative of a rotor temperature, an airgap temperature or an electrical machine temperature (for example, received from a temperature sensor on the rotor 130). Alternatively, it may receive an input indicative of a current or voltage for one or more of the rotor diodes 134. Alternatively, it may receive an input indicative of the voltage across the rotor generator winding 136. Alternatively, it may receive an input indicative of mechanical strain somewhere on the rotor 130, or oil pressure within the electrical machine 100, or oil flow within the electrical machine 100. Alternatively, it may receive an input indicative of a measure of any other characteristic. In a further alternative, it may receive an input indicative of a machine characteristic that is not a measure of something. For example, the machine characteristic may simply be whether one or more of the rotor diodes 134 have failed, such that the input is indicative of either 'working' or 'failed'. Likewise, the machine characteristic may be whether a temperature is above or below a particular threshold temperature, or whether a current is above or below a particular threshold current, or whether a voltage is above or below a particular threshold voltage. Regardless of the machine characteristic that the input to the first loading module 230 is indicative of, the first loading module 230 is configured to apply a load to the first rotor exciter winding 132-1 based on the input and the monitor module 240 is configured to detect an effect on the stator exciter current caused by that applied load and determine the machine characteristic based at least in part on the detected effect.

The effect that the monitor module 240 is configured to detect may be that there has been a change in the stator exciter alternating current (for example, an increase or decrease in a peak value of a pulse in the stator exciter alternating current) and/or a measure (for example, a peak value, or peak-to-peak value, or peak rms, etc) of the stator exciter alternating current. Thus, it may simply detect that there has been a change, which may be indicative of a machine characteristic such as 'rotor temperature exceeds a threshold temperature', and/or it may measure the stator alternating current and determine the machine characteristic that that represents (for example, a measure of the rotor generator winding current).

Thus, a first machine characteristic may be communicated from the rotor 130 to the monitor module 240 with a minimum of additional components added to the electrical machine, meaning that the electrical machine 200 can still be made lightweight and small. Furthermore, only the first loading module 230 and the power supply 220 are added to the rotor 130, meaning that relatively high operating speeds for the electrical machine can still be achieved. Also, all of the additional the modules are capable of withstanding wide temperature ranges, high levels of vibration and immersion in turbine oil, and do not require any regular servicing so that the electrical machine 200 can have long service intervals. Therefore, the electrical machine 200 is particularly effective for use in aviation.

In a further aspect of the present disclosure, two or more machine characteristics may be communicated from the rotor 130 to the monitor module 240 using frequency division multiplexing. For example, a second alternating voltage source may be coupled to the stator exciter winding 122 (for example, via the voltage transformer 212, or via some other voltage transformer or any other means) and configured to apply a second alternating voltage to the stator exciter winding 122. The second alternating voltage may alternate at any suitable frequency, which is different to the frequency of the first alternating voltage (applied by the first alternating voltage source 210). The frequencies of the first alternating voltage and the second alternating voltage may be chosen so that they are non-harmonically related, optionally including sub-harmonics, so as to reduce or prevent distortion between the voltage signals. The voltage level of the second alternating voltage may be any suitable voltage and may be the same as, or different to, the voltage level of the first alternating voltage.

As a result of the second alternating voltage across the stator exciter winding 122, a second alternating magnetic field is established by the stator exciter winding 122 at the frequency of the second alternating voltage. This, in turn, will induce an alternating current in each of rotor exciter windings 132-1, 132-2, 132-3 at the same, or similar, frequency to the second alternating voltage, as they each pass the stator exciter winding 122 as the rotor 130 rotates. The first loading module 230 may be tuned to the frequency of the first alternating voltage source 210 such that the load applied to the first rotor exciter winding 132-1 is presented to the alternating current induced in the first rotor exciter winding 132-1 at, or near to, the frequency of the first alternating voltage source. A multiplexing loading module may also be mounted on the rotor 130 and coupled to the first rotor exciter winding 132-1 and powered by the power supply module 220. The multiplexing loading module may be very similar to the first loading module 230, but configured to receive an input of a different machine characteristic and apply a load (referred to from here on as a 'multiplexing load' for the sake of clarity) to the first rotor exciter winding 132-1 based at least in part on the received input. Furthermore, the multiplexing loading module is tuned to the frequency of the second alternating voltage source such that the load it applies to the first rotor exciter winding 132-1 is presented to the alternating current induced in the first rotor exciter winding 132-1 at the frequency of the second alternating voltage source. Techniques for tuning the loading modules to particular frequencies are described in more detail later with reference to Figure 7.

Thus, the load applied by the first loading module 230 to the first rotor exciter winding 132-1 will affect the level of electrical induction that takes place in the first rotor winding 132-1 at the frequency of the first alternating voltage source 210. This will in turn affect the amount of alternating current drawn by the stator exciter winding 122 at the frequency of the first alternating voltage source 210 as the first rotor exciter winding 132-1 passes. Likewise, the load applied by the multiplexing loading module to the first rotor exciter winding 132-1 will affect the level of electrical induction that takes place in the first rotor winding 132-1 at the frequency of the second alternating voltage source. This will in turn affect the amount of alternating current drawn by the stator exciter winding 122 at the frequency of the second alternating voltage source as the first rotor exciter winding 132-1 passes.

The monitor module 240 may be tuned to the frequency of the first alternating voltage source 210 to detect an effect on the alternating current of the stator exciter winding 122 caused by the load applied to the first rotor exciter winding 132-1 by the first loading module 230. Thus, the first loading module 230 can receive a first input indicative of a first machine characteristic and the monitor module 240 can determine the first machine characteristic from the detected effect on the alternating current of the stator exciter winding 122 that is alternating at the frequency of the first alternating voltage source 210. The monitor module 240 may also be tuned to the frequency of the second alternating voltage source (as described in more detail later with reference to Figure 7) to detect an effect on the alternating current of the stator exciter winding 122 caused by the load applied to the first rotor exciter winding 132-1 by the multiplexing loading module. Thus, the multiplexing loading module can receive an input indicative of a further machine characteristic and the monitor module 240 can determine the further machine characteristic from the detected effect on the alternating current of the stator exciter winding 122 that is alternating at the frequency of the second alternating voltage source.

By tuning the loading modules and the monitor module 240 in this way, not only is frequency division multiplexing possible, changes in current causes by the loads applied to the first rotor exciter winding 132-1 by a loading module may also be more straightforwardly isolated from any other, unrelated changes in the stator exciter winding current (for example, at power generation frequencies and changes in the level of direct current supplied by the main exciter DC driver 110). Thus, an improvement in reliability and accuracy of detection of the effect on the stator exciter winding current may be realised.

This frequency division multiplexing technique may be used to communicate more than two different machine characteristic from the rotor 130 to the monitor module 240 by using more than two different frequencies, for example, three, four, five, etc different frequencies. Each different frequency may be used to communicate a different machine characteristic from the rotor 130 to the monitoring module 240. Therefore, a plurality of machine characteristics can be communicated from the rotor 130 to the monitor module 240 with very few additional components.

It will be appreciated that whilst the above two alternating voltage sources, the first alternating voltage source 210 and the second alternating voltage source, are described as separate modules, they do not necessarily have to be separate modules. For example, a single module may be configured to generate two different alternating voltage signals with different frequencies by any suitable means, and those signals be superimposed on each other and applied to the stator exciter winding 122.

Furthermore, whilst in all of the above description (in respect of the configuration represented in Figure 2 and in respect of the frequency division multiplexing configuration) the loading modules are configured to apply a load to the first rotor exciter winding 132-1, they may alternatively apply a load to the second rotor exciter winding 132-2, or the third rotor exciter winding 132-3, or any two or more of the rotor exciter windings 132-1, 132-2, 132-3.

Figure 4 shows an example representation of an electrical machine 400 in accordance with a further aspect of the present disclosure. The electrical machine 400 is similar to that described in respect of Figure 2. However, the power supply module 410, which is mounted on the rotor 130 at any convenient location, is configured to be coupled to the third rotor exciter winding 132-3 in order to draw power from the third rotor exciter winding 132-3 (i.e., it is coupled across the third rotor exciter winding 132-3). The power supply module 410 is coupled to the first loading module 230 and a second loading module 420 in order to provide electrical power to those loading modules. The power supply module 410 may supply AC power to the first and second loading modules, or may supply DC power to the first and second loading modules, in which case the power supply module 410 may comprise a rectifier and optionally also a smoothing capacitor and/or a regulator.

The first loading module 230 is configured as described above is respect of Figure 2. It is configured to receive a first input indicative of a first machine characteristic, which in this example is the current in the rotor generator winding 136, as measured across the resistor 235, and apply a first load to the first rotor exciter winding 132-1 based at least in part on the received first input. The second loading module 420 is configured similarly to the first loading module 230, but receives a second input indicative of a second machine characteristic. In this example, the second loading module 420 is coupled across the rotor generator winding 136, such that the second machine characteristic is the rotor generator winding voltage. The second loading module 420 is also configured to apply a second load to the second rotor exciter winding 132-2 based at least in part on the received second input.

For the same reasons as explained above in respect of the configuration represented in Figure 2, the size, or magnitude, of the second load applied to the second rotor exciter winding 132-2 will affect the electrical induction of the second rotor exciter winding 132-2 as it passes the stator exciter winding 122. This, in turn, affects the amount of current drawn by the stator exciter winding 122 as the second rotor exciter winding 132-2 passes. Thus, the monitor module 240 can detect an effect of the applied second load on the stator exciter winding alternating current and determine the second machine characteristic based on that.

It will be appreciated that in an alternative configuration, rather than receiving an input indicative of rotor generator winding voltage, the second loading module 420 may receive an input indicative of some other machine characteristic. For example, it may receive an input indicative of a rotor temperature, an airgap temperature or an electrical machine temperature (for example, received from a temperature sensor on the rotor 130). Alternatively, it may receive an input indicative of a current or voltage for one or more of the rotor diodes 134.

Alternatively, it may receive an input indicative of mechanical strain somewhere on the rotor 130, or oil pressure within the electrical machine 400, or oil flow within the electrical machine 400. Alternatively, it may receive an input indicative of a measure of any other characteristic. In a further alternative, it may receive an input indicative of a machine characteristic that is not a measure of something. For example, the machine characteristic may simply be whether one or more of the rotor diodes 134 have failed, such that the input is indicative of either 'working' or 'failed'. Likewise, the machine characteristic may be whether a temperature is above or below a particular threshold temperature, or whether a current is above or below a particular threshold current, or whether a voltage is above or below a particular threshold voltage. Regardless of the machine characteristic that the input to the second loading module 420 is indicative of, the second loading module 420 is configured to apply a load to the second rotor exciter winding 132-2 based on the input and the monitor module 240 is configured to detect an effect on the stator exciter current caused by that applied load and determine the machine characteristic based at least in part on the detected effect.

Figure 5 shows a simplified example waveform representing changes in the peak value (for example, the peak current, or peak rms current) of alternating current in the stator exciter winding 122 of the electrical machine 400. The waveform of Figure 5 is very similar to that of Figure 3, but between the times t_2 and t_5, the load on the second rotor exciter winding 132-2 is changed by the second loading module 420 because a change in the rotor generator winding voltage has been measured by the second loading module 420. When the second rotor exciter winding 132-2 passes the stator exciter winding 122 at time t_5, this change in loading is detected by the monitor module 240 by the increase in the peak of the stator exciter winding alternating current to I_5. In the same way as described above in respect of Figure 3, the monitor module 240 may therefore detect the effect on the stator exciter winding alternating current caused by the applied second load and determine the second machine characteristic based at least in part on that.

The monitor module 240 may be configured to identify, in any suitable way, which of the pulses in the level of alternating current represented in Figure 5 corresponds to which of the rotor exciter windings 132-1, 132-2, 132-3 and therefore which machine characteristic corresponds to which current pulse. One particular technique is to detect a synchronisation pulse in the stator exciter winding alternating current. A synchronisation pulse may be a pulse in current level that remains substantially the same over time and/or that is of a significantly different magnitude to the other pulses in the current. The synchronisation pulse may be generated when a synchronisation rotor exciter winding on the rotor 130 passes the stator exciter winding 122. In the configuration represented in Figure 5, the third rotor exciter winding 132-3 may be the synchronisation rotor exciter winding, because the loading applied to the third rotor exciter winding 132-3 may remain substantially constant. As a consequence, the monitor module 240 may identify that over time, the pulse in alternating current at times t_3, t_6, t_9 and t_{12} remains at a substantially constant level at I_3 and that those pulses in the alternating current must therefore be the synchronisation pulse that corresponds to the third exciter rotor winding 132-3. Additionally, or alternatively, the monitor module 240 may identify that the pulse in alternating current at times t_3, t_6, t_9 and t_{12} is of a significantly smaller magnitude than the other pulses (the representation in Figure 5 is not drawn to scale for the sake of clarity, so whilst the pulses at t_3, t_6, t_9 and t_{12} may not appear significantly smaller than the other pulses, in practice they may be) and must therefore be the synchronisation pulse. For example, the electrical machine 400 may be configured such that the synchronisation pulse has a magnitude that is below the minimum magnitude of the other pulses in the alternating current, so that it can always be identified in the alternating current signal. Consequently, the monitor module 240 may determine that the pulse in the alternating current that follows each synchronisation pulse corresponds to the first rotor exciter winding 132-1 and, as such, the pulses at times t_4, t_7, t_{10} and t_{13} may be used to determine the first machine characteristic. Likewise, the monitor module 240 may also determine that the pulses in the alternating current at times t_5, t_8 and t_{11} correspond to the second rotor exciter winding 132-2 and, as such, the pulses at t_5, t_8 and t_{11} may be used to determine the second machine characteristic.

It will be appreciated that this is only one particular example of a synchronisation pulse. In particular, whilst Figure 5 shows the pulses at t_3, t_6, t_9 and t_{12}, as being smaller than the other pulses, the electrical machine 400 may be configured to ensure that they are significantly larger than the other pulses, for example by setting the loading applied by the power supply module 410 to be larger (such as 5 times, or 10 times, or 20 times, etc, larger) than the maximum loads that could be applied by the first or second loading modules 230 and 420. In an alternative configuration, the power supply module 410 may be coupled to the rotor generator winding 136 in order to draw power from the rotor generator winding 136, in the same way as power supply module 220 in Figure 3. In this case, the third rotor exciter winding 132-3 may act as the synchronisation rotor exciter winding by being unloaded, or loaded with a fixed load, or loaded with a load that is significantly larger than the maximum loads that could be applied by the first or second loading modules 230 and 420, etc.

Figure 6 shows a further example simplified example waveform representing changes in the peak value (for example, the peak current, or peak rms current) of alternating current in the stator exciter winding 122 of the electrical machine 400. This example waveform represents a configuration where the synchronisation pulse is larger than the other pulses in the alternating current in the stator exciter winding 122. At a rotor position of 0°, there is a synchronisation pulse in the stator exciter winding 122 alternating current. The synchronisation pulse has a peak value of I_s. At a rotor position of 120°, there is a second pulse in the stator exciter winding 122 alternating current. This second pulse has a peak value of I_F. At a rotor position of 240°, there is a third pulse in the stator exciter winding 122 alternating current. This second pulse has a peak value of I_M.

In this example, the second pulse relates to a machine characteristic and the third pulse relates to a different machine characteristic. The electrical machine 400 is configured such that peak value I_S will always be greater than the peak value of the other pulses in alternating current. In particular, I_F represents the full scale current that the pulses relating to machine characteristics can reach (i.e., the pulses other than the synchronisation pulse) and I_M represents the minimum current that the pulses relating to machine characteristics can reach (i.e., the pulses other than the synchronisation pulse). Thus, the peak value of the second pulse and the third pulse may be varied between I_F and I_M by loading modules on the rotor 130 changing the loading on respective rotor exciter windings 132-1, 132-2, 132-2 in order to communicate machine characteristics off the rotor, but the synchronisation pulse will always be distinguishable as it is greater than I_F. Thus, the difference between I_S and I_F may be thought of as a guard band, which ensures that the synchronisation pulse is always distinguishable. It will be appreciated that, as explained with reference to Figure 5 above, in an alternative, the electrical machine 400 may be configured such that the peak value of the synchronisation pulse is less than IM, so that it is always distinguishable in that way. Either way, the electrical machine 400 may be configured such that the peak value I_S of the synchronisation pulse is outside (either greater than or lesser than) of an allowable operating range (I_M to I_F) of the other pulses in the stator current.

In this example, the minimum current I_M may be non-zero, to take into account noise levels that may be present in the alternating current in the stator exciter winding 122. Having the minimum current I_M as a non-zero value may also provide a degree of fault detection.

By using a synchronisation pulse, not only can different pulses within the alternating current in the stator exciter winding 122 be identified in order to determine which machine characteristic they relate to, but it also permits the use of a noise gate to improve signal to noise ratio, measurement dynamic range and accuracy.

Therefore, it can be appreciated the electrical machine 400 enables a plurality of machine characteristics to be communicated from the rotor 130 to the monitor module 240 with very few additional components.

Figure 7 shows the details of a non-limiting example implementation of the first alternating voltage source 210, the power supply module 410, the first loading module 230 and the monitor module 240. Figure 7 also includes a basic representation of some of the windings of the electrical machine, however, it will be understood that these are significantly simplified compared with Figures 2 and 4 for the sake of clarity. It will be readily apparent to the skilled person that whilst one particular detailed implementation of the modules and components is represented in Figure 7 and described below, there are many other ways in which those modules and components may be configured to achieve the functionality described above, all of which are encompassed by the present disclosure.

In Figure 7, the first alternating voltage source 210 comprises an oscillator 610 to generate the alternating signal at the desired frequency. The alternating signal is passed through a variable gain levelling amplifier 612 and on to a power amplifier 614 before being applied to the stator exciter winding 122. The applied alternating voltage is also fed-back to a detector 616, which supplies a feedback signal to the variable gain levelling amplifier 612. The variable gain levelling amplifier 612, power amplifier 614 and detector 616 may all work together to maintain the applied alternating voltage at a fixed voltage, such that any detected changes in the stator exciter winding alternating current are caused only by changes in the load(s) applied by the loading module(s).

The power supply module 410 represented in Figure 7 is configured to supply DC power to the first loading module 230 and comprises a narrow band filter 620, a rectifier and smoothing capacitor 622 and a regulator 624. The narrow band filter 620 is an optional component and is tuned to the frequency of the alternating voltage supplied by the first alternating voltage source 210. Likewise, the smoothing capacitor and regulator 624 are also optional for the supply of DC power.

In Figure 7, the first loading module 230 comprises an input circuit 630 and a gain control 632, wherein the input circuit 630 is configured to supply a control signal to the gain control 632 based on the received first input indicative of a first machine characteristic. The gain control 642 than adjusts the current control 634 (for example, a transistor, or some other suitable variably adjustable component) in order to adjust the amount of the load 636 that is applied to the first rotor exciter winding 132-1. Thus, the size or magnitude of the load 636 that is presented to the first rotor exciter winding 132-1 may be adjusted by the input circuit 630, gain control 632 and current control 634 based on the received first input indicative of the first machine characteristic.

The second loading module 420 and/or the multiplexing loading module may have the same, or similar, arrangement of components as the first loading module 230.

The narrow band filter 638 sits between the current control 634 and the first rotor exciter winding 132-1 to tune the first loading module 230 to a particular range of frequencies. For example, the narrow band filter 638 may be tuned to a narrow band of frequencies that are centred on the frequency of the first alternating voltage source 210. Thus, the load 636 would only be presented to alternating current induced in the first rotor exciter winding 132-1 at the tuned frequency. Any other currents induced in the first rotor exciter winding 132-1 at frequencies outside of the tuned narrow band may not be presented with the load 636. This is particularly useful for the frequency division multiplexing aspect described above, where the narrow band filter 638 can be tuned to the frequency of the first alternating voltage source 210. The multiplexing loading module may have the same configuration as the first loading module 230, but be tuned to the frequency of the second alternating voltage source, in order to achieve frequency division multiplexing. The narrow band filter 638 may be an active filter or a passive filter. It will be appreciated that the first loading module 230 (and likewise, the multiplexing loading module and/or the second loading module 420) may be tuned to particular frequencies in any other suitable way, for example using a high pass, or low pass, filter, or using an L-C tank, or by any other suitable configuration of components. It will also be appreciated that tuning of the loading modules to particular frequencies is optional, particularly for the non-frequency division multiplexing aspects described above.

The monitor module 240 in Figure 7 comprises a narrow band filter 640 to tune the monitor module 240 to a particular range of frequencies. Thus, the monitor module 240 may be tuned to the same, or very similar, frequencies as the narrow band filter 634 of the first loading module 230, such that the effect on the alternating current of the stator exciter winding 122 caused by the first loading module 230 may be detected by the monitor module 240. The narrow band filter 640 may be an adjustable, or tuneable, narrow band filter 640, such that the monitor module 240 may be tuned to one particular range of frequencies (for example, those of the first loading module 230) to detect changes in stator exciter winding alternating current at those frequencies, and then tuned to a different range of frequencies (for example, those of the multiplexing loading module) to detect changes in the stator exciter winding alternating current at those frequencies. In this way, the monitor module 240 may perform the frequency division multiplexing aspects described earlier. Alternatively, the monitor module 240 may comprise one or more duplicates of the circuit comprising components 640-654, wherein the narrow band filter in each duplicate is tuned to a different range of frequencies. In this way, the monitor module 240 may simultaneously detect changes in the stator exciter winding alternating current at a variety of different frequencies. The narrow band filter 640 may be an active filter or a passive filter. It will be appreciated that the monitor module 240 may be tuned to particular frequencies in any other suitable way, for example using a high pass, or low pass, filter, or using an L-C tank, or by any other suitable configuration of components. It will also be appreciated that tuning the monitor module 240 to particular frequencies is optional, particularly for the non-frequency division multiplexing aspects described above.

The monitor module 240 in Figure 7 also comprises a peak detector 642, a pulse shaper & synchroniser 644, a gate 646, a counter 648, a switch 650 (for example, a transistor switch, or any other suitable form of switch), and two peak hold & gain correctors 652 and 654. These components are configured to identify the peak values in the pulses in the stator exciter winding alternating current and to generate output signals at the output 656, using which respective machine characteristics can be determined by subsequent components or blocks of the monitor module 240. In this configuration, there are two channels at the output 656, each relating to a different machine characteristic being communicated from the rotor 130 by a respective loading module. However, a different number of channels may be used, depending on the number of machine characteristics being communicated from the rotor 130. In a basic explanation of the operation of the monitor module 240 represented in Figure 7, the narrow band filter 640 is configured to isolate the alternating current at a particular frequency (for example, the frequency of the first alternating voltage source 210) and reject noise and other frequencies (which is particularly relevant to the frequency division multiplexing aspect described above). The peak detection circuit 642 isolates and identifies the peak of each current pulse and feeds it to the pulse shaper & synchroniser 644. The second output of the peak detection circuit 642 is a facsimile of the output from the narrow band filter 640 and is fed to the gate 646. The pulse shaper in the pulse shaper & synchroniser 644 turns the signal it receives from the peak detector 642 into a square pulse of defined half height duration. The synchroniser in the pulse shaper & synchroniser 644 identifies the synchronisation pulse and each of the machine characteristic pulses and provides this information to the gate 646, counter 648 and switch 650. The square pulse provides the control to open the gate 646 which allows the current pulses through to the switch 650. The counter 648 and switch 650, using the timing information from the pulse shaper & synchroniser 644, routes the correct current pulse to its respective output 656. The peak hold parts of the peak hold & gain correction modules 652 and 654 smooth the output for each channel 656 and the gain correction part of the gain correction modules 652 and 654 provide scaling of the output for each channel 656 to suit the machine characteristic type. Where the machine characteristic is a measurement of a machine parameter (for example, a measurement of rotor current), a signal on one of the channels of the output 656 may be a facsimile of the signal input to the respective loading module (i.e., the signal on which the measurement was based). In this case, the input to the respective loading module on the rotor 130 may be a DC level scaled to represent the parameter being measured and the signal on a channel of the output 656 may be its facsimile.

It will be appreciated that is merely one non-limiting example of how the monitor module 240 may be implemented and that the monitor module 240 may be implemented in any other suitable way that enables it to detect an effect on the stator exciter winding alternating current caused by a load(s) applied to a rotor exciter winding(s) and determine a machine characteristic based in least on part on the detected effect. For example, the functionality of the monitor module 240 may be implemented by software operating on a computing device.

The skilled person will readily appreciate that various alterations or modifications may be made to the above described aspects of the disclosure without departing from the scope of the disclosure. For example, in the aspect represented in Figure 2, the power supply module 220 is coupled to the rotor generator winding 136 in order to draw power from across the rotor generator winding 136. However, in an alternative, the power supply module 220 may be coupled to, and draw power from, any one or more of the rotor exciter windings 132-1, 132-2, 132-3 (similarly to the power supply module 420 represented in Figure 4). Alternatively, the power supply module 220 may not be coupled to any of the rotor windings and instead may draw power from any other suitable source, for example from a battery mounted on the rotor 130.

Likewise, the power supply module 410 in the aspect represented in Figure 4 may alternatively be coupled to, and draw power from, the rotor generator winding 136 (similarly to the power supply module 220 represented in Figure 2). Alternatively, the power supply module 410 may not be coupled to any of the rotor windings and instead may draw power from any other suitable source, for example from a battery mounted on the rotor 130.

Nevertheless, there may be benefits in using the power supply configurations represented in Figure 2 and 4, in order to minimise additional weight added to the rotor 130 and/or to achieve long service intervals for the electrical machines 200 and 400.

All of the electrical machines described above are three-phase, brushless electrical generators. However, the electrical machines may alternatively have any number of phases, for example single phase, two-phase, four phase, etc. For example, in a single phase electrical machine, the first loading module 230 may still apply the first load to the single rotor exciter winding based at least in part on the first input indicative of the first machine characteristic. Optionally, further machine characteristics may also be communicated from the rotor 130 to the monitor module 240 using the frequency division multiplexing technique described above.

In the above, the frequency division multiplexing technique is described with reference to the electrical machine 200 represented in Figure 2. However, the frequency division multiplexing technique may be used in combination with other arrangements, such as that represented in Figure 4 where the rotor 130 comprises multiple loading modules, each applying a load to a different rotor exciter winding 132-1, 132-2, 132-3. For example, an electrical machine may comprise the first loading module 230 and the second loading module 420, and also a multiplexing loading module coupled to the first rotor exciter winding 132-1 or the second rotor exciter winding 132-2. Thus, it will be appreciated that a plurality of different machine characteristics may be communicated from the rotor 130 to the monitor module 240 by applying loads to a plurality of different rotor exciter windings and/or using frequency division multiplexing. Where a synchronisation pulse is used, as described above, this may be present in only one of the frequencies used for frequency division multiplexing. The synchronisation provided by the synchronisation pulse may then be applied across all of the frequencies.

The skilled person will readily appreciate that whilst all of the electrical machines described above are brushless electric generators, they may alternatively be electric motors, since the operation of electric motors is analogous to that of electric generators. Furthermore, whilst the benefits of the present disclosure may be particularly apparent for brushless electric machines, it can be appreciated that the electrical machine according to the present disclosure may be of any type, for example brushed electric machines.

The electrical machines 200 and 400 represented in Figures 2 and 4 include DC blocking capacitors in the couplings between the rotor exciter windings 132-1, 132-2, 132-2, however these capacitors are optional.

In Figures 2 and 4, the main exciter DC drive 110, the first alternating voltage source 210 and the monitor module 240 are all represented as separate entities. However, it will be appreciated that a single module may be configured to perform the functionality of any two of the main exciter DC drive 110, the first alternating voltage source 210 and the monitor module 240 (for example, a machine control unit, which may or may not be integrated with the electrical machine). Likewise, the loading modules and the power supply modules of Figures 2 and 4 are all represented as separate entities. However, it will be appreciated that a single module may be configured to perform the functionality of all of the loading module(s) and power supply module. In a further alternative, any of the modules represented in Figures 2 and 4 may be implemented by two or more interconnected modules or entities.

In Figures 2 and 4, whilst the first loading module alternating voltage source 210 and monitor module 240 are represented as separate entities, it will be appreciated that a single module or entity may perform the functionality of both. Likewise, the functionality of the power supplies and loading modules in Figure 2 and 4 may be implemented by a single module. In a further alternative, each of the modules or entities represented in Figures 2 and 4 may be implemented by two or more interconnected modules or entities. Any suitable distribution of functionality between different functional units or processors may be implemented, with only one particular implementation represented in Figures 2 and 4 for the sake of clarity.

It will also be appreciated that, whilst tuned loading modules and a tuned monitor module 240 are described above with particularly with reference to frequency division multiplexing, the loading module(s) and monitor module 240 optionally be tuned in other implementations as well, and, indeed, there may be benefits in doing so. For example, if there is a single loading module on the rotor 130, tuning that single loading module and the monitor module 240 to a particular band of frequencies centred on the frequency of the first alternating voltage source 210 may mean that changes in current causes by a load applied to a rotor exciter winding 132-1, 132-2, 132-3 by a loading module may be more straightforwardly isolated from any other, unrelated changes in the stator exciter winding current (for example, at power generation frequencies and changes in the level of direct current supplied by the main exciter DC driver 110). Thus, an improvement in reliability and accuracy of detection of the effect on the stator exciter winding current may be realised.

Whilst in the above disclosed aspects, the electrical machines 200 and 400 comprise at least a first alternating voltage 210, and the monitor module 240 is configured to detect an effect on the alternating current in the stator exciter winding 122, these features are not essential. For example, all alternating voltage sources may be omitted and the monitor module 240 configured to detect an effect on the direct current from the main exciter DC drive 110 caused by a load applied to a rotor exciter winding 132-1, 132-2, 132-3 by a loading module (for example, a change in the load applied to a rotor exciter winding 132-1, 132-2, 132-3 may cause a change in the amount of direct current drawn by the stator exciter winding 122 as the rotor exciter winding passes the stator exciter winding 122) . Nevertheless, it may be preferable to utilise an alternating voltage source and detect an effect on the alternating current in the stator exciter winding 122 so that changes in current causes by a load applied to a rotor exciter winding 132-1, 132-2, 132-3 by a loading module may be more straightforwardly isolated from any other, unrelated changes in the stator exciter winding current (for example, at power generation frequencies and changes in the level of direct current supplied by the main exciter DC driver 110).

In all of the electrical machines described above in accordance with the present disclosure, the loading modules 230 and 420 apply a load to a single one of the rotor exciter windings 132-1, 132-2, 132-3. However, in an alternative, the first loading module 230 and/or second loading module 420 may apply a load to a plurality (two or more) of the rotor exciter windings 132-1, 132-2, 132-3. For example, in the electrical machine 200 represented in Figure 1, the first loading module 420 may apply a load to two of the rotor exciter windings 132-1, 132-2, 132-3, or all three of the rotor exciter windings 132-1, 132-2, 132-3. Optionally, this may also be used in the frequency division multiplexing aspect described above, whereby the first loading module 420 applies the first load to two or more of the rotor exciter windings 132-1, 132-2, 132-3 and the multiplexing loading module applies the multiplexing load to two or more of the rotor exciter windings 132-1, 132-2, 132-3. Since the speed with which the monitor module 240 determines the machine characteristic(s) is related to the rotational speed of the electrical machine (for example, the more quickly, or more often, the rotor exciter winding to which the loading module has applied the load passes the stator exciter winding 122, the more quickly it can determine the machine characteristic), applying a load to two or more of the rotor exciter windings 132-1, 132-2, 132-3 should increase the speed with which the monitor module 240 determines the machine characteristic(s). Furthermore, it would not be necessary to use a synchronisation pulse, thereby simplifying the configuration and operation of the electrical machine.

Claims

1. An electrical machine comprising:

a rotor comprising one or more rotor exciter windings;

a stator exciter winding for receiving a stator current to establish a magnetic field for causing electrical induction in the one or more rotor exciter windings;

a first loading module mounted on the rotor and configured to:

receive a first input indicative of a first machine characteristic; and

apply a first load to a first rotor exciter winding of the one or more rotor exciter windings based at least in part on the received first input; and

a monitor module coupled to the exciter stator and configured to:

detect an effect of the applied first load on the stator current; and

determine the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current.

2. The electrical machine of any preceding claim, wherein the effect of the applied first load on the stator current comprises a first pulse in the stator current corresponding to the first rotor exciter winding passing the stator exciter winding.

3. The electrical machine of claim 2, wherein the monitor module is further configured to:

detect a synchronisation pulse in the stator current; and

detect the first pulse in the stator current using at least the synchronisation pulse.

4. The electrical machine of claim 3, wherein the synchronisation pulse is generated by a synchronisation rotor exciter winding of the one or more rotor windings passing the stator exciter winding.

5. The electrical machine of claim 3 or claim 4, wherein the synchronisation pulse is a pulse in the stator current with a peak value that is outside of an allowable operating range of the first pulse in the stator current.

6. The electrical machine of any preceding claim, further comprising a power supply module mounted on the rotor, wherein the power supply module is coupled to the first loading module to provide electrical power to the first loading module.

7. The electrical machine of claim 6, when dependent on any of claims 2 to 4, wherein:

the power supply module is coupled to the synchronisation rotor exciter winding to draw electrical power from the synchronisation rotor exciter winding.

8. The electrical machine of claim 6, wherein the power supply module is coupled to a rotor generator winding to draw electrical power from the rotor generator winding.

9. The electrical machine of any preceding claim, further comprising:

a second loading module mounted on the rotor and configured to:

receive a second input indicative of a second machine characteristic; and

apply a second load to a second rotor exciter winding of the one or more rotor exciter windings based at least in part on the received second input; and wherein

the monitor module is further configured to:

detect an effect of the applied second load on the stator current; and

determine the second machine characteristic based at least in part on the detected effect of the applied second load on the stator current.

10. The electrical machine of claim 9, wherein the effect of the applied second load on the stator current comprises a second pulse in the stator current corresponding to the second rotor exciter winding passing the stator exciter winding.

11. The electrical machine of any preceding claim, further comprising:

a first alternating voltage source coupled to the stator exciter winding and configured and to apply a first alternating voltage to the stator exciter winding at a first frequency.

12. The electrical machine of claim 11, wherein the monitor module is tuneable to the first frequency to detect the effect of the applied first load on the stator current at the first frequency and determine the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current at the first frequency.

13. The electrical machine of claim 11 or claim 12, wherein the first loading module is tuned to the first frequency so that the applied first load is presented to an electrical signal induced in the first rotor exciter winding and alternating at the first frequency.

14. The electrical machine of any of claims 11 to 13, wherein the electrical machine is further configured to communicate the first machine characteristic and a further machine characteristic from the rotor to the monitor module using frequency division multiplexing

15. The electrical machine of claim 14, further comprising:

a multiplexing loading module mounted on the rotor, wherein the multiplexing loading module is tuned to a second frequency and is configured to:

receive an input indicative of the further machine characteristic; and

apply a multiplexing load to any of the one or more rotor exciter windings based at least in part on the received first input so that the applied multiplexing load is presented to an electrical signal induced in the rotor exciter winding and alternating at the second frequency; and

the monitor module is further tuneable to the second frequency to detect the effect of the applied multiplexing load on the stator current at the second frequency and determine the further machine characteristic based at least in part on the detected effect of the applied multiplexing load on the stator current at the second frequency.

16. The electrical machine of claim 15, further comprising:

a second alternating voltage source coupled to the stator exciter winding and configured to apply a second alternating voltage to the stator exciter winding at the second frequency.

17. The electrical machine of either claim 15 or claim 16, wherein the rotor exciter winding to which the multiplexing load is applied is the first rotor exciter winding.

18. The electrical machine of any preceding claim, wherein the first machine characteristic comprises any of:

a rotor temperature;
an airgap temperature;
an electrical machine temperature;
a rotor diode current;
a rotor diode voltage;
a rotor generator winding current;
a rotor generator winding voltage;
a mechanical strain on the rotor;
an oil pressure;
an oil flow.

19. The electrical machine of any preceding claim, wherein the first loading module is configured to apply the first load to at least one further rotor exciter winding of the one or more rotor exciter windings based at least in part on the received first input.

20. A rotor for use in the electrical machine of any preceding claim, the rotor comprising:

one or more rotor exciter windings; and
a first loading module configured to:

receive a first input indicative of a first machine characteristic; and

apply a first load to a first rotor exciter winding of the one or more rotor exciter windings based at least in part on the received first input.

21. A monitor module for coupling to the stator exciter winding of the electrical machine of any of claims 1 to 19, the monitor module being configured to:

detect an effect on the stator current caused by a first load applied to a first rotor winding of the rotor of the electrical machine, wherein the first load is applied by a first loading module based at least in part on a first input that is indicative of a first machine characteristic; and

determine the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current.

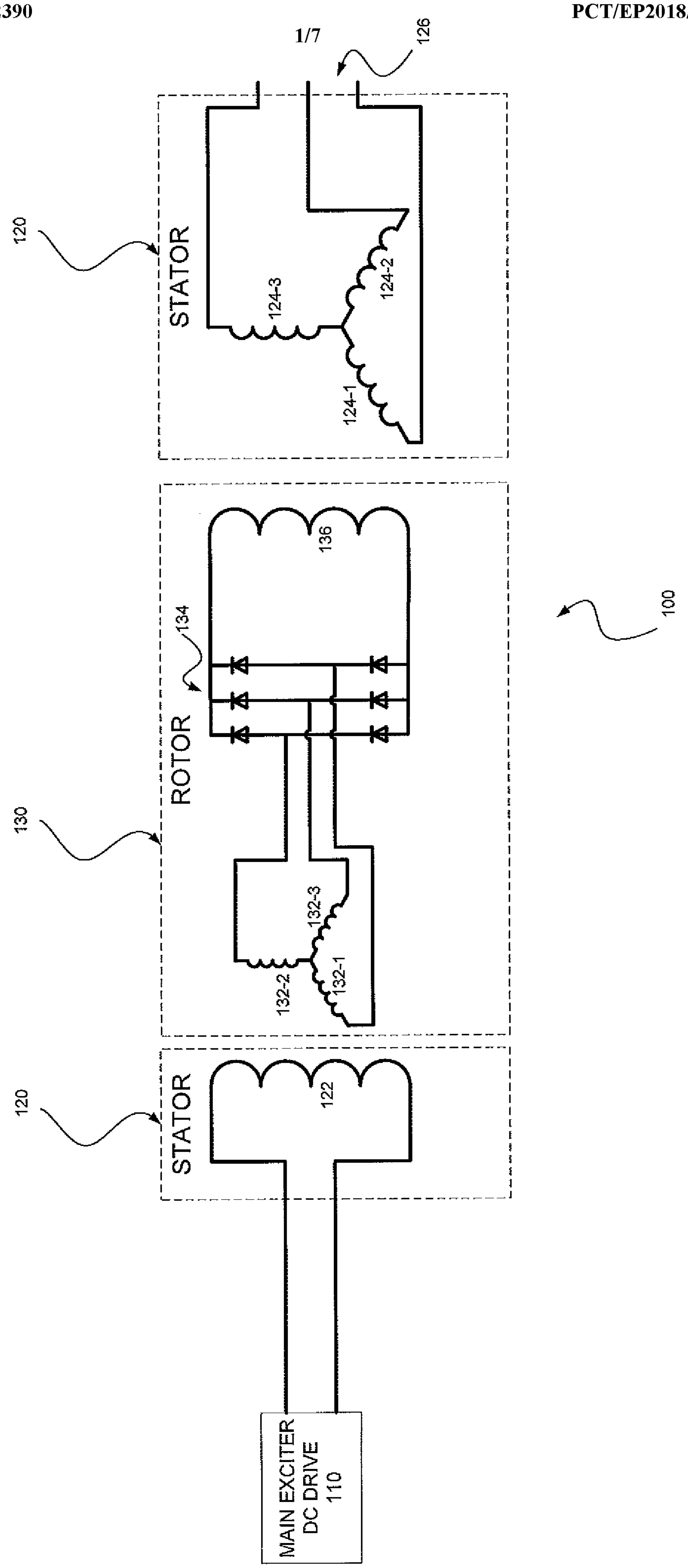
22. A method of determining a first machine characteristic of an electrical machine during operation of the electrical machine, the method comprising:

applying a voltage across a stator exciter winding of the electrical machine;

applying a first load to a first rotor exciter winding of the rotor based at least in part on a signal indicative of the first machine characteristic;

detecting an effect of the applied first load on a stator current through the stator exciter winding; and

determining the first machine characteristic based at least in part on the detected effect of the applied first load on the stator current.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124-3
124-2
124-1
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134
136
ROTOR
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132-3
132-1
132-2
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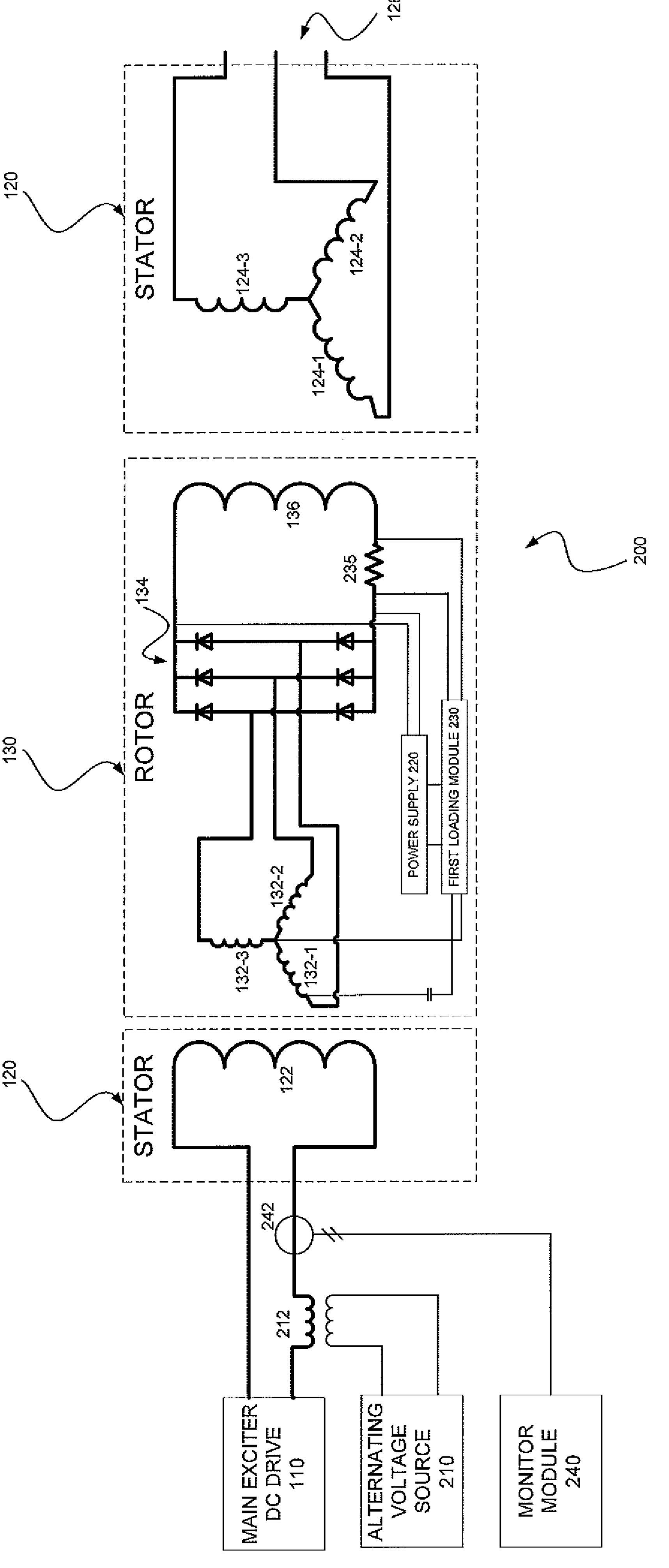
STATOR
122
MAIN EXCITER
DC DRIVE
110

FIG. 1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ROTOR
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235
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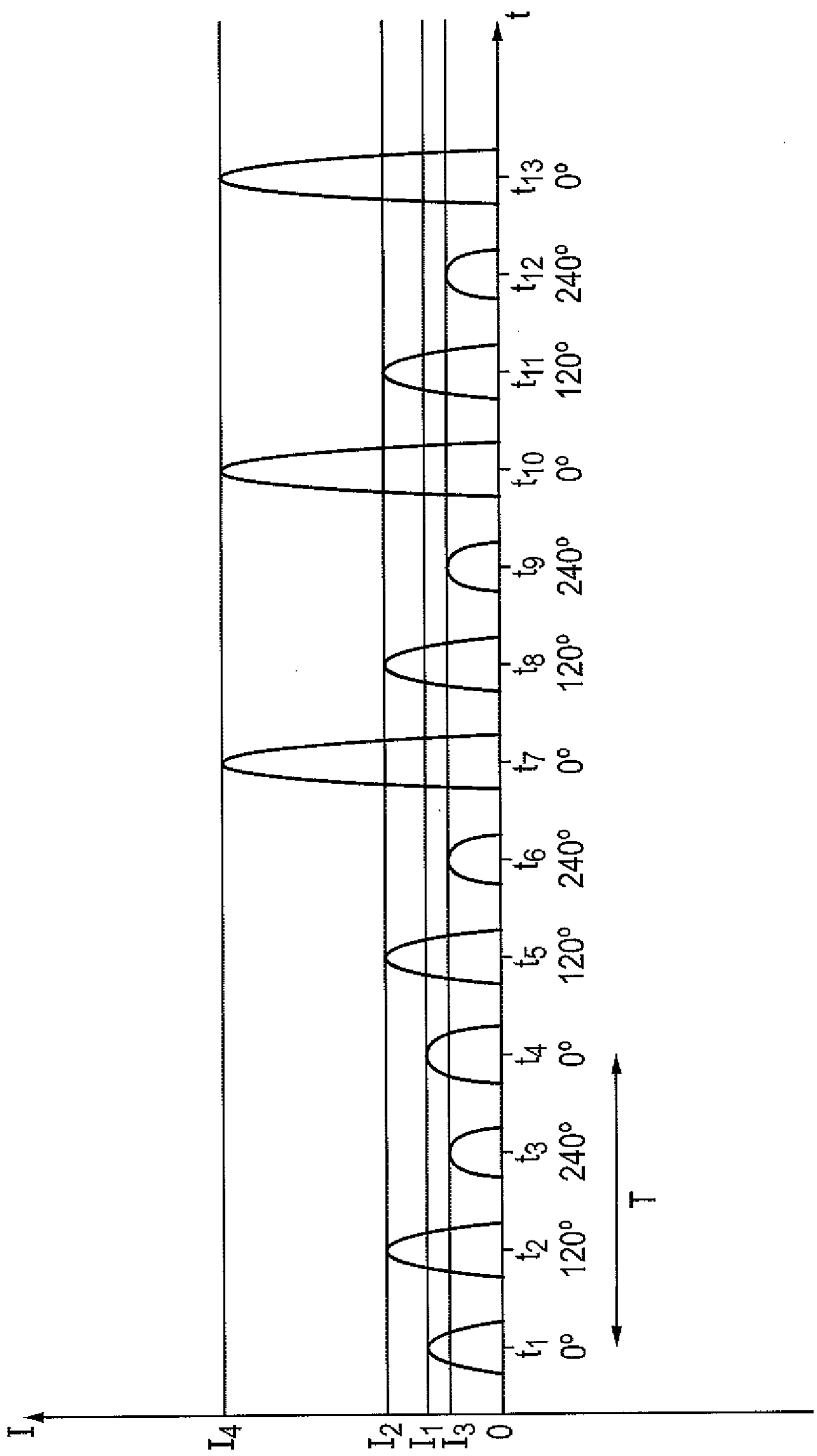
200
POWER SUPPLY 220
FIRST LOADING MODULE 230
132-2
132-3
132-1
120
STATOR
122
242
212
MAIN EXCITER DC DRIVE 110
ALTERNATING VOLTAGE SOURCE 210
MONITOR MODULE 240

FIG. 2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t6
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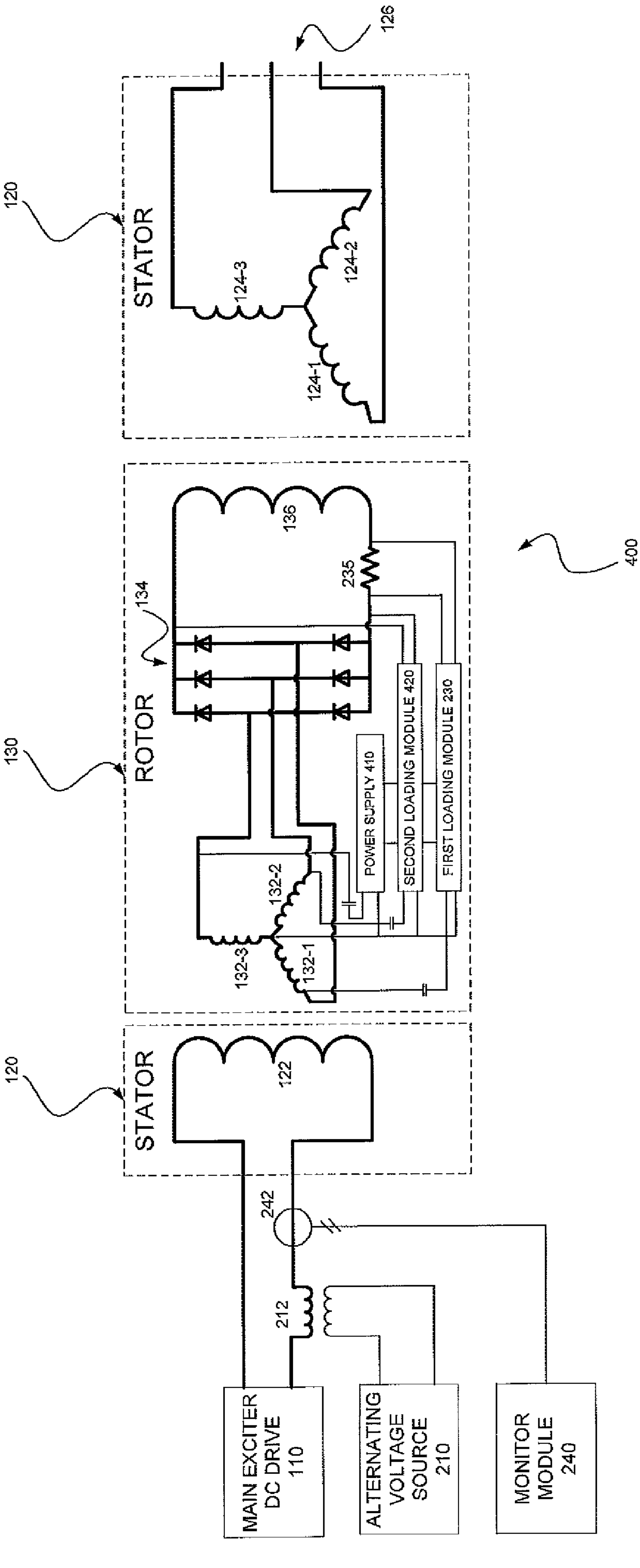
FIG. 3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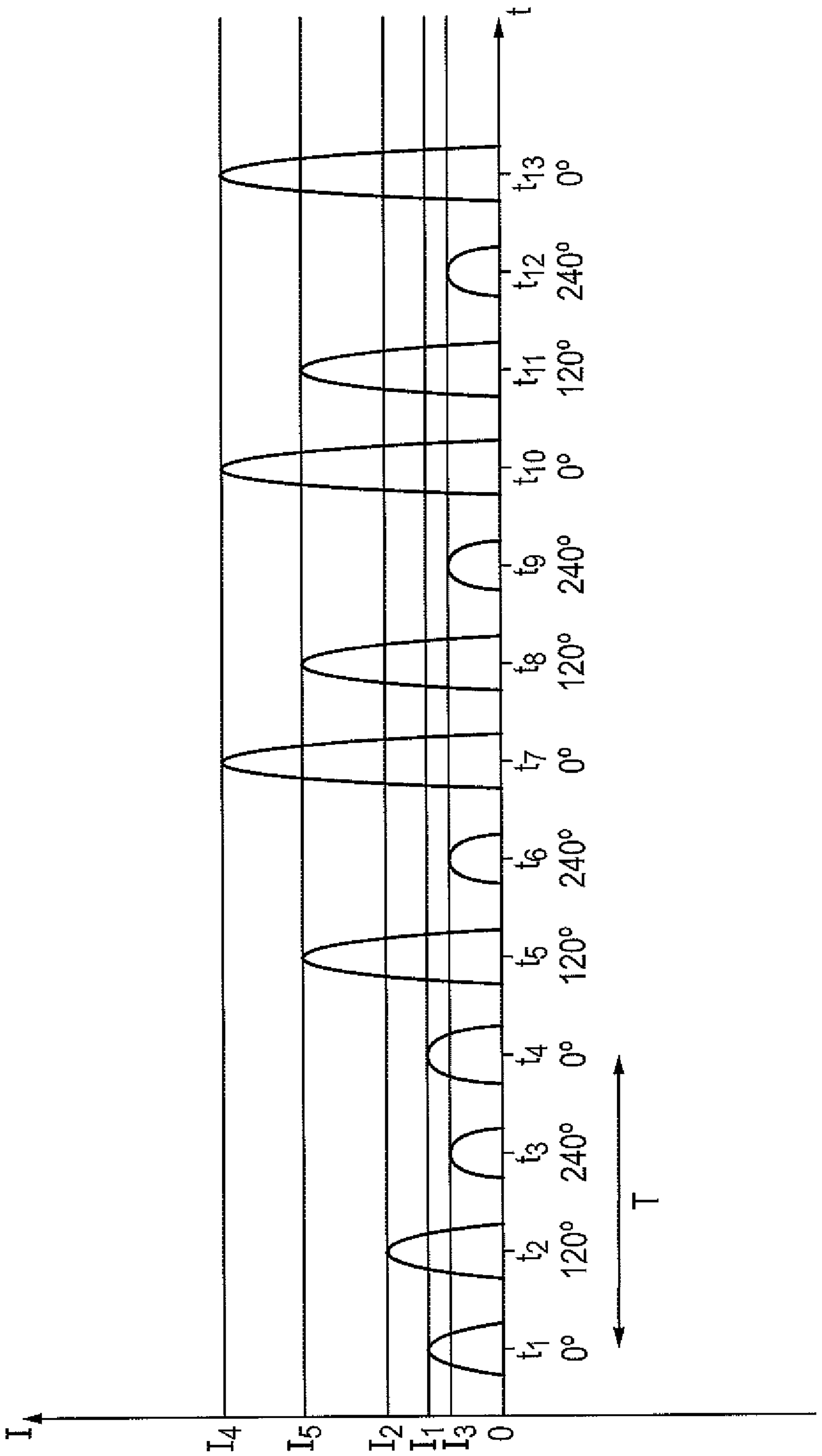
124-2
124-3
126
120
ROTOR
130
134
136
235
132-1
132-2
132-3
POWER SUPPLY 410
SECOND LOADING MODULE 420
FIRST LOADING MODULE 230
400
STATOR
120
122
242
212
MAIN EXCITER DC DRIVE 110
ALTERNATING VOLTAGE SOURCE 210
MONITOR MODULE 240

FIG. 4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I5
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T

FIG. 5

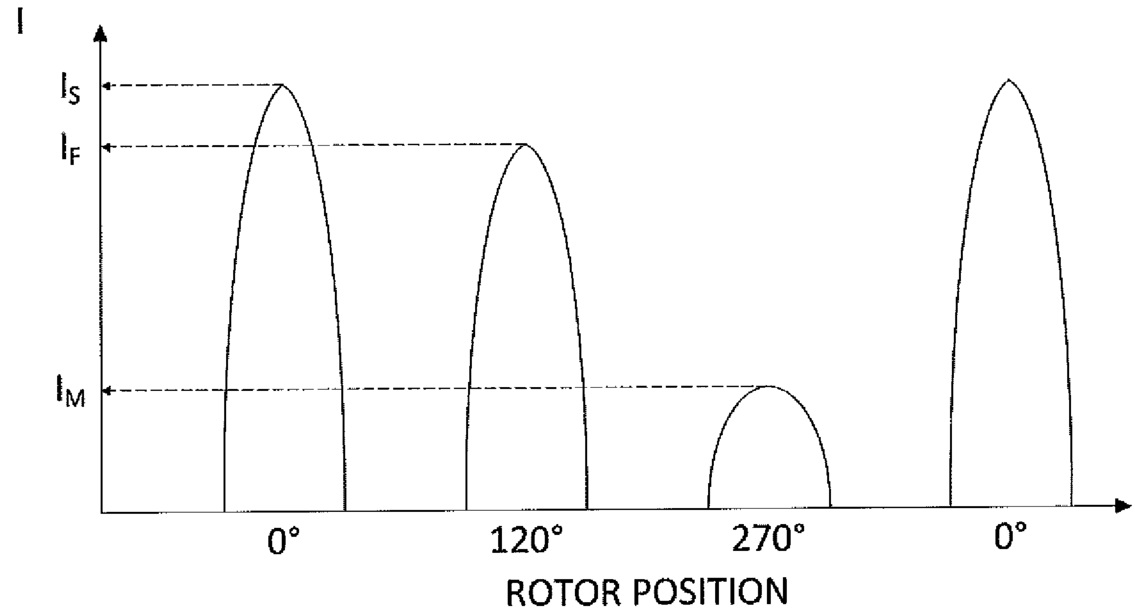

FIG. 6

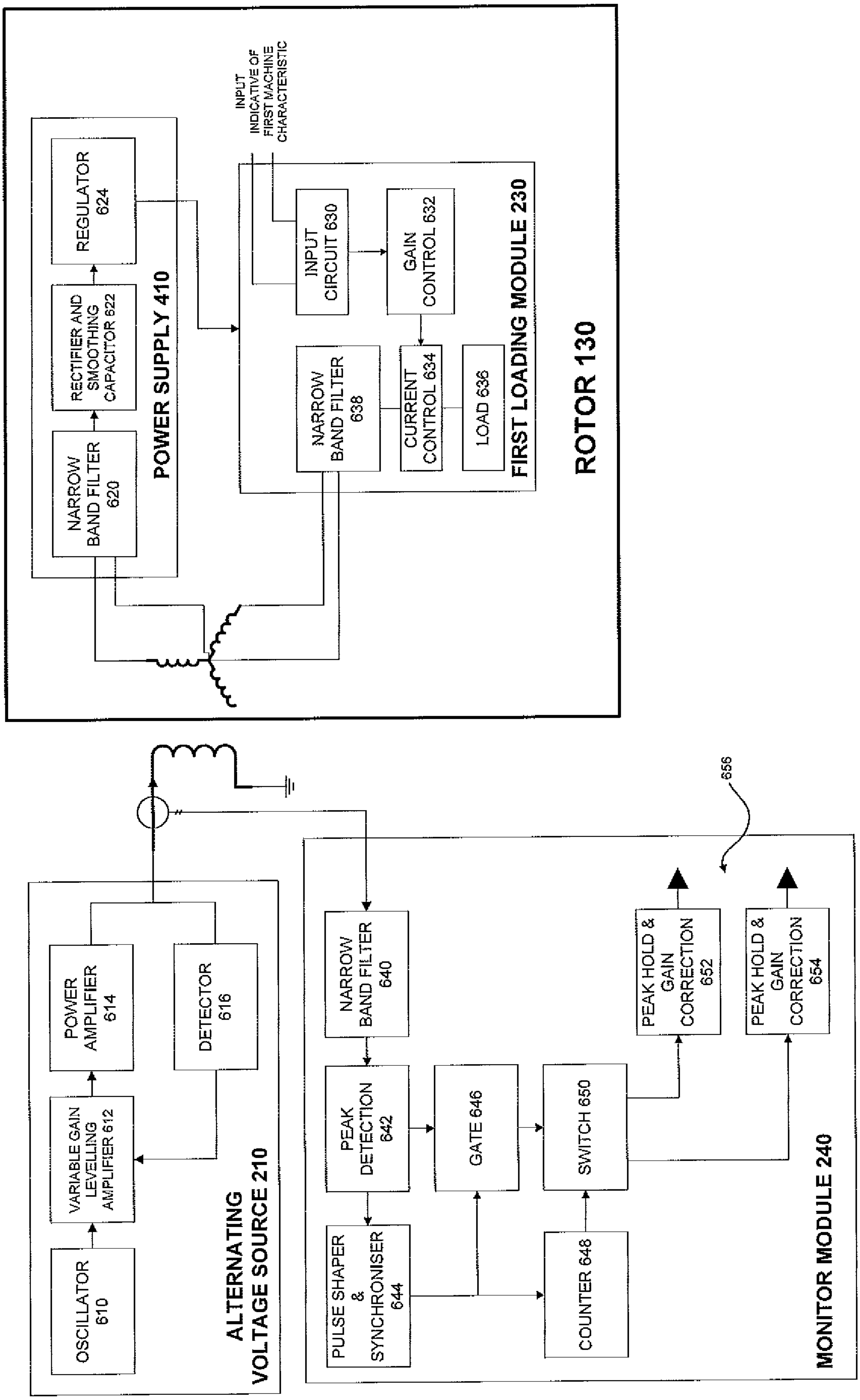
ROTOR 130
POWER SUPPLY 410
NARROW BAND FILTER 620
RECTIFIER AND SMOOTHING CAPACITOR 622
REGULATOR 624
FIRST LOADING MODULE 230
INPUT INDICATIVE OF FIRST MACHINE CHARACTERISTIC
INPUT CIRCUIT 630
GAIN CONTROL 632
NARROW BAND FILTER 638
CURRENT CONTROL 634
LOAD 636
ALTERNATING VOLTAGE SOURCE 210
OSCILLATOR 610
VARIABLE GAIN LEVELLING AMPLIFIER 612
POWER AMPLIFIER 614
DETECTOR 616
MONITOR MODULE 240
NARROW BAND FILTER 640
PEAK DETECTION 642
PULSE SHAPER & SYNCHRONISER 644
GATE 646
COUNTER 648
SWITCH 650
PEAK HOLD & GAIN CORRECTION 652
PEAK HOLD & GAIN CORRECTION 654
656

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/055308

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02P9/48 H02P9/18 H02P9/30
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 G01R H02K G06K H02H H04B

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.
Y	WO 00/67355 A1 (ABB AB [SE]; GERTMAR LARS [SE]; NYSVEEN ARNE [NO]) 9 November 2000 (2000-11-09) page 12, line 31 - page 15, line 4; figure 1 -----	1-22
Y	US 5 856 710 A (BAUGHMAN JAMES STUART [US] ET AL) 5 January 1999 (1999-01-05) column 1, line 62 - line 67; figures 1,3A,3B column 3, line 7 - column 6, line 27 -----	1-22
Y	US 2016/149527 A1 (FRAMPTON ISAAC S [US] ET AL) 26 May 2016 (2016-05-26) paragraph [0043] - paragraph [0066]; figures 1,2,3A,3B,11 paragraph [0080] - paragraph [0103] ----- -/--	1-22

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"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
24 May 2018	01/06/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gospodinova, M

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/055308

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 1 705 604 A1 (COMMISSARIAT ENERGIE ATOMIQUE [FR]) 27 September 2006 (2006-09-27) paragraph [0026] - paragraph [0077]; figures 1-7 -----	1-22

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2018/055308

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
WO 0067355	A1	09-11-2000	AU	4632500	A	17-11-2000
			AU	4787900	A	17-11-2000
			CA	2367386	A1	09-11-2000
			CA	2367389	A1	09-11-2000
			EA	200100962	A1	25-04-2002
			EP	1175718	A1	30-01-2002
			EP	1192701	A1	03-04-2002
			WO	0067355	A1	09-11-2000
			WO	0067363	A1	09-11-2000
US 5856710	A	05-01-1999	NONE			
US 2016149527	A1	26-05-2016	CN	105656250	A	08-06-2016
			US	2016149527	A1	26-05-2016
			US	2016149528	A1	26-05-2016
			US	2016301345	A1	13-10-2016
			US	2018131301	A1	10-05-2018
EP 1705604	A1	27-09-2006	AT	443901	T	15-10-2009
			EP	1705604	A1	27-09-2006
			FR	2883433	A1	22-09-2006
			JP	4868903	B2	01-02-2012
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