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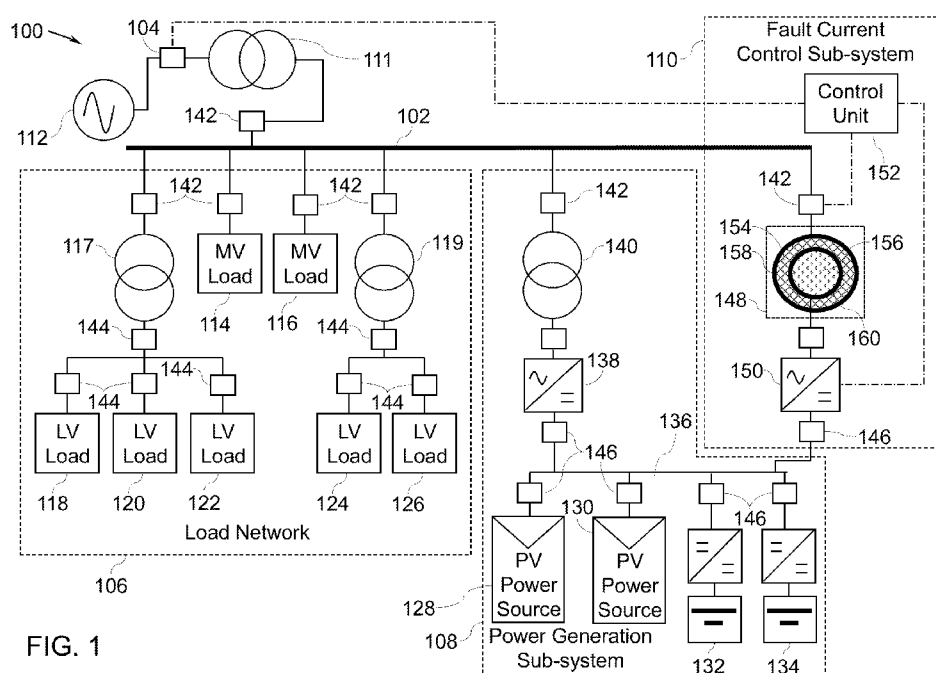


FIG. 1

(57) Abstract: A system (100) includes a facility power bus (102) coupled to a utility power grid (112), a power generation sub-system (108) coupled to the facility power bus via one or more first power converters (138), and a fault current control sub-system (110). The fault current control sub-system includes an electric machine (148), a second power converter (150) coupled to the electric machine, and a control unit (152). The control unit controls the electrical current flowing through the electric machine such that at least a part of a fault current through the facility power bus flows via the electric machine if the facility power bus is disconnected from the utility power grid. If the facility power bus is connected to the utility power grid, a flow of the fault current through the electric machine is reduced compared to the fault current in the disconnected situation.



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FAULT CURRENT CONTROL SUB-SYSTEM AND RELATED METHOD

TECHNICAL FIELD

[0001] Embodiments of the present specification generally relate to a fault current control sub-system and, in particular to a fault current control sub-system for a system, where the fault current control sub-system is configured to reduce a fault current flowing via a doubly-fed induction generator (DFIG) when the system is connected to a utility power grid in an event of a fault in the system.

BACKGROUND

[0002] Recently, renewable energy based power generation sources such as solar energy based power generation systems are growing in demand. Typically, the solar energy based power generation systems are advantageous because of high availability of solar energy and its cost effectiveness at wide range of power scales, from a few kilowatts to hundreds of megawatts. Further, use of the distributed solar energy based power generation systems remains more attractive because its collocation with the load results in eliminating transmission system losses and its entitlement to improve system resiliency. Distributed solar energy sources are able to provide full or partial power during an outage of a utility power grid without a need for stockpiling or delivering fuel for backup generators. These properties make the solar-powered microgrids attractive for powering critical infrastructure during outages of the utility power grid.

[0003] Further, in recent years, due to technological advancements, there has been a significant cost reduction in the solar energy based power generation systems. Additionally, due to an emergence of increasingly cost-effective energy storage (ES) technologies, the solar-powered microgrids are generally cost-effective in regions with high-quality of solar resources, and a viable option in applications where long-term resiliency or minimizing carbon footprint are important.

[0004] Despite such increasingly cost effective and viable use of the solar-powered microgrids having integrated energy storage, some traditional microgrid solutions are designed to be hybrid solutions where a synchronous source of voltage is provided by traditional generators powered by fossil fuels. In such traditional microgrid solutions,

the synchronous source of voltage is used because, commonly available inverters being used with photovoltaic (PV) and energy storage are typically grid-following type. The grid-following type inverters require a source of voltage provided by other generators. Additionally, power-electronic converters that are used with the PV and the energy storage have an inherent current limit which restricts their capability of providing sufficient short-circuit current to operate traditional protection devices. In hybrid microgrids the short-circuit current is provided by traditional, fossil-fuel powered, generators. This is suitable for retrofit applications where the traditional fossil-fuel powered generators already exist, and limited amount of solar generation and energy storage is added to reduce the cost, but relying on fossil fuel generators for new microgrid designs defeats the purpose in installations where long-term resiliency or minimizing carbon footprint are important. If the fossil-fuel powered generators were simply to be removed, then, in a situation when the microgrid experiences a fault during an islanded operation, either a sufficient short-circuit current must be provided from the power-electronic converters to operate the protection devices to isolate the fault, or a protection design must be updated to function with limited short-circuit current available from the power-electronic converters, which remains a challenge.

[0005] One way to address the challenge of supplying the sufficient short-circuit current to operate the protection devices without relying on fossil-fuel powered generators or oversizing the converters is to add an appropriately sized synchronous condenser to the solar-powered microgrids. However, use of the synchronous condenser complicates integration of the solar-powered microgrids with the utility power grid because the synchronous condenser would also supply significant short-circuit current to the utility power grid during faults at a utility power grid side of a point of common connection. In particular, an accounting for such additional short-circuit currents to clear the fault at the utility power grid side would require revisiting protection coordination on a utility circuit and potentially updating settings or even replacing some of utility-owned protective devices. A traditional way to avoid adding short-circuit currents to the utility system is to perform an indiscriminate disconnection of a condenser-equipped microgrid from the utility grid during all grid disturbances. Such disconnections would worsen power quality to loads within the solar-powered microgrids under almost all practical circumstances, because the solar-powered microgrids' transition from a grid-connected

to the islanded mode would be sudden which may not allow for orderly shutdown of non-essential loads. As a result, the traditional solar-powered microgrid would incur an outage and need to be restarted in the islanded mode.

BRIEF DESCRIPTION

[0006] In accordance with one embodiment of the present specification, a system is presented. The system includes a facility power bus coupled to a utility power grid. The system further includes a power generation sub-system having at least one renewable energy based power source, at least one energy storage device, or a combination thereof electrically coupled to the facility power bus via one or more first power converters. Furthermore, the system includes a fault current control sub-system electrically coupled to the facility power bus. The fault current control sub-system includes an electric machine having a first winding and a second winding rotatable with respect to the first winding, where the first winding is electrically coupled to the facility power bus. The fault current control sub-system further includes a second power converter configured to facilitate a flow of an electrical current through the electric machine via the second winding. Moreover, the fault current control sub-system includes a control unit operatively coupled to the second power converter and configured to determine whether the facility power bus is disconnected from the utility power grid. In response to determining that the facility power bus is disconnected from the utility power grid, the control unit is further configured to control the electrical current flowing through the electric machine via the second power converter such that at least a part of a fault current through the facility power bus flows via the electric machine. Moreover, in response to determining that the facility power bus is connected to the utility power grid, the control unit is configured to control the electrical current flowing through the electric machine via the second power converter such that a flow of the fault current through the electric machine is reduced in comparison to the fault current when the facility power bus is disconnected from the utility power grid.

[0007] In accordance with another embodiment of the present specification, a fault current control sub-system for a system is presented. The system includes a facility power bus coupled to a utility power grid, a power generation sub-system having at least

one renewable energy based power source and at least one energy storage device coupled to the facility power bus via one or more first power converters. The fault current control sub-system includes a doubly-fed induction generator (DFIG) having a stator winding and a rotor winding, where the stator winding is electrically coupled to the facility power bus. The fault current control sub-system further includes a second power converter configured to facilitate a flow of an electrical current through the DFIG via the rotor winding. Furthermore, the fault current control sub-system includes a control unit operatively coupled to the second power converter. The control unit is configured to determine whether the facility power bus is disconnected from the utility power grid. In response to determining that the facility power bus is disconnected from the utility power grid, the control unit is configured to control the electrical current flowing through the DFIG via the second power converter such that at least a part of a fault current through the facility power bus flows via the DFIG. Moreover, in response to determining that the facility power bus is connected to the utility power grid, the control unit is configured to control the electrical current flowing through the DFIG the second power converter such that a flow of the fault current through the DFIG is reduced in comparison to the fault current when the facility power bus is disconnected from the utility power grid.

[0008] In accordance with yet another embodiment of the present specification, a method for controlling a fault current contribution in a system is presented. The system includes a facility power bus coupled to a utility power grid, a power generation sub-system having at least one renewable energy based power source and at least one energy storage device coupled to the facility power bus via one or more first power converters. The method includes determining whether the facility power bus is disconnected from the utility power grid. In response to determining that the facility power bus is disconnected from the utility power grid, the method further includes controlling an electrical current flowing through a rotor winding of a DFIG via a second power converter such that at least a part of a fault current through the facility power bus flows via the DFIG, where a stator winding of the DFIG is connected to the facility power bus. Moreover, in response to determining that the facility power bus is connected to the utility power grid, the method includes controlling the electrical current flowing through the rotor winding of the DFIG via the second power converter such that a flow of the

fault current through the DFIG is reduced in comparison to the fault current when the facility power bus is disconnected from the utility power grid.

DRAWINGS

[0009] These and other features, aspects, and advantages of the present specification will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0010] FIG. 1 is a schematic diagram of a system having a fault current control sub-system, in accordance with one embodiment of the present specification;

[0011] FIG. 2 is a schematic diagram of a system having a fault current control sub-system, in accordance with another embodiment of the present specification;

[0012] FIG. 3 is a flow diagram of a method for controlling a fault current contribution in the systems of FIGs. 1 and 2, in accordance with one embodiment of the present specification;

[0013] FIG. 4 is a schematic diagram of a fault current control sub-system, in accordance with one embodiment of the present specification;

[0014] FIG. 5 is a flow diagram of a method for black-starting a doubly-fed induction generator (DFIG) in the fault current control sub-system of FIG. 4, in accordance with one embodiment of the present specification;

[0015] FIG. 6 is a schematic diagram of a fault current control sub-system, in accordance with another embodiment of the present specification;

[0016] FIG. 7 is a flow diagram of a method for black-starting a DFIG in the fault current control sub-system of FIG. 6, in accordance with one embodiment of the present specification;

[0017] FIG. 8 is a schematic diagram of a fault current control sub-system, in accordance with another embodiment of the present specification;

[0018] FIG. 9 is a flow diagram of a method for black-starting a DFIG in the fault current control sub-system of FIG. 8, in accordance with one embodiment of the present specification;

[0019] FIG. 10 is a schematic diagram of a fault current control sub-system, in accordance with yet another embodiment of the present specification; and

[0020] FIG. 11 is a flow diagram of a method for black-starting a DFIG in the fault current control sub-system of FIG. 10, in accordance with one embodiment of the present specification.

DETAILED DESCRIPTION

[0021] In an effort to provide a concise description of these embodiments, all features of an actual implementation may not be described in the specification. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous implementation-specific decisions may be made to achieve the developer's specific goals such as compliance with system-related and business-related constraints.

[0022] Unless defined otherwise, technical and scientific terms used herein have the same meaning as is commonly understood by one of ordinary skill in the art to which this specification belongs. The terms "first", "second", and the like, as used herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another. Also, the terms "a" and "an" do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced items. The use of "including," "comprising" or "having" and variations thereof herein are meant to encompass the items listed thereafter and equivalents thereof as well as additional items. The terms "connected" and "coupled" are not restricted to physical or mechanical connections or couplings, and can include electrical connections or couplings, whether direct or indirect.

[0023] As used herein, the terms "may" and "may be" indicate a possibility of an occurrence within a set of circumstances; a possession of a specified property, characteristic or function; and/or qualify another verb by expressing one or more of an

ability, capability, or possibility associated with the qualified verb. Accordingly, usage of “may” and “may be” indicates that a modified term is apparently appropriate, capable, or suitable for an indicated capacity, function, or usage, while taking into account that in some circumstances, the modified term may sometimes not be appropriate, capable, or suitable.

[0024] As will be described in detail hereinafter, various embodiments of a system are presented. The system includes a facility power bus coupled to a utility power grid. The system further includes a power generation sub-system having at least one renewable energy based power source, at least one energy storage device, or a combination thereof electrically coupled to the facility power bus via one or more first power converters. Furthermore, the system includes a fault current control sub-system electrically coupled to the facility power bus. The fault current control sub-system includes an electric machine having a first winding and a second winding rotatable with respect to the first winding, wherein the first winding is electrically coupled to the facility power bus. The fault current control sub-system further includes a second power converter configured to facilitate a flow of an electrical current through the electric machine via the second winding. Moreover, the fault current control sub-system includes a control unit operatively coupled to the second power converter and configured to determine whether the facility power bus is disconnected from the utility power grid. In response to determining that the facility power bus is disconnected from the utility power grid, the control unit is further configured to control the electrical current flowing through the electric machine via the second power converter such that at least a part of a fault current through the facility power bus flows via the electric machine. Moreover, in response to determining that the facility power bus is connected to the utility power grid, the control unit is configured to control the electrical current flowing through the electric machine via the second power converter such that a flow of the fault current through the electric machine is reduced in comparison to the fault current when the facility power bus is disconnected from the utility power grid.

[0025] Referring now to FIG. 1, a schematic diagram of a system 100 is presented, in accordance with one embodiment of the present specification. In some embodiments, the system 100 may represent a microgrid. Accordingly, in the description hereinafter,

the system 100 is also referred to as a microgrid 100. The microgrid 100 includes a facility power bus 102, a tie-breaker 104, a load network 106, a power generation sub-system 108, and a fault current control sub-system 110. The microgrid 100 may be coupled to a utility power grid 112 via the tie-breaker 104 and a transformer 111.

[0026] The facility power bus 102 may include one or more metal conductors that allow flow of electricity therethrough. In some embodiments, the facility power bus 102 may be a direct current (DC) power bus. In some embodiments, the facility power bus 102 may be a single-phase or multi-phase power bus, for example, a three-phase alternating current (AC) power bus. In a non-limiting example, the facility power bus 102 may be a medium voltage (MV) AC power bus. In the description hereinafter, the facility power bus 102 is described as the MVAC power bus for the consistency of illustration. By way of non-limiting example, a voltage range supported by such MVAC power bus may be in a range of 4160 volts to 34.5 kilo volts (kV). The load network 106, the power generation sub-system 108, and the fault current control sub-system 110 are electrically connected to the facility power bus 102 for example via one or more switching devices 142 (described later).

[0027] The tie-breaker 104 may be operated to connect the facility power bus 102 with the utility power grid 112 or to disconnect the facility power bus 102 from the utility power grid 112. The tie-breaker 104 is representative of a device having one or more switches to connect or disconnect the facility power bus 102 with the utility power grid 112. The tie-breaker 104 is operated in an open state when the facility power bus 102 needs to be disconnected from the utility power grid 112. Commonly this is the case when the utility power grid 112 is having an outage, or is likely to have an outage, due to an inclement weather and the resilient operation of the microgrid 100 is desired. An operating mode of the microgrid 100 when the facility power bus 102 is disconnected from the utility power grid 112 is generally referred to as an islanded mode.

[0028] The tie-breaker 104 is operated in a closed state when the facility power bus 102 is required to be connected to the utility power grid 112. This is a common operating state because it allows the economically optimal operation of the microgrid 100. In particular, it allows the microgrid 100 to trade energy with a utility system (i.e., the utility

power grid 112), deliver its surplus energy to the utility system and import energy from the utility system to avoid the unnecessary cycling of the energy storage devices. An operating of the microgrid 100 when the facility power bus 102 is connected to the utility power grid 112 is generally referred to as a grid-connected mode.

[0029] Further, the load network 106 may represent one or more loads that are connected directly or indirectly to the facility power bus 102. The term “load” may represent any device or equipment that consumes electricity. The load network 106 includes certain loads that may operate at medium voltage (MV) levels, in some embodiments. For example, blocks marked with reference numerals 114, 116 represent loads operable at the MV levels. The loads 114, 116 are hereinafter referred to as MV loads 114, 116. The MV loads 114, 116 may be connected to the facility power bus 102 directly or via a transformer. Further, in some embodiments, the load network 106 may include some loads, for example, loads 118, 120, 122, 124, 126, that are operable at low voltage (LV) level that is lower than the MV levels. By way of non-limiting example, the LV levels may be in a range of 0 volts to 690 volts. The loads 118-126 are hereinafter referred to as LV loads 118-126. The LV loads 118-126 may be connected to the facility power bus 102 via one or more step-down transformers 117, 119, as shown in FIG. 1. Although two MV loads 114, 116 and five LV loads 118-126 are shown as connected to the facility power bus 102 in FIG. 1, embodiments of the present application are not restricted with respect to the number of loads that can be connected to the facility power bus 102. Any number of loads as supported by the facility power bus 102 may be connected to the facility power bus 102.

[0030] The power generation sub-system 108 may include one more power sources capable of generating electricity. In some embodiments, the power generation sub-system 108 may include at least one renewable energy based power source 128, 130, at least one energy storage device 132, 134, or a combination thereof. Further, the power generation sub-system 108 includes a DC-link 136. In particular, the renewable energy based power sources 128, 130 and/or the energy storage devices 132, 134 are coupled to the DC-link 136. The DC-link 136 is coupled to facility power bus 102 via one or more first power converters, for example, a first power converter 138. In the embodiment of FIG. 1, the first power converter 138 is disposed such that an AC side of the first power

converter 138 is connected to the facility power bus and a DC side of the first power converter 138 is connected to the DC-link 136. The first power converter 138 may be a bi-directional AC-DC converter that is configured to convert an AC power into a DC power and vice-versa. The first power converter 138 may include one or more switches, for example, semiconductor switches, configured to facilitate power conversion from AC to DC and vice-versa. In some embodiments, to provide an electrical isolation between the first power converter 138 and the facility power bus 102, the first power converter 138 may be coupled to the facility power bus 102 via a transformer 140.

[0031] In the embodiment of FIG. 1, the renewable energy based power sources 128, 130 are shown as photovoltaic (PV) power sources, for example. Each of the PV power sources 128, 130 may include one or more PV modules. The PV modules may be arranged in a series connection, parallel connection, or a series-parallel connection. Each of the PV modules may include a plurality of PV panels arranged in a series connection, parallel connection, or a series-parallel connection. The PV power sources 128, 130 having such PV modules may generate a DC power depending on solar insolation, weather conditions, and/or time of the day. Although, the renewable energy based power sources shown in FIG. 1 are the PV power sources 128, 130, other types of renewable energy based power sources may also be employed, without limiting the scope of the present specification. Moreover, while two PV power sources 128, 130 are shown in FIG. 1, any number of PV power sources may be installed in the power generation subsystem 108, without limiting the scope of the present specification.

[0032] The energy storage devices 132, 134 may include one or more batteries, capacitors, flywheel-based energy storage, or a combination thereof. The energy storage devices 132, 134 may be coupled to the DC-link 136 and are configured to supply a DC power to the DC-link 136 or absorb the DC-power from the DC-link 136. Although not shown in FIG. 1, in some embodiments, one or more energy storage devices may be coupled to the facility power bus 102 via a bi-directional DC-AC converter. Further, in certain other embodiments, while one or more energy storage devices (e.g., the energy storage devices 132, 134) are connected to the DC-link 136, additional one or more energy storage devices may be connected to the facility power bus 102. Moreover, while two energy storage devices 132, 134 are shown in FIG. 1, any number of energy storage

devices may be installed in the power generation sub-system 108, without limiting the scope of the present specification.

[0033] Further, in some embodiments, connection of any devices to the facility power bus 102 may be accompanied via switching devices 142. In some embodiments, the MV loads 114, 116 and/or the LV loads 118-126 may also be connected to the respective step-down transformers 117, 119 via the switching devices 144. Also, connection of any devices to the DC-link 136 may be accompanied via switching devices 146. The switching devices 142, 144, 146 may be operated to selectively connect or disconnect corresponding devices from the facility power bus 102, the step-down transformers 117, 119, or the DC-link 136. Each of the switching devices 142, 144, 146 may be operated in an open state or in a closed state. In the open state, the switching devices 142, 144, 146 block a flow of electrical current therethrough. In the closed state, the switching devices 142, 144, 146 allow the electrical current to pass therethrough.

[0034] In some embodiments, the switching devices 142, 144, 146 may be implemented using protective devices such as circuit breakers / act as the circuit breakers. During operation of the microgrid 100, a fault such as short-circuit may occur in any component of the load network 106 and the power generation sub-system 108. In an event of such fault, the protective devices are configured to disconnect the corresponding faulty devices respectively from the facility power bus 102, the step-down transformers 117, 119, or the DC-link 136.

[0035] For the protective devices to operate, certain minimum amount of fault current is required be passed through the protective devices. Typically, such required fault current is multiples of normal operating current. In accordance with aspects of the present specification, the fault current control sub-system 110 is configured to facilitate the fault current in the microgrid 100. Also, the fault current control sub-system 110 is configured to control the fault current depending on whether the microgrid 100 operates in the islanded mode or the grid-connected mode. The fault current control sub-system 110 is electrically coupled to the facility power bus 102 and operatively coupled to the tie-breaker 104. In some embodiments, the fault current control sub-system 110 may

include one or more of an electric machine 148, a second power converter 150, and a control unit 152.

[0036] The electric machine 148 may be representative of any machine that includes at least two windings that are mutually coupled to each other. Examples of machines that may be used as the electric machine 148 may include, but are not limited to, a doubly-fed induction generator (DFIG), an electrically excitable synchronous machine, an electrically excitable asynchronous machine, a synchronous condenser, or combinations thereof. For illustration in description hereinafter, the DFIG is considered as the electric machine 148, however, other machines such as the electrically excitable synchronous machine, the electrically excitable asynchronous machine, the synchronous condenser may also be used in place of the DFIG 148.

[0037] The DFIG 148 includes a stator 154 and a rotor 156. The DFIG 148 further includes a first winding, herein after referred to as a stator winding 158 that is wound on the stator 154. Further, the DFIG 148 also includes a second winding, hereinafter referred to as a rotor winding 160, that is wound on the rotor 156 which is rotatable with respect to the first winding/ stator winding 158. The stator winding 158 is electrically connected to the facility power bus 102. In some embodiments, the stator winding 158 is electrically connected to the facility power bus 102 via the switching device 142. In some embodiments, both the stator winding 158 and the rotor winding 160 may be multi-phase windings such as a three-phase winding. By way of example, the stator winding 158 includes three phase windings and the rotor winding 160 also includes three phase windings.

[0038] Moreover, in some embodiments, the second power converter 150 is electrically connected between the DFIG 148 and the DC-link 136. In particular, the second power converter 150 may be a bi-directional AC-DC converter that is configured to convert an AC power into a DC power and vice-versa. The second power converter 150 may include one or more switches, for example, semiconductor switches, configured to facilitate power conversion from AC to DC and vice-versa. In the embodiment of FIG. 1, the second power converter 150 is disposed such that an AC side of the second

power converter 150 is connected to the rotor winding 160 and a DC side of the second power converter 150 is connected to the DC-link 136.

[0039] During operation of the microgrid 100, in an event of the fault within the microgrid 100, the second power converter 150 is configured to facilitate a flow of an electrical current through the DFIG 148 via the rotor winding 160. In some embodiments, the second power converter 150 may supply the electrical current to the rotor winding 160 in the event of the fault within the microgrid 100.

[0040] Furthermore, the control unit 152 is operatively coupled to the second power converter 150 and the tie-breaker 104. The control unit 152 may include a specially programmed general-purpose computer, an electronic processor such as a microprocessor, a digital signal processor, and/or a microcontroller. Further, the control unit 152 may include input/output ports, and a storage medium, such as an electronic memory. Various examples of the microprocessor include, but are not limited to, a reduced instruction set computing (RISC) architecture type microprocessor or a complex instruction set computing (CISC) architecture type microprocessor or either of the two augmented by the high-speed logic within a field programmable gate arrays (FPGA). Further, the microprocessor may be a single-core type or multi-core type. Alternatively, the control unit 152 may be implemented as hardware elements such as circuit boards with processors or as software running on a processor such as a personal computer (PC), or a microcontroller. Further, in some embodiments, the control unit 152 may be implemented using logic gates, electronic switches, including but not limited to MOSFETS.

[0041] During operation of the microgrid 100, the control unit 152 is configured to determine whether the facility power bus 102 is disconnected from the utility power grid 112. In some embodiments, the control unit 152 may monitor an operating state of the tie-breaker 104 to determine whether the facility power bus 102 is disconnected from the utility power grid 112. For example, if the tie-breaker 104 is operating in the closed state, it is determined by the control unit 152 that the facility power bus 102 is connected to the utility power grid 112. However, if the tie-breaker 104 is operating in the open state, it is determined by the control unit 152 that the facility power bus 102 is disconnected

from the utility power grid 112. Further, in response to determining that the facility power bus 102 is disconnected from the utility power grid 112 and the occurrence of a fault, the control unit 152 is configured to control the electrical current flowing through the electric machine (e.g., the DFIG 148) via the second power converter 150 such that at least a part of a fault current through the facility power bus 102 flows via the electric machine (e.g., the DFIG 148). Alternatively, if it is determined that the facility power bus 102 is connected to the utility power grid 112 and that a fault is occurring, the control unit 152 is configured to control the electrical current flowing through the DFIG 148 via the second power converter 150 such that the flow of the fault current through the DFIG 148 is reduced in comparison to the fault current in the islanded mode of the microgrid 100. Additional details of operations performed by the control unit 152 is described in conjunction with the flow diagrams of FIGs. 3, 5, 7, 9, and 11.

[0042] Referring now to FIG. 2, a schematic diagram of a system 200, hereinafter referred to as a microgrid 200, is presented, in accordance with another embodiment of the present specification. The microgrid 200 shown in FIG. 2 is representative of one embodiment of the microgrid 100 of FIG. 1 and include certain components that are similar to the components used in FIG. 1. In FIG. 2, these components are marked using same reference numerals as used in FIG. 1 and description of such components is not repeated. The microgrid 200 includes the facility power bus 102, the tie-breaker 104, the load network 106, a fault current control sub-system 202, and a power generation sub-system 206. The microgrid 200 may be coupled to a utility power grid 112 via the tie-breaker 104. The fault current control sub-system 202 and the power generation sub-system 206 of FIG. 2 have different configurations in comparison to the configurations of the corresponding sub-systems shown in FIG. 1.

[0043] The power generation sub-system 206 of FIG. 2 may represent one embodiment of the power generation sub-system 108 of FIG. 1. In comparison to the power generation sub-system 108, the power generation sub-system 206 includes a dedicated DC-bus 136a (hereinafter referred to as a first DC-bus 136a) coupled to a set of the PV power sources 128, 130 and a dedicated DC-bus 136b (hereinafter referred to as a second DC-bus 136b) coupled to a set of the energy storage devices 132, 134. The first DC-bus 136a is coupled to the facility power bus 102 via a first power converter

138a and a transformer 140a. Further, the second DC-bus 136b is coupled to the facility power bus 102 via a first power converter 138b and a transformer 140b. The first power converters 138a, 138b and the transformers 140a, 140b are respectively representative of one embodiment of the first power converter 138 and the transformer 140 of FIG. 1.

[0044] Further, the fault current control sub-system 202 of FIG. 2 may represent one embodiment of the fault current control sub-system 110 of FIG. 1. In comparison to the fault current control sub-system 110, the fault current control sub-system 202 includes a dedicated energy storage device 204 in addition to the energy storage devices 132, 134. The energy storage device 204 may include one or more batteries, capacitors, flywheel based energy storage, or a combination thereof. As depicted in FIG. 2, the energy storage device 204 may be disposed in the fault current control sub-system 202 such that the DC side of the second power converter 150 is connected to the energy storage device 204. The second power converter 150 is configured to absorb the electrical current from the dedicated energy storage device 204 or to supply the electrical current to the dedicated energy storage device 204. Moreover, while a single dedicated energy storage device 204 is shown in FIG. 2, any number of energy storage devices may be installed in the power generation sub-system 108, without limiting the scope of the present specification.

[0045] Moving now to FIG. 3, a flow diagram 300 of a method for controlling the fault current contribution in the systems of FIGs. 1 and 2 is presented, in accordance with one embodiment of the present specification. At step 302, the control unit 152 is configured to monitor the operating state of the tie-breaker 104. As previously noted, at a given point in time, the tie-breaker 104 operates in one of the closed state or the open state. In some embodiments, the tie-breaker 104 may send status signals to the control unit 152 at periodic intervals, in others a status signal may be sent on every state change of the tie-breaker 104. The status signals may be indicative of the operating state of the tie-breaker 104. In certain other embodiments, the fault current control sub-system 110, 202 may include a sensor (not shown), for example, a current sensor disposed at the tie-breaker 104. The current sensor may sense a magnitude of current flowing through the tie-breaker 104 and generate an electrical signal indicative of the sensed magnitude of the current to the control unit 152. Further, the control unit 152 receives the electrical signal from the sensor.

[0046] Further, at step 304, the control unit 152 is configured to determine the operating state of the tie-breaker 104. In some embodiments, the control unit 152 may determine the operating state of the tie-breaker 104 based on the status signals received from the tie-breaker 104. In certain other embodiments, when the current sensors are employed, the control unit 152 may determine the operating state of the tie-breaker 104 based on the electrical signal received from the sensor disposed at the tie-breaker 104. In one embodiment, if the magnitude of the electrical signal is smaller than a predetermined value, the control unit 152 may determine that the operating state of the tie-breaker 104 is the open state. Alternatively, if the magnitude of the electrical signal is greater than or equal to the predetermined value, the control unit 152 may determine that the operating state of the tie-breaker 104 is the closed state. By way of example, the predetermined value may be zero (0) or substantially equal to zero.

[0047] Further, at step 306, the control unit 152 is configured to determine whether the facility power bus 102 is disconnected from the utility power grid 112 based on an operating state of the tie-breaker 104. If the operating state of the tie-breaker 104 is the closed state, the control unit 152 determines that the facility power bus 102 is connected to the utility power grid 112 (i.e., the microgrid 100, 200 operating in the grid-connected mode). However, if the operating state of the tie-breaker 104 is the open state, the control unit 152 determines that the facility power bus 102 is disconnected from the utility power grid 112 (i.e., the microgrid 100, 200 operating in the islanded mode).

[0048] At step 306, if it is determined that facility power bus 102 is disconnected from the utility power grid 112, the control unit 152, at step 308, is configured to control the electrical current flowing through the DFIG 148 via the second power converter 150 such that at least a part of the fault current through the facility power bus 102 flows via the DFIG 148 in an event of a fault in the microgrid 100, 200. In particular, in one embodiment, the second power converter 150 may be operated to source/supply AC current (i.e., fault current) to the rotor winding 160 in the event of fault within the microgrid 100, 200.

[0049] However, at step 306, if it is determined that the facility power bus 102 is connected to the utility power grid 112, the control unit 152, at step 310, is configured to control the electrical current flowing through the DFIG 148 via the second power

converter 150 such that a flow of the fault current through the DFIG 148 is reduced in comparison to the fault current when the facility power bus 102 is disconnected from the utility power grid 112 in the event of the fault condition in the utility power grid 112 or the microgrid 100, 200. For example, in some embodiments, if the fault condition arises in the grid-connected mode of the microgrid 100, 200, the control unit 152 is configured to operate the second power converter 150 such that zero and substantially close to zero current is sourced to or received from the rotor winding 160 of the DFIG 148. Instead, when the facility power bus 102 is connected to the utility power grid 112, the fault current is received from the utility power grid 112 for any fault condition in the microgrid 100, 200. Advantageously, in the grid-connected mode, the contribution of the DFIG 148 is restricted.

[0050] During normal operation of the microgrid 100, 200, the DFIG 148 operates as a synchronous condenser, with the rotor 156 rotating at a frequency just below the line frequency (e.g., frequency of the voltage at the utility power grid 112) and the second power converter 150 is set to control the stator voltage to source or sink reactive power (VARs) as required by the microgrid 100, 200 or the utility power grid 112. To enter this normal operating condition, a DFIG 148 has to be started so to bring the rotor 156 to a rotating frequency just below the line frequency. The initial condition for DFIG 148 starting is a condition where voltage (herein referred to as stator voltage) at the stator winding 158 of the DFIG 148 may be zero and the rotor 156 of the DFIG 148 is stationary (i.e. not rotating). Such a start of the DFIG 148 is also referred to as a black-start of the DFIG 148 or black-start of the microgrid 100, 200. In accordance with aspects of the present specification, the fault current control sub-system 110 is provided with various arrangements to black-start the DFIG 148. For example, fault current control sub-system depicted in FIGs. 4, 6, 8, and 10 includes suitable arrangements for facilitating the black-start of the DFIG 148.

[0051] Referring now to FIG. 4, a schematic diagram of a fault current control sub-system 400 is presented, in accordance with one embodiment of the present specification. The fault current control sub-system 400 of FIG. 4 is representative of one embodiment of the fault current control sub-system 110 of FIG. 1 and include certain components that are similar to the components used in the fault current control sub-system 110 FIG. 1. In

FIG. 4, these components are marked using same reference numerals as used in FIG. 1 and description of such components is not repeated.

[0052] In some embodiments, in addition to the components of the fault current control sub-system 110 of FIG. 1, the fault current control sub-system 400 of FIG. 4 includes a separately powered start-up motor 402 connected to the rotor 156 of the DFIG 148. By way of example, the start-up motor 402 may be energized using power from one or more of the DC-link 136 (i.e., in the configuration of FIG. 1), the DC-links 136a, 136b and/or the dedicated energy storage 204 (i.e., in the configuration of FIG. 2), or any other power source (not shown). In some embodiments, the start-up motor 402 is coupled to the rotor 156 via a shaft 404 and a coupler 406. The shaft 404 is mechanically coupled to the rotor 156 of the DFIG. Further, the coupler 406 represent any mechanical or electro-mechanical arrangement for connecting and disconnecting the start-up motor 402 with the shaft 404. Further, the control unit 152 is also operatively coupled to the start-up motor 402 and the coupler 406 and configured to black-start the DFIG 148 using the start-up motor 402. Details of a method for black starting the DFIG 148 using the start-up motor 402 is described in conjunction with FIG. 5.

[0053] In FIG. 5, a flow diagram 500 of a method for black-starting the DFIG 148 using the start-up motor 402 is presented, in accordance with one embodiment of the present specification. At step 502, the DFIG 148 is disconnected from the facility power bus 102. In order to disconnect the DFIG 148 from the facility power bus 102, the control unit 152 may operate the switching device 142 in the open state by sending one or more control signals to the switching device 142. Further, at step 504, the control unit 152 operates the start-up motor 402 thereby causing the rotor 156 of the DFIG 148 to rotate. In some embodiments, if the start-up motor 402 is not mechanically engaged with the shaft 404, the control unit 152 sends one or more control signals to the coupler 406 to engage the start-up motor 402 with the shaft 404 prior to operating the start-up motor 402. Furthermore, at step 506, the second power converter 150 is configured to apply AC voltage at slip frequency (the frequency difference between the frequency of the voltage at the facility bus and the equivalent electrical frequency of a rotational speed of the rotor 156) to the rotor winding 160 when the rotational speed of the rotor 156

(hereinafter referred to as a rotor speed) approaches a synchronous speed to induce voltage in the stator winding 158 of the DFIG 148.

[0054] Moreover, at step 508 a check may be performed by the control unit 152 to determine whether the stator voltage has attained a nominal frequency of a grid voltage. By way of example, the nominal frequency of the grid voltage in the United States of America (USA) is 60 Hz. It may be noted that the nominal frequency of the grid voltage may be set to a value defined by regulations in a given geographic region where the microgrid 100, 200 is configured to supply power. At step 508, if it is determined that the stator voltage has not attained the nominal frequency of grid voltage, the second power converter 150 continues to vary the AC voltage to the rotor winding 160 to achieve the synchronism. However, at step 508, if it is determined that the stator voltage has attained the nominal frequency of the grid voltage, the start-up motor 402 may be disengaged from the rotor 156, as indicated by step 510. To disengage the start-up motor 402 from the rotor 156, the control unit 152 sends one or more control signals to the start-up motor 402. Additionally, at step 512, the DFIG 148 is connected back to the facility power bus 102. In order to connect the DFIG 148 to the facility power bus 102, the control unit 152 may operate the switching device 142 in the closed state.

[0055] Advantageously, use of the start-up motor 402 as shown in FIG. 4 and the method of FIG. 5 aids in black-starting a micro-grid that includes grid-following converters operating when operated in the islanded mode.

[0056] Further, in FIG. 6, a schematic diagram of a fault current control sub-system 600 is presented, in accordance with one embodiment of the present specification. The fault current control sub-system 600 of FIG. 6 is representative of one embodiment of the fault current control sub-system 110 of FIG. 1 and include certain components that are similar to the components used in the fault current control sub-system 110 FIG. 1. In FIG. 6, these components are marked using same reference numerals as used in FIG. 1 and description of such components is not repeated.

[0057] In some embodiments, in addition to the components of the fault current control sub-system 110 of FIG. 1, the fault current control sub-system 600 of FIG. 6 includes a start-up switch 602 connected to the stator winding 158 of the DFIG 148. In

particular, the start-up switch 602 is connected between the stator winding 158 and the switching device 142, as depicted in FIG. 6. In some embodiments, the start-up switch 602 may include one or more switches, for example, a set of anti-parallel thyristors connected to each phase winding of the stator winding 158, as depicted in FIG. 6. Use of other types of semiconductor switches in the start-up switch 602 is also envisioned within the purview of the present specification. Further, the control unit 152 is also operatively coupled to the start-up switch 602 and configured to start the DFIG 148 using the start-up switch 602. Details of a method for starting the DFIG 148 using the start-up switch 602 is described in conjunction with FIG. 7.

[0058] In FIG. 7, a flow diagram 700 of a method for starting the DFIG 148 using the start-up switch 602 is presented, in accordance with one embodiment of the present specification. At step 702, the DFIG 148 is disconnected from the facility power bus 102 in a similar fashion as described in conjunction with FIG. 5. Further, at step 704, the rotor winding 160 is short-circuited via the second power converter 150. The short-circuiting of the rotor winding 160 includes connecting all phase windings of the rotor winding 160 with each other. In order to short-circuit the rotor winding 160, the control unit 152 is configured to send one or more control signals to the second power converter 150. Furthermore, at step 706, the stator winding 158 of the DFIG is connected to the facility power bus 102 via the start-up switch 602. Such connection of the stator winding 158 to the facility power bus exerts a magnetic force on the rotor 156 thereby causing rotations of the rotor 156. If the utility power grid 112 is available (i.e., if the facility power bus 102 is connected to the utility power grid 112), the utility power grid 112 energizes the facility power bus 102. If the electrical grid is not available (i.e., if the facility power bus 102 is disconnected from the utility power grid 112), the facility power bus 102 may be energized by the first power converter 138.

[0059] Moreover, at step 708, a check may be performed by the control unit 152 to determine whether the rotor speed has reached a predetermined value. By way of example, the predetermined value may be equal to a synchronous speed of the DFIG 148. At step 708, if it is determined that the rotor speed has not reached the predetermined value, the stator winding 158 of the DFIG is continued to be connected the facility power bus 102 via the start-up switch 602. However, at step 708, if it is determined that the

rotor speed has reached the predetermined value, at step 710, the short-circuit is removed from the rotor winding 160 and the second power converter 150 enters normal operation.

[0060] Referring now to FIG. 8, a schematic diagram of a fault current control sub-system 800 is presented, in accordance with one embodiment of the present specification. The fault current control sub-system 800 of FIG. 8 is representative of one embodiment of the fault current control sub-system 110 of FIG. 1 and include certain components that are similar to the components used in the fault current control sub-system 110 FIG. 1. In FIG. 8, these components are marked using same reference numerals as used in FIG. 1 and description of such components is not repeated.

[0061] In some embodiments, in addition to the components of the fault current control sub-system 110 of FIG. 1, the fault current control sub-system 800 of FIG. 8 includes a stator short-circuit contactor 802 connected to the stator winding 158 of the DFIG 148. The stator short-circuit contactor 802 is electrically connected to the stator winding 158. By way of example, the stator short-circuit contactor 802 may include one or more phase-switches, where one terminal of each phase-switch connected to each phase winding of the stator winding 158 and another terminal of each phase-switch is connected with each other. The stator short-circuit contactor 802 may be operated in a closed state or in an open state. The stator short-circuit contactor 802 when operated in the closed state, connects (i.e., short-circuits) the stator winding 158 with each other. Further, the stator short-circuit contactor 802 when operated in the open state, keeps the ends of the phase windings of the stator winding 158 disconnected from each other. The control unit 152 is also operatively coupled to the stator short-circuit contactor 802 and configured to black-start the DFIG 148 using the stator short-circuit contactor 802. Details of a method for black starting the DFIG 148 using the stator short-circuit contactor 802 is described in conjunction with FIG. 9.

[0062] Moving to FIG. 9, a flow diagram 900 of a method for black-starting the facility power bus 102 using the stator short-circuit contactor 802 is presented, in accordance with one embodiment of the present specification. At step 902, the DFIG 148 is disconnected from the facility power bus 102 by operating the switching device 142. Further, at step 904, the stator winding 158 is short-circuited via the stator short-circuit contactor 802. In order to short-circuit the stator winding 158, the control unit

152 is configured to operate the stator short-circuit contactor 802 in the closed state so that all phase windings of the stator winding 158 are connected with each other.

[0063] Further, at step 906, an AC voltage is applied to the rotor winding 160 from the second power converter 150 thereby causing rotations of the rotor 156. Further, at step 908, a check may be performed to determine if the rotor speed has reached the synchronous speed (i.e., DFIG 148 operating at slip value of zero). At step 908, if it is determined that the rotor speed has attained synchronous speed, at step 912, the stator short-circuit contactor 802 may be operated in the open state and the switching device 142 may be operated in the closed state. Further, the frequency of the stator voltage is set to the nominal frequency of the grid voltage. Furthermore, at step 914, a grid following inverter such as the first power converter 138 is energized and an output voltage of the first power converter 138 is synchronized with the stator voltage of the DFIG 148. Moreover, at step 916, when the reconnection to a restored utility power grid 112 is desired, the stator voltage of the DFIG 148 is modified to synchronize it with the grid voltage by controlling the rotor voltage, for example.

[0064] At step 918, a check may be performed by the control unit 152, to determine whether the stator voltage has synchronized with the grid voltage. At step 918, if it is determined that the stator voltage has not synchronized with the grid voltage, the second power converter 150 is operated to continue applying the AC voltage to the rotor winding 160. However, at step 918, if it is determined that the stator voltage has synchronized with the grid voltage, at step 920, the control unit 152 is configured to connect the facility power bus 102 with the utility power grid 112 by operating the tie-breaker 104 in the closed state.

[0065] Advantageously, use of the stator short-circuit contactor 802 as shown in FIG. 8 and the method of FIG. 9 aids in black-starting a micro-grid that includes grid-following converters (e.g., the first power converter 138) operating when the microgrid 100, 200 operated in the islanded mode. Further, use of the stator short-circuit contactor 802 and the method of FIG. 9 may provide bump-less transition to the grid-connected mode from the islanded mode.

[0066] In FIG. 10, a schematic diagram of a fault current control sub-system 1000 is presented, in accordance with one embodiment of the present specification. In FIG. 11, a flow diagram 1100 of a method for black-starting the DFIG 148 in the fault current control sub-system 1000 of FIG. 10 is presented, in accordance with one embodiment of the present specification. The fault current control sub-system 1000 shown in FIG. 10 and the method of black starting as described in FIG. 11 rely on performing a re-design of the DFIG and power converters to achieve a 1 per-unit slip range.

[0067] In general, the stator and rotor windings of a DFIG are magnetically coupled to each other. This coupling allows transfer of current and voltage between the stator winding and the rotor winding in a manner similar to that of a transformer. An effective turns ratio of this transformer action from stator winding to rotor winding is given by equation (1):

$$N = \frac{N_s}{sN_r} \quad \dots \text{(Equation 1)}$$

[0068] Where, N represents the effective turns ratio, s represents a slip value of the DFIG ($s = 0$ implies the rotor speed being the synchronous speed, $s = 1$ implies the rotor speed being zero), N_s represents the number of turns of the stator winding, and N_r represents the number of turns of the rotor winding of the DFIG. The rotor voltage of the DFIG is the stator voltage divided by the effective turns ratio (N), while the current on the rotor winding of the DFIG is the stator current multiplied by the effective turns ratio (N). The voltage rating of a rotor converter (for example, any power converter connected to the rotor winding of the DFIG), such as the, the second power converter 150, is given by equation (2):

$$v_{rotor,max} = \frac{v_{stator}}{N} = v_{stator} \frac{sN_r}{N_s} \quad \dots \text{(Equation 2)}$$

Where $v_{rotor,max}$ represents the rotor voltage rating and v_{stator} represents the stator voltage. As indicated in equation 2, the rotor converter voltage rating is directly proportional to the slip. In a traditional configuration, a power converter that is connected to a rotor winding of the DFIG, is sized/designed to operate within 20 - 30% of the synchronous speed of the DFIG (i.e., maintaining maximum value of s between 0.2 and 0.3). The DFIG 148 and/or power converters of FIG. 10 are designed to allow a unity slip-range which can be accomplished by increasing $v_{rotor,max}$ by stacking

multiple converters in series or decreasing the turns ratio $\frac{N_s}{N_r}$ from the nominal design condition. While, stacking multiple converters may lead to increase in the rotor converter's volt-ampere rating, reducing the turns ratio $\frac{N_s}{N_r}$ may cause lowering the fault-contribution capability of the DFIG 148. If a design of the DFIG 148 is altered such that the second power converter 150 can support a unity slip value (i.e., $s = 1$), soft-starting of the DFIG 148 becomes relatively trivial.

[0069] Turning now to FIG. 10, the fault current control sub-system is representative of one embodiment of the fault current control sub-system 110 of FIG. 1 and include certain components that are similar to the components used in the fault current control sub-system 110 FIG. 1. In FIG. 10, these components are marked using same reference numerals as used in FIG. 1 and description of such components is not repeated. In some embodiments, in the fault current control sub-system 1000 of FIG. 10, series connected second power converters 1002, 1004, 1006 replace the second power converter 150. The second power converters 1002, 1004, 1006 are similar to the second power converter 150 of FIG. 1 and are connected in series with each other so that voltage that can be applied to the rotor winding 160 is increased.

[0070] Moving to FIG. 11, at step 1102, the DFIG 148 is disconnected from the facility power bus 102 by operating the switching device 142 in the open state. Further, at step 1104, AC voltage is applied to the rotor winding 160 from the series connected second power converters 1002, 1004, 1006. In particular, the AC voltage has a frequency and magnitude equal to that of the grid voltage. Accordingly, the stator voltage builds up at the stator winding 158.

[0071] Further, at step 1106 the DFIG 148 is connected to the facility service bus 102 by operating the switching device 142. Furthermore, at step 1108, the grid following inverter such as the first power converter 138 is energized and the output voltage of the first power converter 138 is synchronized with the stator voltage of the DFIG 148. Moreover, at step 1110, torque on the rotor 156 is controlled by controlling the frequency and/or the magnitude of the AC voltage applied to the rotor winding 160 to operate the rotor 156 at the synchronous speed to generate a stator voltage at the stator winding. In order to control the torque on the rotor 156, the series connected second power converters

1002, 1004, 1006 are configured to gradually reduce frequency and/or magnitude of the AC voltage applied to the rotor winding 160.

[0072] Furthermore, at step 1112, a check may be performed by the control unit 152 to determine whether the rotor speed has reached the synchronous speed. At step 1112, if it is determined that rotor speed has not reached the synchronous speed, the control is transferred back to the step 1110. However, at step 1112, if it is determined that the rotor speed has reached the synchronous speed, at step 1114, another check may be performed by the control unit 152 to determine whether the stator voltage has synchronized with the grid voltage. At step 1114, if it is determined that the stator voltage has not synchronized with the grid voltage, the series connected second power converters 1002, 1004, 1006 continue to apply AC voltage to the rotor winding 160 and the check at the step 1114 is performed again. However, at step 1114, if it is determined that the stator voltage has synchronized with the grid voltage, at step 1116, the facility power bus 102 is connected to the utility power grid 112. The control unit 152 operates the tie-breaker 104 in the closed state to connect the facility power bus 102 with the utility power grid 112.

[0073] Advantageously, use of series connected second power converters 1002, 1004, 1006 as shown in FIG. 10 and the method of FIG. 11 aids in black-starting a micro-grid that includes grid-following converters operating when operated in the islanded mode. Further, use of the series connected second power converters 1002, 1004, 1006 and the method of FIG. 11 may provide bump-less transition to the grid-connected mode from the islanded mode.

[0074] Any of the foregoing steps in any of FIGs. 3, 5, 7, 9, and 11 may be suitably replaced, reordered, or removed depending on the needs of a particular application. Also, while certain steps are shown separately, some steps may also be performed simultaneously depending on the needs of a particular application.

[0075] In accordance with the aspects of the present specification, the control unit 152 facilitates a controlled contribution of the fault current. In particular, in the grid-connected mode of operation of the microgrid 100, 200, the control unit 152 operates the second power converter 150 such that contribution to the fault current via the DFIG 148 is reduced in comparison to the islanded mode of operation of the DFIG. Moreover,

various system arrangement of the fault current control sub-systems in accordance with aspects of the present specification, facilitates black-starting the microgrids 100, 200 and also facilitates bump-less transition of the microgrid 100, 200 to the grid-connected mode from the islanded mode.

[0076] This written description uses examples to disclose the invention, including the preferred embodiments, and to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims. Aspects from the various embodiments described, as well as other known equivalents for each such aspects, can be mixed and matched by one of ordinary skill in the art to construct additional embodiments and techniques in accordance with principles of this application.

CLAIMS

1. A system, comprising:
 - a facility power bus coupled to a utility power grid;
 - a power generation sub-system comprising at least one renewable energy based power source, at least one energy storage device, or a combination thereof electrically coupled to the facility power bus via one or more first power converters; and
 - a fault current control sub-system electrically coupled to the facility power bus, wherein the fault current control sub-system comprises:
 - an electric machine comprising a first winding and a second winding rotatable with respect to the first winding, wherein the first winding is electrically coupled to the facility power bus;
 - a second power converter configured to facilitate a flow of an electrical current through the electric machine via the second winding; and
 - a control unit operatively coupled to the second power converter and configured to:
 - determine whether the facility power bus is disconnected from the utility power grid;
 - control, in response to determining that the facility power bus is disconnected from the utility power grid, the electrical current flowing through the electric machine via the second power converter such that at least a part of a fault current through the facility power bus flows via the electric machine; and
 - control, in response to determining that the facility power bus is connected to the utility power grid, the electrical current flowing through the electric machine via the second power converter such that a flow of the fault current through the electric machine is reduced in comparison to the fault current when the facility power bus is disconnected from the utility power grid.
2. The system of claim 1, wherein the electric machine comprises one or more of a doubly-fed induction generator (DFIG) or an electrically excitable synchronous machine.

3. The system of claim 1, further comprising a tie-breaker coupling the facility power bus coupled to the utility power grid, wherein the control unit is further operatively coupled to the tie-breaker and configured to monitor an operating state of the tie-breaker to determine whether the facility power bus is disconnected from the utility power grid, wherein the operating state of the tie-breaker comprises one of an open state or a closed state, and wherein, in the open state the tie-breaker disconnects the facility power bus from the utility power grid and, in the closed state, tie-breaker connects the facility power bus to the utility power grid.

4. The system of claim 1, wherein facility power bus receives the fault current from the utility power grid when the facility power bus is connected to the utility power grid.

5. The system of claim 1, wherein the facility power bus is further coupled to one or more loads.

6. The system of claim 5, wherein the facility power bus is a medium voltage alternating current (AC) power bus, wherein a load of the one or more loads that is operable at medium voltage is electrically connected to the facility power bus via a switching device and a load of the one or more loads that is operable at voltage levels lower than medium voltage is connected to the facility power bus via a step-down transformer.

7. The system of claim 1, wherein the power generation sub-system further comprises a first DC-link and a second DC-link, wherein the at least one renewable energy based power source is coupled to the first DC-link and the at least one energy storage device is coupled to the second DC-link.

8. The system of claim 1, wherein the power generation sub-system further comprises a direct current (DC) link connected to the facility power bus via the one or

more first power converters, and wherein the at least one renewable energy based power source and the at least one energy storage device are connected to the DC-link.

9. The system of claim 8, wherein the second power converter is electrically coupled to the DC-link to absorb the electrical current from the DC-link or to supply the electrical current to the DC-link.

10. The system of claim 1, wherein the fault current control sub-system further includes a dedicated energy storage device connected to the second power converter, wherein the second power converter is configured to absorb the electrical current from the dedicated energy storage device or to supply the electrical current to the dedicated energy storage device.

11. A fault current control sub-system for a system comprising a facility power bus coupled to a utility power grid, a power generation sub-system comprising at least one renewable energy based power source and at least one energy storage device coupled to the facility power bus via one or more first power converters, the fault current control sub-system comprising:

- a doubly-fed induction generator (DFIG) comprising a stator winding and a rotor winding, wherein the stator winding is electrically coupled to the facility power bus;

- a second power converter configured to facilitate a flow of an electrical current through the DFIG via the rotor winding; and

- a control unit operatively coupled to the second power converter, wherein the control unit is configured to:

- determine whether the facility power bus is disconnected from the utility power grid;

- control, in response to determining that the facility power bus is disconnected from the utility power grid, the electrical current flowing through the DFIG via the second power converter such that at least a part of a fault current through the facility power bus flows via the DFIG; and

control, in response to determining that the facility power bus is connected to the utility power grid, the electrical current flowing through the DFIG the second power converter such that a flow of the fault current through the DFIG is reduced in comparison to the fault current when the facility power bus is disconnected from the utility power grid.

12. The fault current control sub-system of claim 11, wherein the control unit is further configured to monitor an operating state of a tie-breaker coupling the facility power bus to the utility power grid to determine whether the facility power bus is disconnected from the utility power grid, wherein the operating state of the tie-breaker comprises one of an open state or a closed state, and wherein, in the open state the tie-breaker disconnects the facility power bus from the utility power grid and, in the closed state, tie-breaker connects the facility power bus to the utility power grid.

13. The fault current control sub-system of claim 11, further comprising a start-up motor connected to the rotor of the DFIG, wherein the control unit is operatively coupled to the start-up motor and configured to black-start the DFIG, wherein to black-start the DFIG, the control unit is configured to:

- operate the start-up motor to rotate the rotor of the DFIG;

- apply voltage to the rotor winding from the second power converter when a rotational speed of the rotor approaches a synchronous speed to induce a stator voltage in the stator winding of the DFIG;

- disengage the start-up motor from the rotor after the stator voltage has synchronized with a grid voltage; and

- connect the DFIG to the facility power bus after the stator voltage has synchronized with a grid voltage.

14. The fault current control sub-system of claim 11, further comprising a start-up switch connected to the stator winding of the DFIG, wherein the control unit is operatively coupled to the start-up switch and configured to start the DFIG, wherein to start the DFIG, the control unit is configured to:

- short-circuit the rotor winding via the second power converter;

connect the stator winding to the facility power bus via the start-up switch thereby causing rotations of the rotor; and

remove the short-circuit from the rotor winding when a rotational speed of the rotor reaches to a predetermined value.

15. The fault current control sub-system of claim 14, wherein, if the facility power bus is connected to the utility power grid, the facility power bus is energized by the utility power grid.

16. The fault current control sub-system of claim 14, wherein, if the facility power bus is disconnected from the utility power grid, the first power converter is configured to energize the facility power bus.

17. The fault current control sub-system of claim 11, further comprising a stator short-circuit contactor connected to the stator winding of the DFIG, wherein the control unit is operatively coupled to the stator short-circuit contactor and configured to black-start the DFIG, wherein to black-start the facility power bus, the control unit is configured to:

short-circuit the stator winding by operating the stator short-circuit contactor in a closed state;

apply AC voltage to the rotor winding from the second power converter thereby causing rotations of the rotor; and

operate the stator short-circuit contactor in an open state and set a frequency of a stator voltage of the DFIG to the nominal frequency of grid voltage if a rotor speed has reached a synchronous speed.

18. The fault current control sub-system of claim 11, wherein to black-start the DFIG, the control unit is configured to:

apply AC voltage to the rotor winding from the second power converter to generate a stator voltage at the stator winding;

energize a first power converter and synchronize its output voltage to the stator voltage at the stator winding;

control torque on the rotor by controlling a frequency and a magnitude of the AC voltage applied to the rotor winding until the rotor attains a synchronous speed; and

connect the facility power bus to the utility power grid after the stator voltage has synchronized with a grid voltage.

19. A method for controlling a fault current contribution in a system comprising a facility power bus coupled to a utility power grid, a power generation sub-system comprising at least one renewable energy based power source and at least one energy storage device coupled to the facility power bus via one or more first power converters, the method comprising:

determining whether the facility power bus is disconnected from the utility power grid;

controlling, in response to determining that the facility power bus is disconnected from the utility power grid, an electrical current flowing through a rotor winding of a doubly-fed induction generator (DFIG) via a second power converter such that at least a part of a fault current through the facility power bus flows via the DFIG, wherein a stator winding of the DFIG is connected to the facility power bus; and

controlling, in response to determining that the facility power bus is connected to the utility power grid, the electrical current flowing through the rotor winding of the DFIG via the second power converter such that a flow of the fault current through the DFIG is reduced in comparison to the fault current when the facility power bus is disconnected from the utility power grid.

20. The method of claim 19, further comprising monitoring an operating state of a tie-breaker coupling the facility power bus to the utility power grid, wherein the operating state of the tie-breaker comprises one of an open state or a closed state.

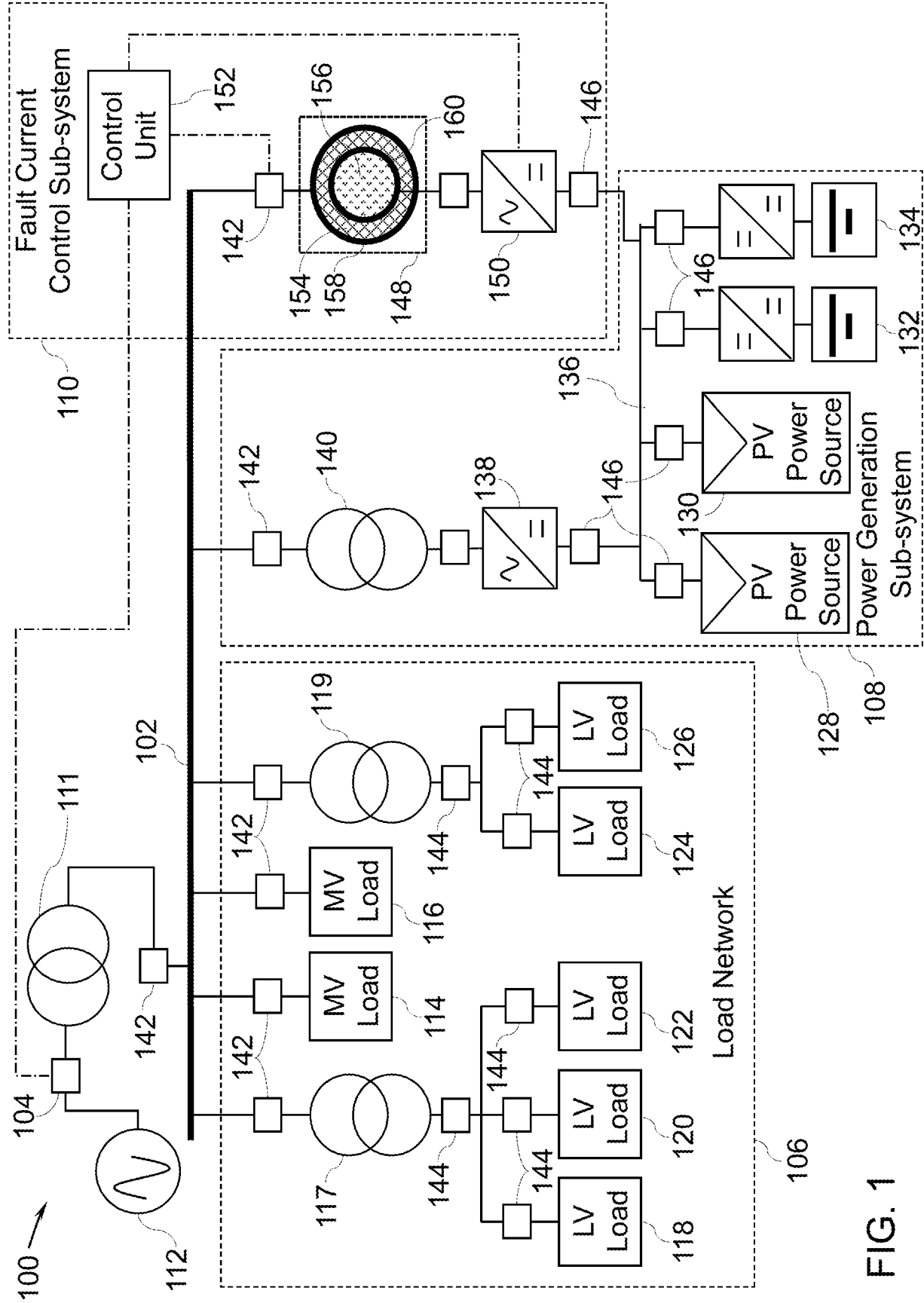


FIG. 1

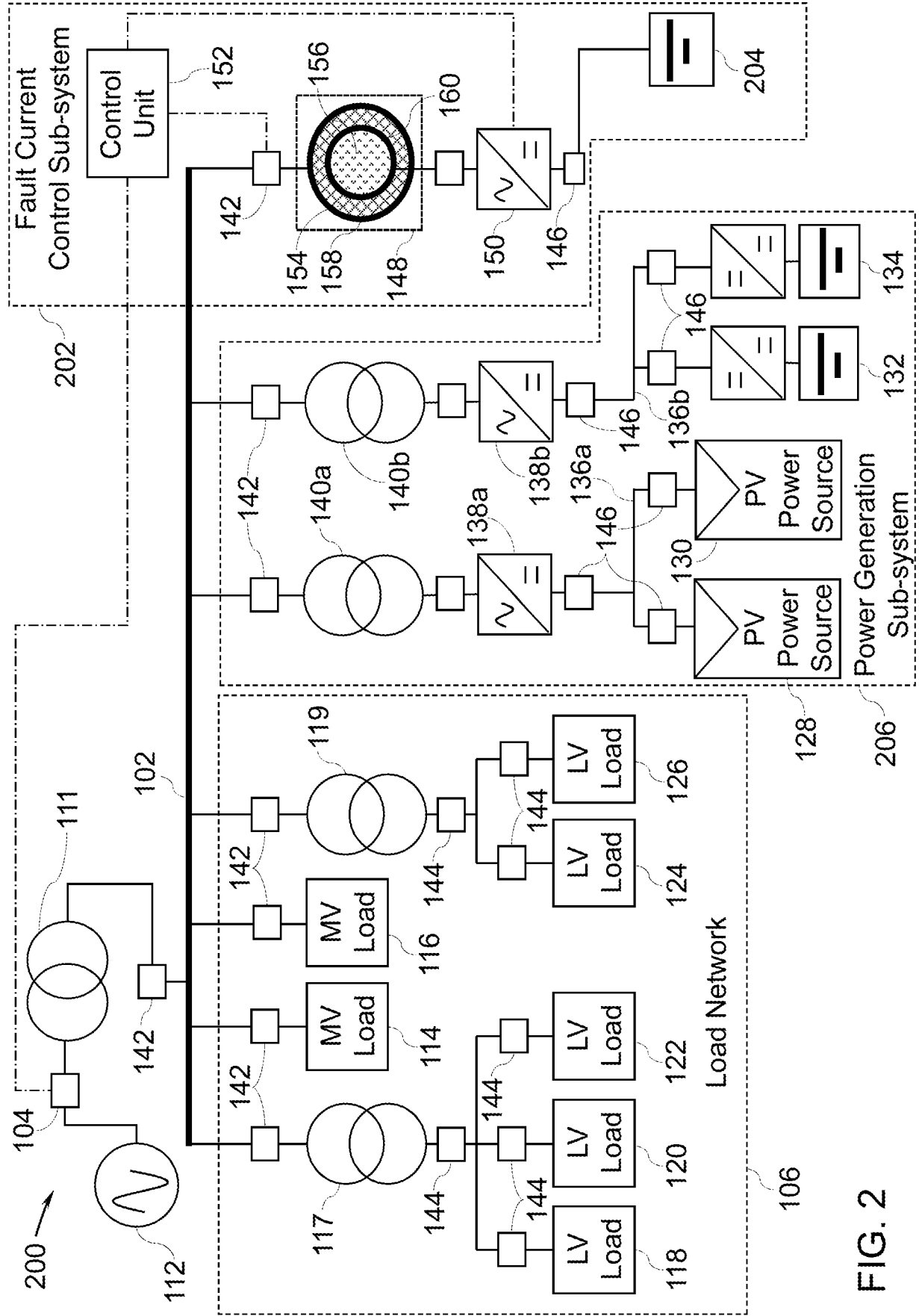


FIG. 2

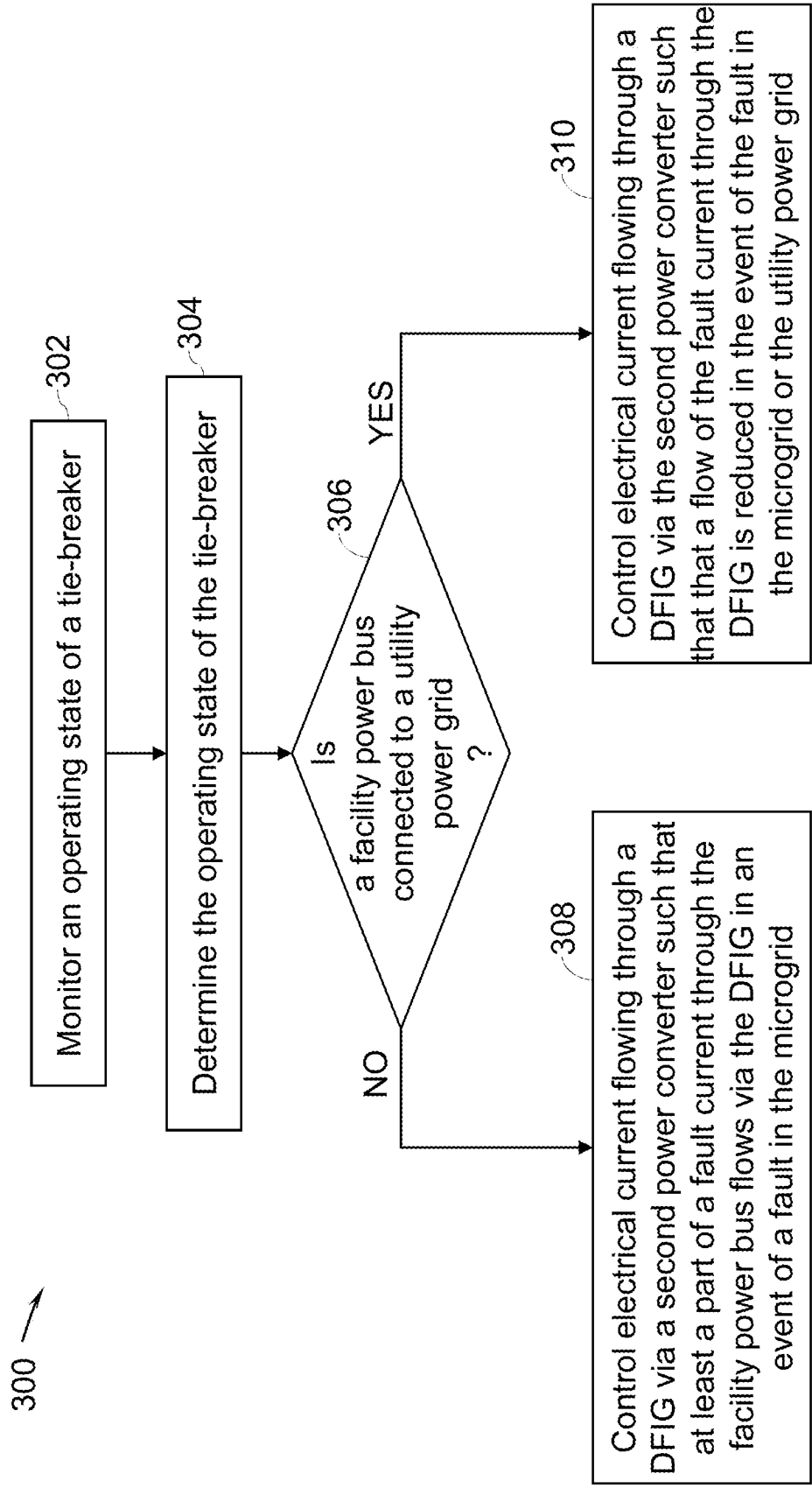


FIG. 3

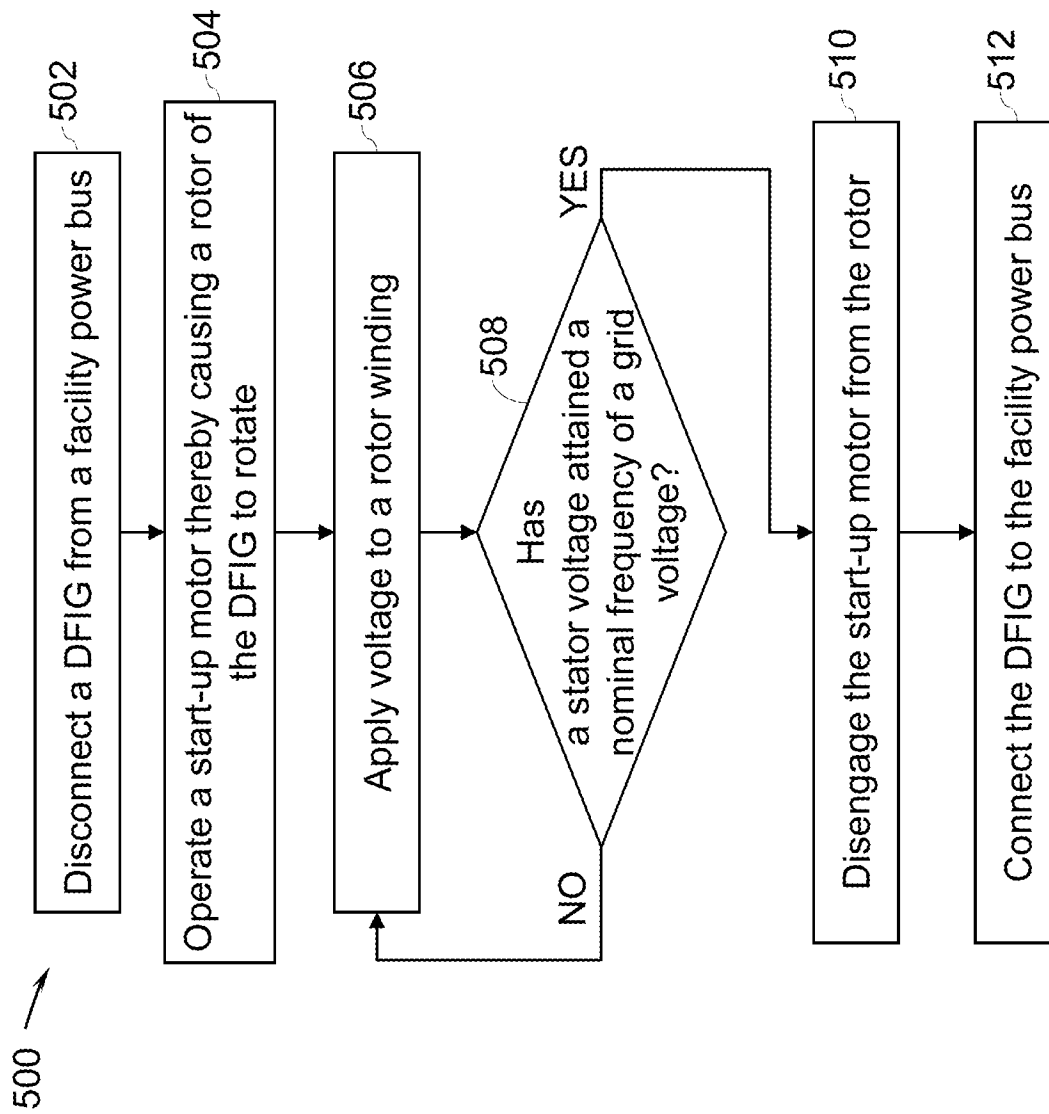


FIG. 5

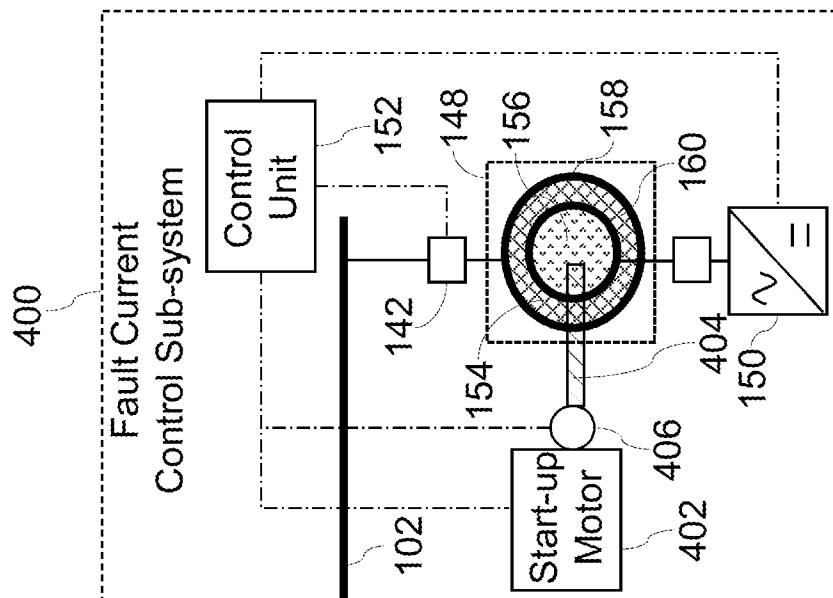


FIG. 4

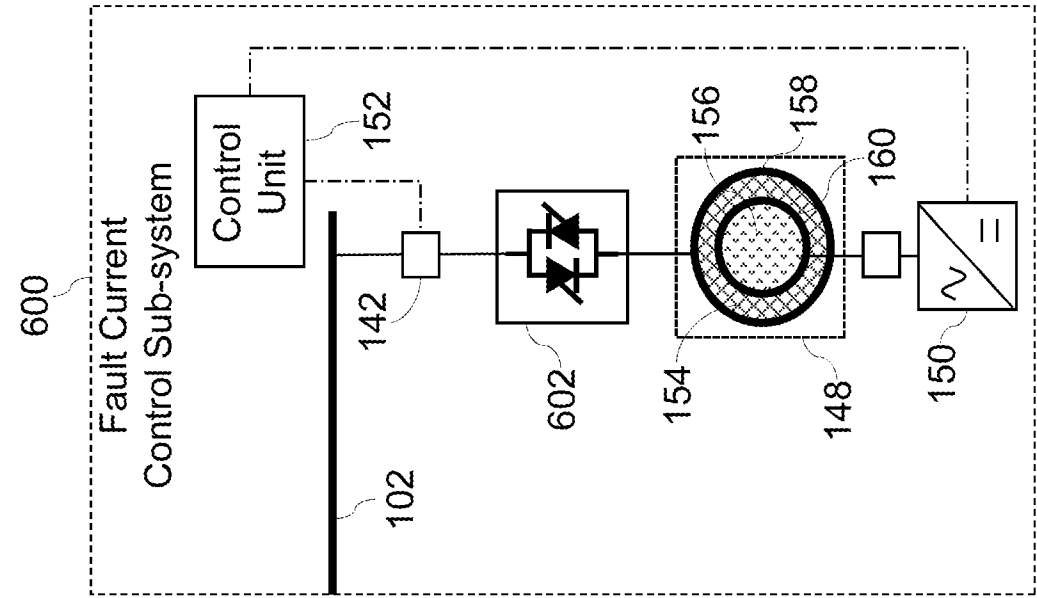


FIG. 6

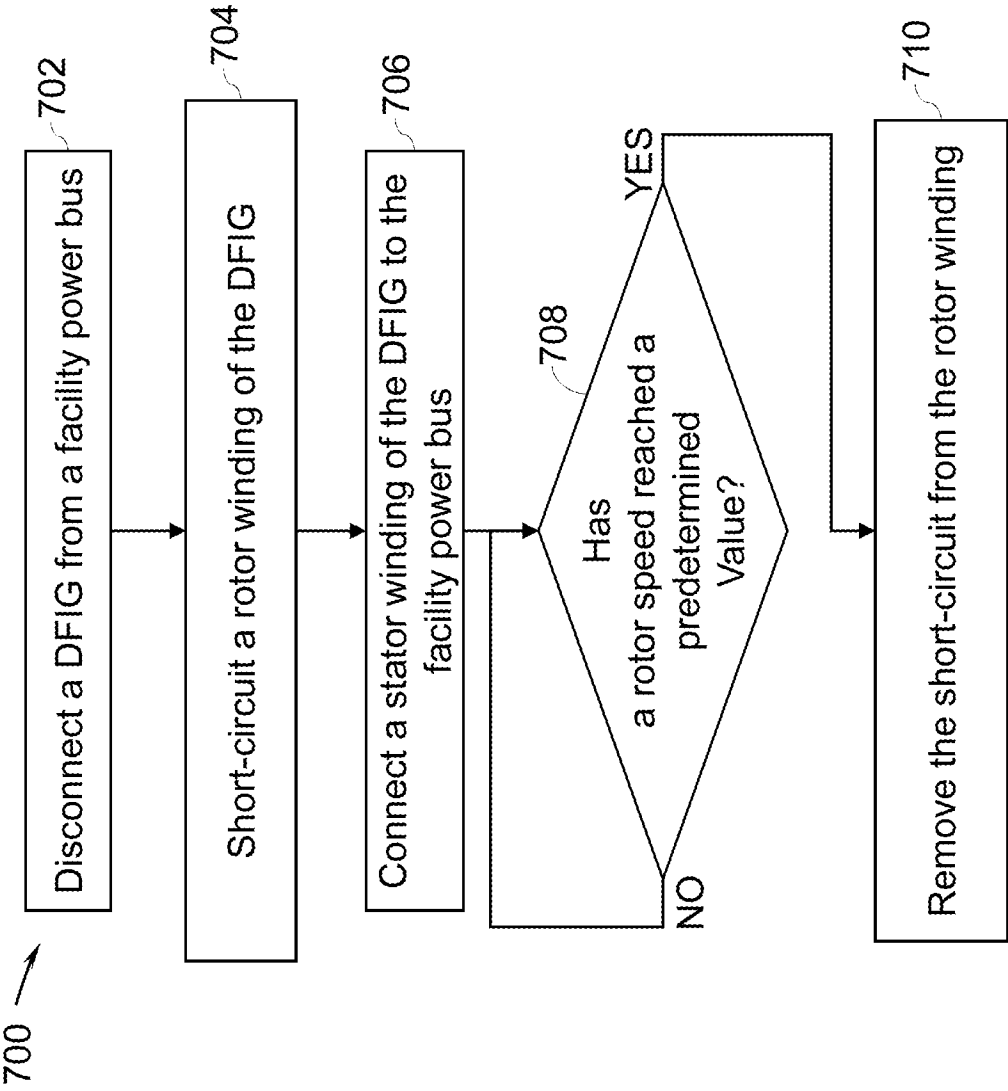


FIG. 7

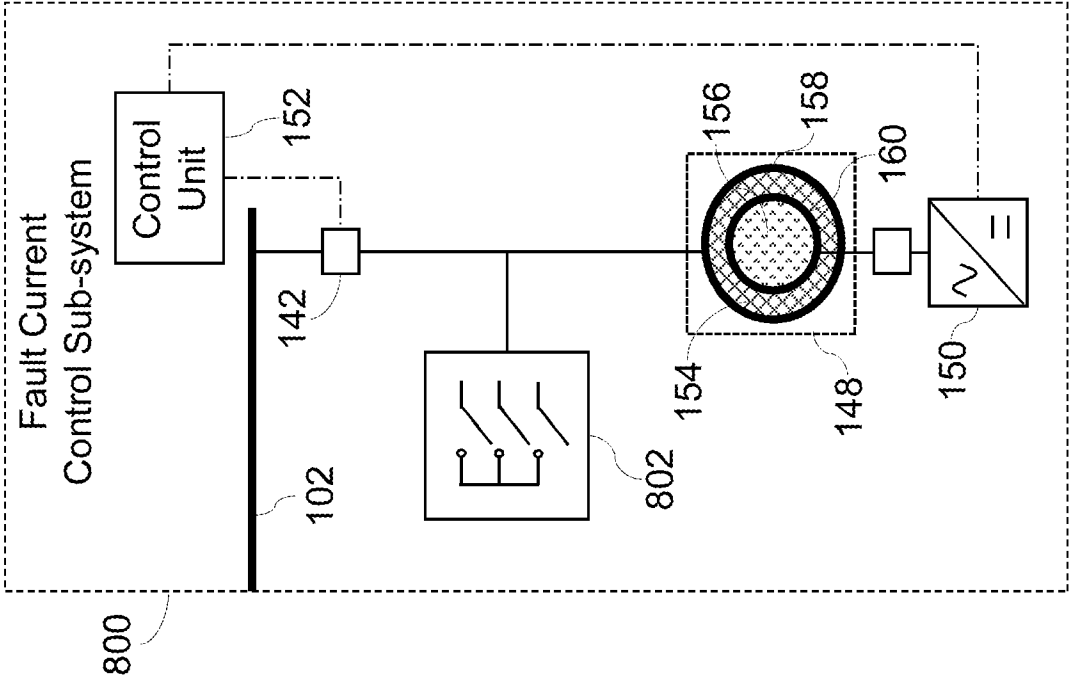


FIG. 8

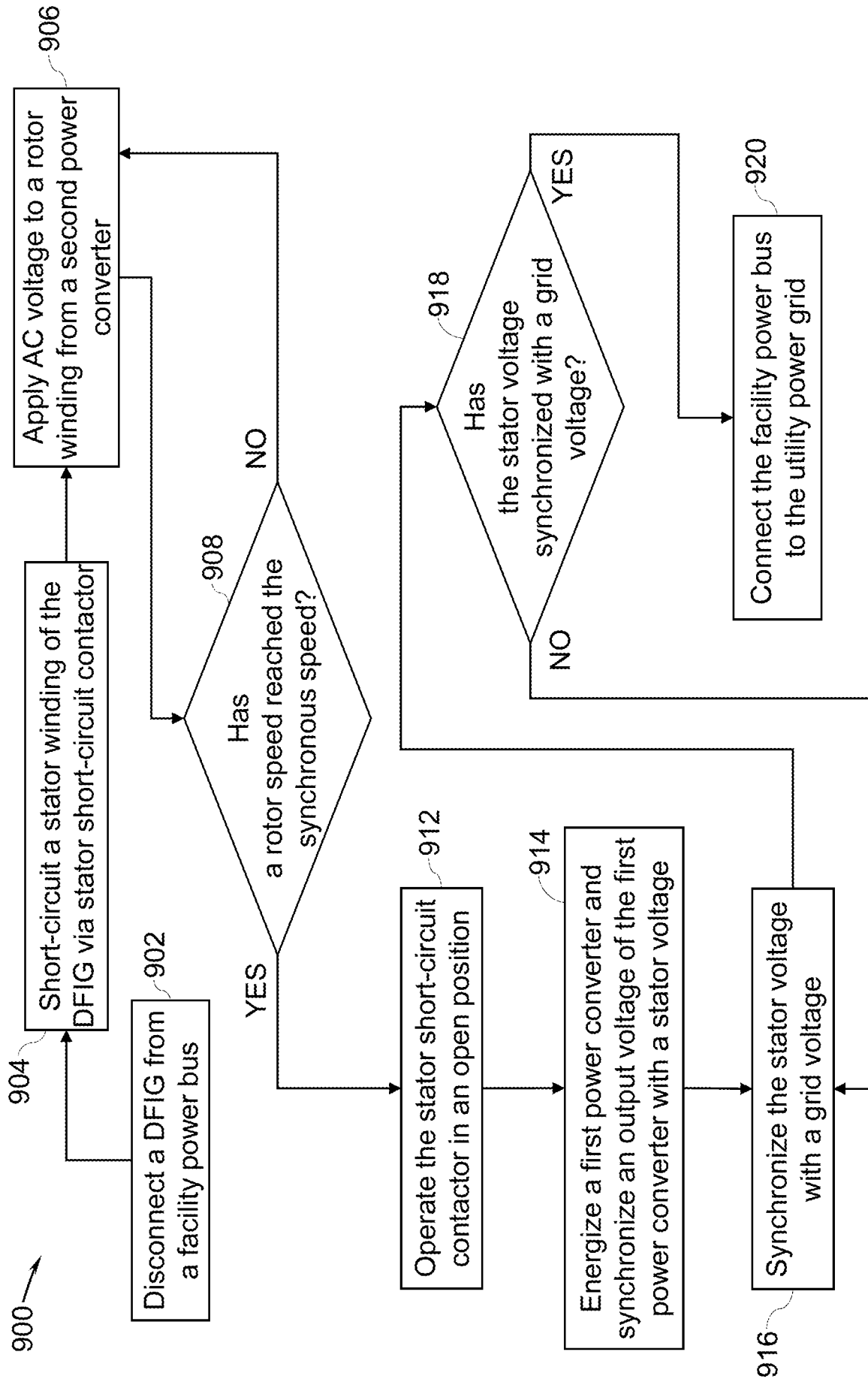


FIG. 9

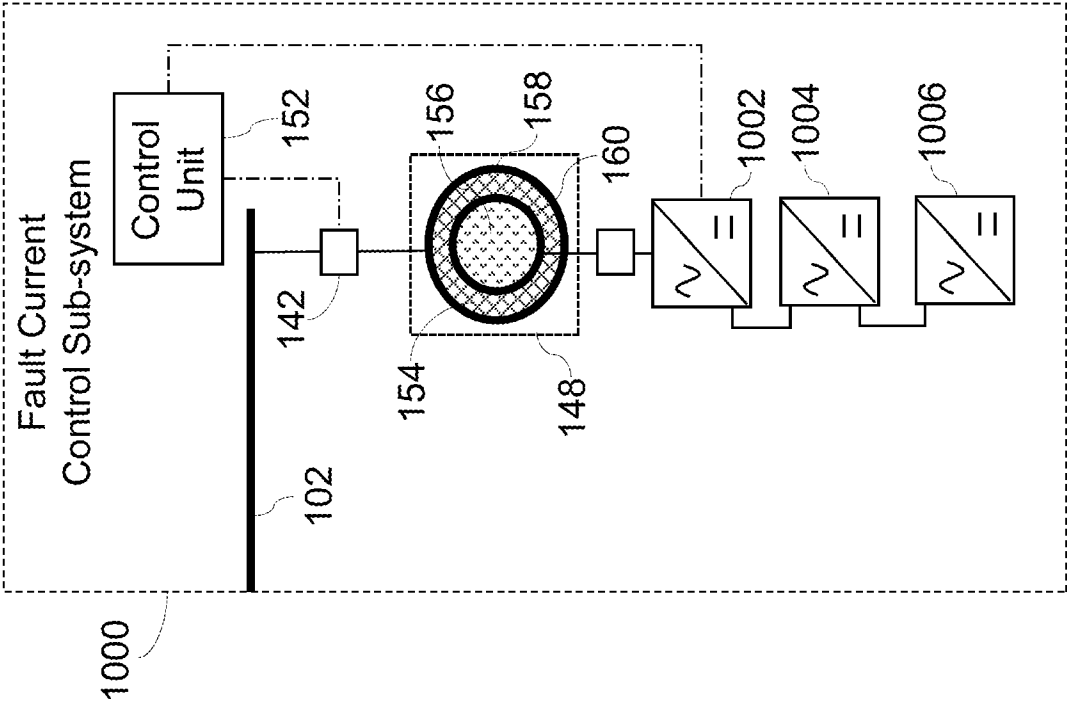


FIG. 10

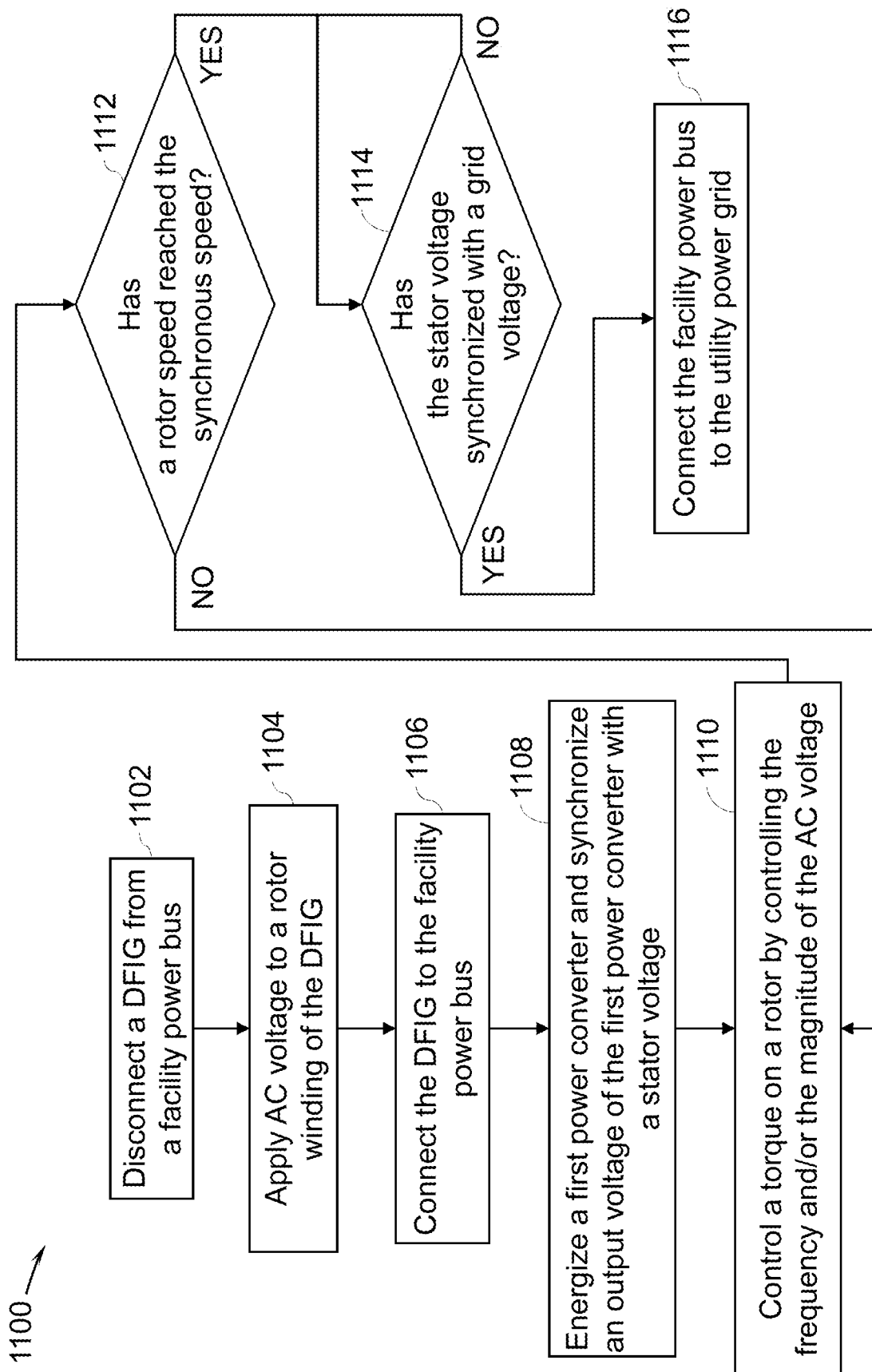


FIG. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/065933

A. CLASSIFICATION OF SUBJECT MATTER

INV. H02J3/28 H02H1/06 H02J3/38 H02P9/00
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)

H02J H02P H02H

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)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

23 August 2019

Date of mailing of the international search report

03/09/2019

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/065933

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	EP 3 113 312 A1 (GEN ELECTRIC [US]) 4 January 2017 (2017-01-04) page 4, paragraph 21 - paragraph 23; figure 1 page 5, paragraph 29 - paragraph 30; figure 2 -----	1-20

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Information on patent family members

International application No

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