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(54) **Title**: MITIGATION OF ARC FLASH HAZARD IN PHOTOVOLTAIC POWER PLANTS

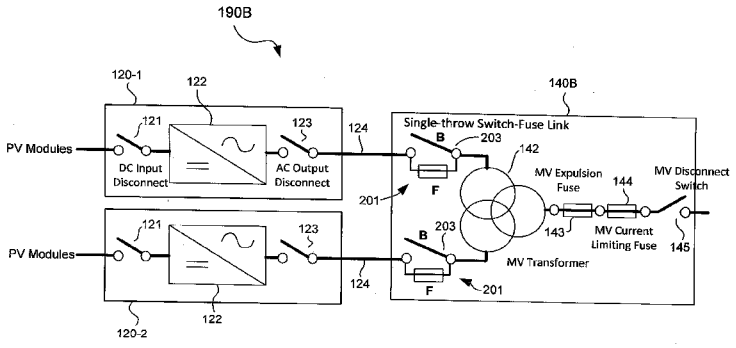


FIG. 8

(57) **Abstract**: Arc flash mitigation devices are employed to protect personnel during maintenance of photovoltaic inverters. During normal operation, an alternating current (AC) output of a photovoltaic inverter is coupled to a low voltage winding of a step up transformer through a bus-bar (B) (e.g., an electrically conductive interconnect), which has higher current rating than a fuse (F). During maintenance, the bus-bar (B) is replaced with the fuse (F). The fuse (F) may be employed in conjunction with a switch. The switch may be a disconnect switch that places the bus-bar (B) in parallel with the fuse during normal operation, and decouples the bus-bar from the fuse (F) during maintenance. The switch may also be a transfer switch that places either the bus-bar (B) or the fuse (F) in series with the AC output of the photovoltaic inverter and the low voltage winding of the step up transformer.

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MITIGATION OF ARC FLASH HAZARD IN PHOTOVOLTAIC POWER PLANTS

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TECHNICAL FIELD

[0001] Embodiments of the subject matter described herein relate generally to solar cells. More particularly, embodiments of the subject matter disclosed herein relate to photovoltaic power plant operation and maintenance.

BACKGROUND

[0002] Photovoltaic power plants employ solar cells to convert solar radiation to electrical energy. Photovoltaic power plants also include photovoltaic inverters ("inverters"), which convert direct current (DC) generated by the solar cells to alternating current (AC) suitable for delivery to a point of interconnect with a utility grid through a network of transformers and transmission lines. Inverters are often employed in inverter stations that comprise multiple inverters connected to a single multiple-winding medium voltage step-up transformer, which in turn is connected to a medium voltage grid.

[0003] Arc flash is a serious workplace hazard when working on inverters, such as during maintenance. Mitigating arc-flash hazard in inverter stations poses several design challenges because the utility grid to which the inverter stations are connected serve as large fault current sources, leading to high arc-flash energies within the inverter stations during arc faults. In addition, effective commissioning and maintenance activities often require full internal access to inverters while the inverters are powered ON and connected live to the utility grid. The documents IEEE 1584-2002 by the Institute of Electrical and Electronic Engineers and NFPA-70E by the National Fire Protection Association provide guidelines to analyze and estimate the arc-flash energy at various locations within the electrical systems such as AC inverter stations and to determine the appropriate personal protective equipment (PPE) required for protection against potential arc flash events.

[0004] For generic, i.e., not necessarily for photovoltaic applications, electric equipment, arc flash mitigation solutions may include reducing arc current, increasing the working distance, and reducing the clearing time. These solutions, however, may be difficult to achieve or inadequate to protect workers at inverter stations.

[0005] Certain protective devices are current limiting by design. By limiting or reducing the current available for an arc fault, the corresponding incident energy is reduced during fault-clearing times that are typically short in duration (e.g., 1-3 cycles). Fault currents at these protective devices must be in the current limiting range for them to be effective. The potential problem of this solution is that below the fault current limit, the clearing time goes up significantly and, therefore, the incident energy level may exceed workable levels for a range of grid operating conditions of a photovoltaic power plant.

[0006] Increasing the working distance will significantly reduce the incident energy level because the incident energy is proportional to the square of the distance in open air. Working distance can be increased by using remote operating devices and extension tools (e.g., hot-sticks). However, in the case of inverter stations, many maintenance or commissioning activities need to have internal access to the inverters while the inverters are powered ON and connected live to the utility grid. Therefore, increasing the working distance may not be practical in inverter stations.

[0007] One popular method of reducing clearing times is to lower the current setting of the protective device, such as a circuit breaker. A disadvantage of this solution, in particular for inverter stations, is that the level to which the current setting can be lowered is limited for normal operating conditions due to the need to coordinate the breaker tripping characteristics with equipment protection needs and avoiding normal short-term transient currents from tripping the breaker.

[0008] Other solutions for mitigating arc flash hazards in general include provision of bus differential protection and zone selective interlocking, the specific implementations of which are highly system-dependent, typically complex, and not cost effective.

BRIEF SUMMARY

[0009] In one embodiment, arc flash mitigation devices are employed to protect personnel during maintenance of photovoltaic inverters. During normal operation, an

alternating current (AC) output of a photovoltaic inverter is coupled to a low voltage winding of a step up transformer through a bus-bar (e.g., an electrically conductive interconnect), which has higher current rating than a fuse. During maintenance, the bus-bar is replaced with the fuse. The fuse may be employed in conjunction with a switch. The switch may be a disconnect switch that places the bus-bar in parallel with the fuse during normal operation, and decouples the bus-bar from the fuse during maintenance. The switch may also be a transfer switch that places either the bus-bar or the fuse in series with the AC output of the photovoltaic inverter and the low voltage winding of the step up transformer.

[0010] These and other features of the present invention will be readily apparent to persons of ordinary skill in the art upon reading the entirety of this disclosure, which includes the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] A more complete understanding of the subject matter may be derived by referring to the detailed description and claims when considered in conjunction with the following figures, wherein like reference numbers refer to similar elements throughout the figures.

[0012] FIG. 1 shows a schematic diagram of a photovoltaic power plant in accordance with an embodiment of the present invention.

[0013] FIGS. 2 and 3 show schematic diagrams of a system in the form of an inverter station in accordance with an embodiment of the present invention.

[0014] FIG. 4 shows a schematic diagram illustrating bus-bar links of the system of FIG. 2 in accordance with an embodiment of the present invention.

[0015] FIG. 5 shows a schematic diagram illustrating fuse links of the system of FIG. 3 in accordance with an embodiment of the present invention.

[0016] FIG. 6 show a schematic diagram of bus-bar links on interconnect holders in accordance with an embodiment of the present invention.

[0017] FIG. 7 show a schematic diagram of fuse links on interconnect holders in accordance with an embodiment of the present invention.

[0018] FIG. 8 shows a schematic diagram of another system in the form of an inverter station in accordance with an embodiment of the present invention.

[0019] FIG. 9 schematically shows switch-fuse links of the system of FIG. 8 in accordance with an embodiment of the present invention.

[0020] FIG. 10 schematically shows further details of the switch-fuse links of the system of FIG. 8 in accordance with an embodiment of the present invention.

[0021] FIG. 11 shows a schematic diagram of yet another system in the form of an inverter station in accordance with an embodiment of the present invention.

[0022] FIG. 12 schematically shows switch-fuse links of the system of FIG. 11 in accordance with an embodiment of the present invention.

[0023] FIGS. 13 and 14 schematically illustrate operation of a maintenance lever in accordance with an embodiment of the present invention.

[0024] FIG. 15 shows a flow diagram of a method of switching an inverter station from normal operation mode to maintenance mode in accordance with an embodiment of the present invention.

[0025] FIG. 16 shows a flow diagram of a method of switching an inverter station from maintenance mode to normal operation mode in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

[0026] In the present disclosure, numerous specific details are provided, such as examples of apparatus, components, and methods, to provide a thorough understanding of embodiments of the invention. Persons of ordinary skill in the art will recognize, however, that the invention can be practiced without one or more of the specific details. In other instances, well-known details are not shown or described to avoid obscuring aspects of the invention.

[0027] Conventional solutions to arc flash hazard described above are based on the premise that the solution should be common to both normal operational and maintenance conditions, i.e., the solution needs to guarantee the arc flash risk category is not higher than appropriate for safely performing commissioning and maintenance activities while ensuring the normal operating conditions are not impacted. However, a single setting of a protective device for both operation and maintenance does not guarantee the protective device can clear the fault quickly for all available short-circuit current levels. For example, a circuit breaker may trip within 50ms for currents higher than 1000A but may take over 10s for currents less than 800A. Given that arc flash energy is a non-linear

function of available fault current and is proportional to the fault clearing time, the highest potential short-circuit current level and its corresponding clearing time may not represent the worst-case scenario in terms of arc flash energy. In fact, the highest arc flash energy may correspond to a fault current level much below the maximum.

[0028] Also, while performing arc flash hazard analysis, it is quite common to assume that the utility grid is an infinite bus or that maximum fault current is available from the utility grid. However, these assumptions could yield inaccurate results, often underestimating the arc flash energy. In addition, these assumptions do not take into account future plant expansions or modifications that may significantly impact the available fault currents. In a large photovoltaic (PV) power plant where inverter stations are dispersed over hundreds of acres, the line impedances from inverter stations to the substation may vary significantly. Therefore, the available short circuit currents and hence the arc flash energy levels may widely vary among different inverter stations. A single point setting of the protective devices within a large PV power plant may not be sufficient for all the aforementioned complexities.

[0029] Furthermore, a single point setting of tripping time for the traditional circuit breaker solution, when the tripping current is set low, may introduce nuisance tripping that may result in undesired interruptions, frequent shutdowns, and restarts that impact reliable power production. On the other hand, if the tripping current setting is too high, the arc currents below the tripping level may still result in arc flash hazard simply because the resulting breaker trip time increases significantly. More specifically, if the arcing current exceeds the instantaneous setting, incident energy levels are very low. At arc currents lower than the instantaneous setting, the additional clearing time more than offsets the lower arc current to produce higher incident energy and therefore results in a more hazardous situation.

[0030] Solutions conventionally used for generic electric equipment and systems that involve reducing the protection device trip setting prior to performing maintenance activities to reduce fault clearance time and inserting a high impedance element between the utility grid and the equipment prior to performing maintenance activities to reduce fault current levels are not easily extendable to inverter stations due to high implementation costs and the extended procedural steps necessary for safely performing maintenance.

[0031] Accordingly, embodiments of the present invention provide arc flash mitigation solutions that are especially advantageous, cost effective, and practical for performing maintenance on inverters.

[0032] Referring now to FIG. 1, there is shown a schematic diagram of a PV power plant 100 in accordance with an embodiment of the present invention. The PV power plant 100 may include a plurality of transformer housings 140, a plurality of photovoltaic inverters 120, a plurality of photovoltaic modules 110, and a high voltage (HV) step up transformer 160. Control and other components of the PV power plant 100 not necessary for the understanding of the invention are not shown for clarity of illustration.

[0033] In the example of FIG. 1, an inverter station 190 includes one or more inverters 120 connected to a transformer housing 140. A transformer housing 140 may include a single multiple-winding medium voltage (MV) transformer to which all inverters 120 in the same inverter station 190 are connected. Groups of solar cells 115 may be packaged together in a photovoltaic module 110, which may be connected to an inverter 120 along with other photovoltaic modules 110. The solar cells 115 may comprise commercially-available solar cells, such as those available from SunPower Corporation of San Jose California. It is to be noted that only some of the solar cells 115 are labeled in FIG. 1 in the interest of clarity.

[0034] An inverter 120 converts DC current generated by a set of photovoltaic modules to AC current suitable for delivery to the utility grid at a point of interconnect (POI) 161. In the example of FIG. 1, the output of an inverter 120 is stepped up by an MV transformer of a transformer housing 140 and further stepped up by the transformer 160 before being provided to the utility grid, which may be operated by a utility company that provides electrical service to consumers.

[0035] FIGS. 2 and 3 show schematic diagrams of a system in the form of an inverter station 190A in accordance with an embodiment of the present invention. The inverter station 190A is a particular embodiment of an inverter station 190 of the PV power plant 100 shown in FIG. 1. The inverter station 190A is illustrated using two inverters 120 (i.e., 120-1, 120-2) that are connected to a single multiple winding step up MV transformer 142. In general, an inverter station may have fewer or more inverters connected to an MV transformer. In one embodiment, the MV transformer 142 has two low voltage windings and a single high voltage winding. Each of the low voltage

windings is coupled to an inverter 120 and the high voltage winding is coupled to the utility grid.

[0036] The transformer housing 140A shown in FIG. 2 is a particular embodiment of a transformer housing 140 of the PV power plant 100. The transformer housing 140A may enclose the MV transformer 142, an MV expulsion fuse 143, an MV current limiting fuse 144, and an MV disconnect switch 145 in the same protective housing for safety reasons. As will be more apparent below, a transformer housing may include different inverter-transformer links (e.g., bus-bar or contact links, fuse links, and switch-fuse links) within its housing in various embodiments of the present invention. The inverter-transformer links, which connect the inverters 120 to the MV transformer 142, may also be located outside a transformer housing.

[0037] The inverter station 190A is an example of a configuration with two inverters 120 connected to a single three-winding MV transformer 142. Other circuit configurations of an inverter station may include a single inverter or multiple parallel inverters connected through a two winding MV transformer.

[0038] An inverter 120 may comprise an inverter circuit 122, an AC output disconnect 123 and a DC input disconnect 121. The inverter circuit 122 comprises an electrical circuit for converting the DC power received from the photovoltaic modules 110 to a utility grid compatible output. The DC input disconnect 121 and the AC output disconnect 123 may comprise switches for disconnecting the inverter 120 from the photovoltaic modules 110 and the MV transformer 142, respectively. The inverters 120 may comprise commercially available photovoltaic inverters.

[0039] An inverter 120 has a DC input for receiving the DC output of the photovoltaic modules 110 and an AC output that is provided to the utility grid. The AC output of the inverter 120 is stepped up by the MV transformer 142 before being provided to the utility grid. In addition to stepping up the AC voltage, the MV transformer 142 provides galvanic isolation between the utility grid and the inverters 120, and hence to the photovoltaic modules 110.

[0040] Given that the inverters 120 are connected to a large utility grid with potentially large available fault current, potential for the occurrence of arc flash at the inverters 120 is a major safety concern. Although overcurrent protection is typically provided at the high voltage side of the MV transformer 142 by the fuses 143 and 144, the corresponding fault clearance times for faults at the low voltage side of the MV

transformer 142 and the inverters 120 are generally long and widely varies, resulting in high incident arc energies in the region between the low voltage terminals of the MV transformer 142 and the AC outputs of the inverters 120. Insertion of an appropriate arc flash mitigation solution at this location between the MV transformer 142 and the inverters 120 will help ensure personnel safety, specifically while operating, commissioning, maintaining, or servicing the inverters 120. Preferably, the arc flash mitigation solution reduces the incident energy level from PPE class 4 or higher (> 40 cal/cm^2) to PPE class 2 or lower (< 8 cal/cm^2) consistently for all potentially available fault currents from the utility grid.

[0041] A conventional arc flash mitigation solution is to install dedicated circuit breakers within the MV transformer housing and in series with the inverter outputs. The circuit breakers help ensure that any potential occurrence of arc fault at the inverter outputs is instantly cleared by the associated circuit breaker such that the associated incident energies do not exceed PPE class 2 level. However, proper setting of circuit breaker tripping characteristics is a difficult task at best because the setting needs to ensure that the circuit breaker trips instantly for a wide range of arc fault currents with levels dependent on the available fault currents, while not responding to over and surge currents expected during normal operation. Also, in the cases where the circuit breakers are located within the MV transformer housing, the housing should be suitably designed to meet the environmental requirements of the circuit breakers, resulting in increased implementation costs.

[0042] In one embodiment, the inverter station 190A may have different inverter-transformer links depending on whether the inverter station 190A is on normal operation mode or maintenance mode. As its name implies, normal operation mode is when the inverters 120 are normally operating to provide solar generated power to the utility grid. Maintenance mode is when the inverters 120 are being maintained, serviced, or commissioned.

[0043] FIG. 2 shows the connection configuration of the outputs of the inverters 120 to the MV transformer 142 in normal operation mode. In normal operation, a bus-bar link 141 (e.g., an electrically conductive interconnect) serves as an inverter-transformer link connecting an inverter 120 to the MV transformer 142. A bus-bar link 141 is preferably, but not necessarily, enclosed within the transformer housing 140A. A single

wire or multi-wire conductor 124 may connect a bus-bar link 141 to an AC output of an inverter 120.

[0044] During normal operation, the bus-bar links 141 connect the AC outputs of the inverters 120 to corresponding low voltage terminals of the MV transformer 142. The bus-bar links 141 are designed such that they carry the full rated current of the inverters 120, and are arranged in a mechanical configuration such that they can be easily removed and replaced with a set of fuse-links 146 (see FIG. 3) for maintenance mode. FIG. 4 shows a schematic diagram illustrating bus-bar links 141 connecting the terminals L1A, L2A, and L3A from the inverter 120-1 to corresponding low voltage winding terminals X1A, X2A, and X3A of the MV transformer 142, and connecting the terminals L1B, L2B, and L3B from the inverter 120-2 to corresponding low voltage winding terminals X1B, X2B, and X3B of the MV transformer 142. The example shown is for a three-phase wiring, one wiring for each phase, for illustration purposes only.

[0045] FIG. 3 shows the connection configuration of the inverters 120 to the MV transformer 142 in maintenance mode. In maintenance mode, fuse links 146 (instead of the bus-bar links 141) serve as the inverter-transformer links. Prior to performing a maintenance task on the inverters 120, each bus-bar link 141 is replaced with a fuse link 146. Unlike the bus-bar links 141, which are rated to carry the full rated current of the inverters 120, the fuse-links 146 are rated to carry a fraction of the rated current of the inverters 120 such that fault-clearance time of the fuse-links 146 is sufficiently short to reduce arc flash energy well below the levels corresponding to PPE class 2 for the full range of available fault currents. A fuse-link 146 may comprise a fast acting fuse. With the fuse links 146, maintenance tasks that require the inverters 120 to remain powered ON may thus be employed in relative safety. Examples of maintenance tasks that require the inverters 120 to be powered ON include inverter output current and voltage measurements, leakage current measurements, harmonics measurements, thermal measurements, control, communication and monitoring circuits and functionalities diagnostics, or any other multimeter or oscilloscope measurements that may arise during maintenance and commissioning activities that require close access to live components inside the inverters. Should an arc fault situation were to arise during maintenance, the fast acting fuse links 146 are able to clear the arc within a few milliseconds to a few hundred milliseconds, thereby limiting the incident energy significantly well below 8 cal/cm^2. This allows maintenance personnel to safely perform maintenance tasks on the

inverter station 190 using only PPE 2 level protection. On completion of the maintenance task, the fuse links 146 are removed and replaced with the bus-bar links 141 so that normal operation can be resumed. FIG. 5 shows a schematic diagram illustrating fuse links 146 connecting the terminals L1A, L2A, and L3A from the inverter 120-1 to corresponding low voltage winding terminals X1A, X2A, and X3A of the MV transformer 142, and connecting the terminals L1B, L2B, and L3B from the inverter 120-2 to corresponding low voltage winding terminals X1B, X2B, and X3B of the MV transformer 142.

[0046] In one embodiment, the bus-bar links and the fuse links share a common physical spacing layout, termination footprint, and termination devices, such that procedures for replacing bus-bar links 141 with fuse links 146, and vice versa, can be performed reliably with ease and with minimal number of steps. This feature is schematically illustrated in FIGS. 6 and 7 where an interconnect holder 192 physically accommodates either a bus-bar link 141 or a fuse link 146. Each holder 192 allows for connecting a low voltage winding terminal of the MV transformer 142 (i.e., X1A, X2A, X3A, X1B, X2B, or X3B) to a corresponding terminal from an inverter 120 (i.e., L1A, L2A, L3A, L1B, L2B, or L3B). To change from normal mode to maintenance mode, the maintenance person simply has to remove the bus-bar links 141 from the interconnect holders 192 and install the fuse links 141 onto the holders 192. Similarly, to change from maintenance mode to normal operation mode, the maintenance person simply has to remove the fuse links 146 from the interconnect holders 192 and install the bus-bar links 141 onto the holders 192. During the swapping of the bus-bar links 141 with the fuse links 146 and vice versa, the entire inverter station 190A needs to be powered OFF and disconnected from the utility grid, which may be achieved by opening the MV disconnect switch 145 (shown in FIGS. 2 and 3), which is typically present at the high voltage side of the MV transformer 142.

[0047] With reference to FIGS. 2 and 3, a method of performing maintenance on an inverter 120 of a PV power plant 100 in one embodiment of the invention may involve putting the inverter station 190A in maintenance mode by powering OFF the inverters 120, disconnecting the inverter station 190A from the utility grid by opening the MV disconnect switch 145, replacing the bus-bar links 141 with the fuse-links 146, closing the MV disconnect switch 145, powering ON the inverters 120, and performing maintenance on one or more inverters 120 (while powered ON) with the fuse-links 146

in-place instead of the bus-bar links 141. The method further involves putting the inverter station 190A in normal operation mode by powering OFF the inverters 120, disconnecting the inverter station 190A from the utility grid by opening the MV disconnect switch 145, replacing the fuse links 146 with the bus-bar links 141, closing the MV disconnect switch 145, and powering ON the inverters 120 with the bus-bar links 141 in place instead of the fuse links 146.

[0048] Referring now to FIG. 8, there is shown a schematic diagram of a system in the form of an inverter station 190B in accordance with an embodiment of the present invention. The inverter station 190B is a particular embodiment of the inverter station 190A where the inverter-transformer links comprise switch-fuse links 201. The switch-fuse links 201 may be incorporated within the protective enclosure of the transformer housing, which is relabeled as "140B." Other components of the inverter 190B are otherwise as described with reference to FIGS. 2 and 3.

[0049] In one embodiment, as shown in FIG. 8, a switch-fuse link 201 comprises a fast acting fuse ***F*** and a single-throw switch 203. Like a fuse-link 146, the fuse ***F*** is rated for a fraction of the rated current of the inverters 120 such that fault-clearance time of the fuse ***F*** is sufficiently short to reduce the arc flash energy well below the levels corresponding to PPE2. The single-throw switch 203 may comprise a two-terminal single-throw disconnect switch.

[0050] During normal operation, the switch 203 is closed and in parallel with the fuse 201. The contacts ***B*** of switch 203 thus connect the inverter 120 to the MV transformer 142 during normal operation, just like the previously described bus-bar link 141 (see FIG. 2). Because of the parallel connection of the contact ***B*** of the switch 203 and the fuse ***F***, the fuse ***F*** carries only a small fraction of the rated current of the inverter 120 during normal operation. During maintenance mode, the switch 203 is opened from being in parallel with the fuse ***F***, allowing the fuse ***F*** to connect the inverter 120 to the MV transformer 142 just like the previously described fuse-links 146 (see FIG. 3).

[0051] FIG. 9 schematically shows the switch-fuse links 201 in accordance with an embodiment of the present invention. As explained, a switch-fuse link 201 may comprise a fuse ***F*** (i.e., F1, F2, F3, F4, F5, or F6) and a corresponding switch contacts ***B*** (i.e., B1, B2, B3, B4, B5, or B6) of switch 203. In the example of FIG. 9, the single-throw switches 203 are ganged together to be operable by a single maintenance lever 204, which may be accessible on the outside of the transformer housing. The MV

transformer 142 winding terminals X1A, X2A, X3A, and X1B, X2B, X3B and the terminals L1A, L2A, L3A, L1B, L2B, and L3B from the inverters 120 are as previously described with reference to FIGS. 4 and 5.

[0052] In the example of FIG. 9, throwing the maintenance lever 204 into a first position (normal operation position) closes all the contacts ***B*** of the switches 203 to place the contacts ***B*** in parallel with corresponding permanently installed fuses ***F*** to place the inverter station 190B in normal operation mode. To place the inverter station 190B in maintenance mode, the maintenance lever 204 is thrown into a second position (maintenance position) to open the contacts ***B*** of the switches 203 such that the inverters and the MV transformer low voltage windings are connected through the fuses ***F***. The maintenance lever 204 may be locked in place in a particular position with a padlock 205 for safety reasons. The switch-fuse links 201 advantageously eliminate the need to manually remove and install bus-bars and fuses to change mode of operations.

[0053] In the switch-fuse links 201, because the fuses ***F*** are always installed, the fuses ***F*** are still present and connected in parallel with the contacts ***B*** during normal operation. Consequently, each fuse ***F*** will carry a small fraction of the normal operating current. The amount of fuse current flowing during the normal operating condition may be reduced to a very small level by a circuit layout design of a switch-fuse link 201 with appropriate impedance matching between the contact ***B*** of a switch 203 and the fuse ***F***. This is illustrated in FIG. 10, which schematically shows a switch-fuse link 201 in accordance with an embodiment of the present invention.

[0054] In the example of FIG. 10, a circuit 206 that comprises the contact ***B*** of switch 203 has an equivalent series resistance 207. A circuit 208 that comprises the fuse ***F*** has an equivalent series resistance 209. If, for example, the equivalent series resistance 207 of the circuit 206 associated with the switch 203 is R_{swi}, then the circuit 208 of the corresponding fuse ***F*** is intentionally designed such that the equivalent series resistance 209 is equal to $k_i R_{swi}$, where $k_i >> 1$. The equivalent impedances should be designed to meet environmental requirements for both normal operating and maintenance conditions.

[0055] Turning now to FIG. 11, there is shown a schematic diagram of a system in the form of an inverter station 190C in accordance with an embodiment of the present invention. The inverter station 190C is a particular embodiment of the inverter station 190A where the inverter-transformer links comprise switch-fuse links 213. The switch-

fuse links 203 may be incorporated within the protective enclosure of the transformer housing, which is relabeled as "140C." Other components of the inverter 190C are otherwise as described with reference to FIGS. 2 and 3.

[0056] In one embodiment depicted in FIG. 11, a switch-fuse link 203 comprises a fast acting fuse 214, a bus-bar 213, and a double-throw switch 215. Like a fuse-link 146, the fuse 214 is rated for a fraction of the rated current of the inverters 120 such that fault-clearance time of the fuse 214 is sufficiently short to reduce the arc flash energy well below PPE 2. The double-throw switch 215 may comprise a transfer switch with two positions to connect the inverter 120 to the MV transformer 142 either through the fuse 214 or the bus-bar 213. That is, only one of the fuse 214 or the bus-bar 213 is connecting the inverter 120 to the low-voltage side of the MV transformer 142 at any given time. The fuse 214 and the bus-bar 213 may be permanently installed.

[0057] An advantage of using switch-fuse links 212 instead of switch-fuse links 201 (see FIG. 8) is that the fuses 214 do not carry any load current during normal operation. Consequently, the fuse sizing and circuit layout design considerations do not need to take into account continuous duty requirements, resulting in simpler electrical design. A trade-off is that the switch-fuse links 212 are typically more expensive to implement and physically bigger than the switch-fuse links 201.

[0058] FIG. 12 schematically shows the switch-fuse links 212 in accordance with an embodiment of the present invention. In the example of FIG. 12, the double-throw switches 215 are ganged together to be operable by the single maintenance lever 204, which may be accessible on the outside of the transformer housing. The MV transformer 142 winding terminals X1A, X2A, X3A, and X1B, X2B, X3B and the terminals L1A, L2A, L3A, L1B, L2B, and L3B from the inverters 120 are as previously described with reference to FIGS. 4 and 5.

[0059] In the example of FIG. 12, throwing the maintenance lever 204 into a first position connects the inverters 120 to the MV transformer 142 through series-connected bus-bar 213 to place the inverter station 190C in normal operation mode. To place the inverter station 190C in maintenance mode, the maintenance lever 204 is thrown into a second position to connect the inverters 120 to the MV transformer 142 through series-connected fuse 214. The maintenance lever 204 may be locked in place in a particular position with a padlock 205 for safety reasons.

[0060] In both the inverter stations 190B (see FIG. 8) and 190C (see FIG. 11), the procedure for switchover between normal operation and maintenance modes is performed with the inverter station completely powered OFF and disconnected from the utility grid to ensure that the switching procedure itself does not pose an arc flash hazard. This may be accomplished by opening the MV disconnect switch 145 (typically through a hot-stick) prior to operating the maintenance lever 204. An interlock mechanism may be employed to ensure the switchover between the two modes of operation is accomplished only with the MV disconnect switch 145 in the open (i.e., OFF) position.

[0061] FIGS. 13 and 14 show the maintenance lever 204 in normal operation position (FIG. 13) and maintenance position (FIG. 14). The maintenance lever 204 may be locked in place using the padlock 205. When the maintenance lever 204 is placed in the normal operation position to place the inverter station in normal operation mode, the inverters 120 are connected to the low-voltage side of the MV transformer 142 through series connected switch contacts and/or bus-bars, e.g., contact ***B*** of switch 203 in the case of the switch-fuse links 201 and bus-bars 213 and the contact of switch 215 in the case of the switch-fuse links 212. When the maintenance lever 204 is placed in the maintenance position to place the inverter station in maintenance mode, the inverters 120 are connected to the low-voltage side of the MV transformer 142 through series connected switch contacts and/or fuses, e.g., fuses ***F*** in the case of the switch-fuse links 201 and fuses 214 and contact of switch 215 in the case of the switch-fuse links 212.

[0062] FIG. 15 shows a flow diagram of a method of switching an inverter station 190 from normal operation mode to maintenance mode in accordance with an embodiment of the present invention. The method of FIG. 15 may be performed as a pre-maintenance procedure.

[0063] In the method of FIG. 15, the inverters 120 are powered OFF, and disconnected by opening their DC input disconnects 121 and AC output disconnects 123 (step 301). The MV disconnect switch 145 is opened (i.e., switched OFF) and locked in the open position with a load disconnect padlock having the same padlock key as the padlock 205 of the maintenance lever 204 (step 302); the padlock key is then released from the load disconnect padlock. The padlock key is used to unlock the maintenance lever 204, and the maintenance lever 204 is turned from the operation position to the maintenance position (step 303). The maintenance lever 204 is locked at the maintenance position and the padlock key is released (step 304). The doors of the

inverter 120 are opened to perform any power-off maintenance actions, and then closed after the maintenance actions have been performed (step 305). Step 305 is repeated for all the inverters 120 in the inverter station (step 306). After performing the power-off maintenance actions, the load disconnect padlock is unlocked using the padlock key to allow the MV disconnect switch 145 to be closed, i.e., switched ON (step 307). The inverters 120 are powered ON, and reconnected by closing their DC input disconnects 121 and AC output disconnects 123 (step 308). Prior to powering on, the output power limit of the inverters 120 are set to a value smaller than the full rating that corresponds with, and is appropriate for, the rating of the fuses ***F*** of the switch-fuse link 201 or fuses 214 of the switch-fuse link 212. Power-on maintenance actions are then performed on the inverters 120. Note that during the power-on maintenance actions (i.e., maintenance actions performed while the inverters 120 are powered ON), the output power level of the inverters 120 are still limited as determined by the fuse ratings of the switch-fuse links 201 or 212, whichever is implemented, because the maintenance lever 204 is still locked in the maintenance position.

[0064] FIG. 16 shows a flow diagram of a method of switching an inverter station 190 from maintenance mode to normal operation mode in accordance with an embodiment of the present invention. The method of FIG. 16 may be performed as a post-maintenance procedure following the method of FIG. 15.

[0065] In the method of FIG. 16, the inverters 120 are powered OFF, and disconnected by opening their DC input disconnects 121 and AC output disconnects 123 (step 320). The MV disconnect switch 145 is opened (i.e., switched OFF) and locked in the open position with the load disconnect padlock (step 321); the padlock key is then released from the load disconnect padlock. The padlock key is used to unlock the maintenance lever 204, and the maintenance lever 204 is turned from the maintenance position to the operation position (step 322). The maintenance lever 204 is locked in the operation position and the padlock key is released. The disconnect padlock of the MV disconnect switch 145 is unlocked, allowing the MV disconnect switch 145 to be closed (step 323). The MV disconnect switch 145 is locked in the closed position and the padlock key 205 is left captive in the disconnect padlock. The inverters 120 are powered ON, and reconnected by closing their DC input disconnects 121 and AC output disconnects 123 (step 324). The output power limit of the inverters 120 are then adjusted back to their full rating

[0066] Note that in embodiments of the invention, the fuses limit the amount of power that can be transferred from the inverters to the utility grid due to their lower current rating in relation to the full rating of the inverters. This limitation does not impact typical maintenance activities and associated tests on the inverters as they do not require the need for full power operation during maintenance. Due to this limitation, during maintenance, as described in step 308 of FIG. 15, the power production from the inverters needs to be curtailed to within the limits allowed by the fuse rating, and this typically can be accomplished by software control of the inverters or by disconnection of several DC input circuits feeding into the inverters.

[0067] Table 1 shows a qualitative comparison of embodiments of the invention that employ switch-fuse links against a conventional solution that is based on circuit breakers. Although the material costs associated with the switch-fuse based solutions of FIGS. 8 and 11 are higher than that of the bus-bar and fuse link based solution of FIGS. 2 and 3, due to the voltage and high current rating of the switches and use of permanently installed fuses, the switch-fuse based solutions are still cost effective when compared to circuit breaker-based solutions. More importantly, both switch-fuse based solutions provide assured safety against potential arc-flash hazards in inverter stations, while the circuit breaker-based solution does not guarantee such assurance in particular when the available fault current and the resulting arc-flash current vary and can reach to a level that is lower than the fixed fast tripping current level of the circuit breaker. Also, depending on the size and the specific maintenance needs of the PV power plant, the bus-bar and fuse link based solution of FIGS. 2 and 3 may be the most cost effective solution.

TABLE 1

	Circuit Breaker Solution	Fuse + Double-throw Switch Solution (FIG. 11)	Fuse + Single-throw Switch Solution (FIG. 8)	Bus-bar + Fuse Link Solution (FIGS. 2 and 3)
Estimated relative cost of the solution (per unit)	1	0.6	0.5	0.3
Power available during maintenance / commissioning	Full	Limited by the fuse sizing. Will require power curtailment of the inverters		
Electrical design complexity	Medium	Medium	High	Low

Physical design complexity	Medium	High	High	Medium
Environmental design complexity	High	Medium-High	Medium-High	Low
Impact on normal operation	Potential for nuisance tripping	None		
Arc-flash mitigation during maintenance	May not be assured for situations with varied and low available fault currents	Assured		
Impact on maintenance operational steps	None	Medium	Medium	High
PPE level during maintenance	Dependent on the variation of the fault current availability	Solution can be tailored to meet PPE 2 or less		

While specific embodiments of the present invention have been provided, it is to be understood that these embodiments are for illustration purposes and not limiting. Many additional embodiments will be apparent to persons of ordinary skill in the art reading this disclosure.

CLAIMS

What is claimed is:

1. A system comprising:

a first photovoltaic inverter that converts direct current (DC) generated by solar cells to alternating current (AC) that is provided at an AC output of the first photovoltaic inverter;

a step up transformer having a first low voltage winding on a low voltage side and a high voltage winding on a high voltage side, the low voltage winding being coupled to the photovoltaic inverter, and the high voltage winding being coupled to a utility grid; and

a first switch-fuse link comprising a first fuse and a first switch, the first switch-fuse link coupling the AC output of the first photovoltaic inverter to the first low voltage winding of the step up transformer through a contact of the first switch during a normal operation mode, the first switch-fuse link coupling the AC output of the first photovoltaic inverter to the first low voltage winding of the step up transformer through the first fuse during a maintenance mode.

2. The system of claim 1 wherein the first switch comprises a single-throw disconnect switch.

3. The system of claim 1 wherein the first fuse is coupled to the AC output of the first photovoltaic inverter and the first low voltage winding of the step up transformer in both the normal operation mode and the maintenance mode.

4. The system of claim 1 wherein the first switch comprises a double-throw transfer switch.

5. The system of claim 1 wherein the first switch-fuse link is installed within a protective enclosure that houses the step up transformer.

6. The system of claim 1 wherein the first switch has a first position that places the contact of the first switch in parallel with the first fuse during the normal operation mode and a second position that removes the contact of the first switch from being in parallel with the first fuse during the maintenance mode.

7. The system of claim 1 further comprising:

a second photovoltaic inverter that converts DC generated by solar cells to AC that is provided at an AC output of the second photovoltaic inverter; and

a second switch-fuse link comprising a second fuse and a second switch, the second switch-fuse link coupling the AC output of the second photovoltaic inverter to the second low voltage winding of the step up transformer through a contact of the second switch during the normal operation mode, the second switch-fuse link coupling the AC output of the second photovoltaic inverter to the second low voltage winding of the step up transformer through the second fuse during the maintenance mode.

8. The system of claim 7 wherein the first and second switches are ganged together to a lever, the lever having a first position that opens the first and second switches during the maintenance mode and a second position that closes the first and second switches during the normal operation mode.

9. The system of claim 7 wherein the first and second switches are ganged together to a lever, the lever having a first position that couples the contact of the first switch to the AC output of first photovoltaic inverter and to the first low voltage winding of the step up transformer and that couples the contact of the second switch to the AC output of the second photovoltaic inverter and the second low voltage winding of the step up transformer during the normal operation mode, and a second position that couples the first fuse to the AC output of the first photovoltaic inverter and to the first low voltage winding of the step up transformer and that couples the second fuse to the AC output of the second photovoltaic inverter and to the second low voltage winding of the step up transformer during the maintenance mode.

10. A system comprising:

a first photovoltaic inverter that converts direct current (DC) generated by solar cells to alternating current (AC) that is provided at an AC output of the first photovoltaic inverter;

a step up transformer having a first low voltage winding on a low voltage side and a high voltage winding on a high voltage side, the high voltage winding being coupled to a utility grid;

a first fuse; and

a first transfer switch having a first position and a second position, the first position of the first transfer switch coupling a first bus-bar through the transfer switch contact but not the first fuse to the AC output of the first photovoltaic inverter and to the first low voltage winding of the step up transformer, the second position of the first transfer switch coupling the first fuse through the transfer switch contact but not the first

bus-bar to the AC output of the first photovoltaic inverter and to the first low voltage winding of the step up transformer.

11. The system of claim 10 wherein the first switch comprises a double-throw transfer switch.

12. The system of claim 10 wherein the first fuse and the bus-bar are installed within a protective enclosure that houses the step up transformer.

13. The system of claim 10 further comprising:

a second photovoltaic inverter that converts DC generated by solar cells to AC that is provided at an AC output of the second photovoltaic inverter;

a second fuse; and

a second transfer switch having a first position and a second position, the first position of the second transfer switch coupling a second bus-bar but not the second fuse to the AC output of the second photovoltaic inverter and to the second low voltage winding of the step up transformer, the second position of the second transfer switch coupling the second fuse but not the second bus-bar to the AC output of the second photovoltaic inverter and to the second low voltage winding of the step up transformer.

14. The system of claim 10 wherein the first and second transfer switches are ganged together to a lever, the lever having a first position that couples first bus-bar to the AC output of first photovoltaic inverter and to the first low voltage winding of the step up transformer and that couples the second bus-bar to the AC output of the second photovoltaic inverter and to the second low voltage winding of the step up transformer during a normal operation mode, and a second position that couples the first fuse to the AC output of first photovoltaic inverter and to the first low voltage winding of the step up transformer and that couples the second fuse to the AC output of the second photovoltaic inverter and to the second low voltage winding of the step up transformer during a maintenance mode.

15. The system of claim 14 wherein the first transfer switch, the second transfer switch, the first bus-bar, and the second bus-bar are located within a protective enclosure that houses the step up transformer.

16. The system of claim 15 wherein the lever is located outside the protective enclosure that houses the step up transformer.

17. A method of performing maintenance on a photovoltaic inverter comprising:

powering OFF the photovoltaic inverter;

replacing a bus-bar that couples an alternating current (AC) output of the photovoltaic inverter to a low voltage winding of a step up transformer with a fuse;

powering ON the photovoltaic inverter; and

performing maintenance on the photovoltaic inverter while the photovoltaic inverter is powered ON and the fuse is in place instead of the bus-bar.

18. The method of claim 17 further comprising:

powering OFF the photovoltaic inverter after performing maintenance on the photovoltaic inverter;

replacing the fuse with the bus-bar; and

powering ON the photovoltaic inverter for normal operation with the bus-bar in place instead of the fuse.

19. The method of claim 17 further comprising:

disconnecting a high voltage side of the step up transformer prior to replacing the bus-bar with the fuse.

20. The method of claim 17 wherein the method is performed for another photovoltaic inverter in a same inverter station as the photovoltaic inverter.

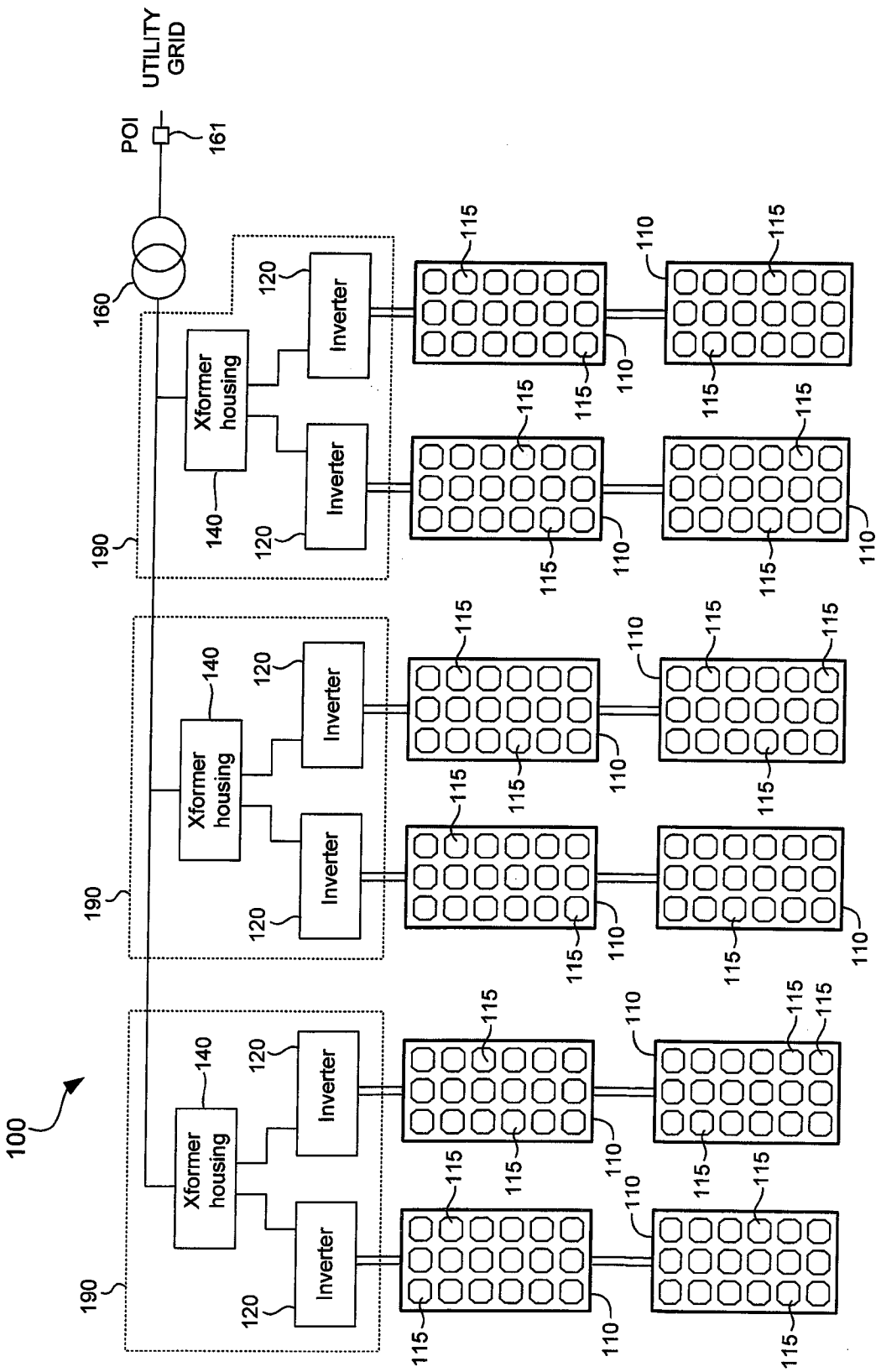

UTILITY GRID
POI
161
160
100
190
Xformer housing
140
Inverter
120
115
110

FIG. 1

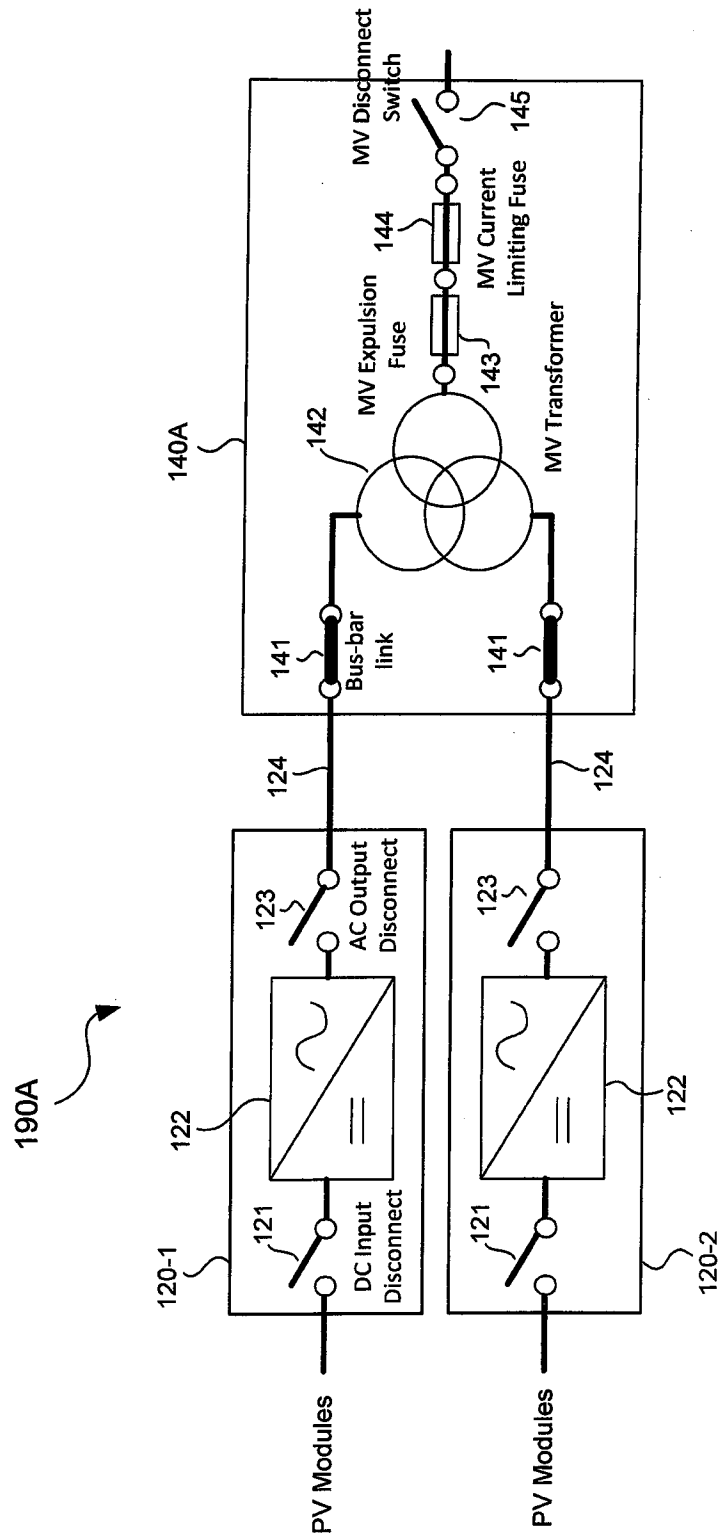

190A
140A
120-1
120-2
PV Modules
PV Modules
DC Input Disconnect
AC Output Disconnect
Bus-bar link
MV Expulsion Fuse
MV Current Limiting Fuse
MV Disconnect Switch
MV Transformer
121
122
123
124
141
142
143
144
145

FIG. 2

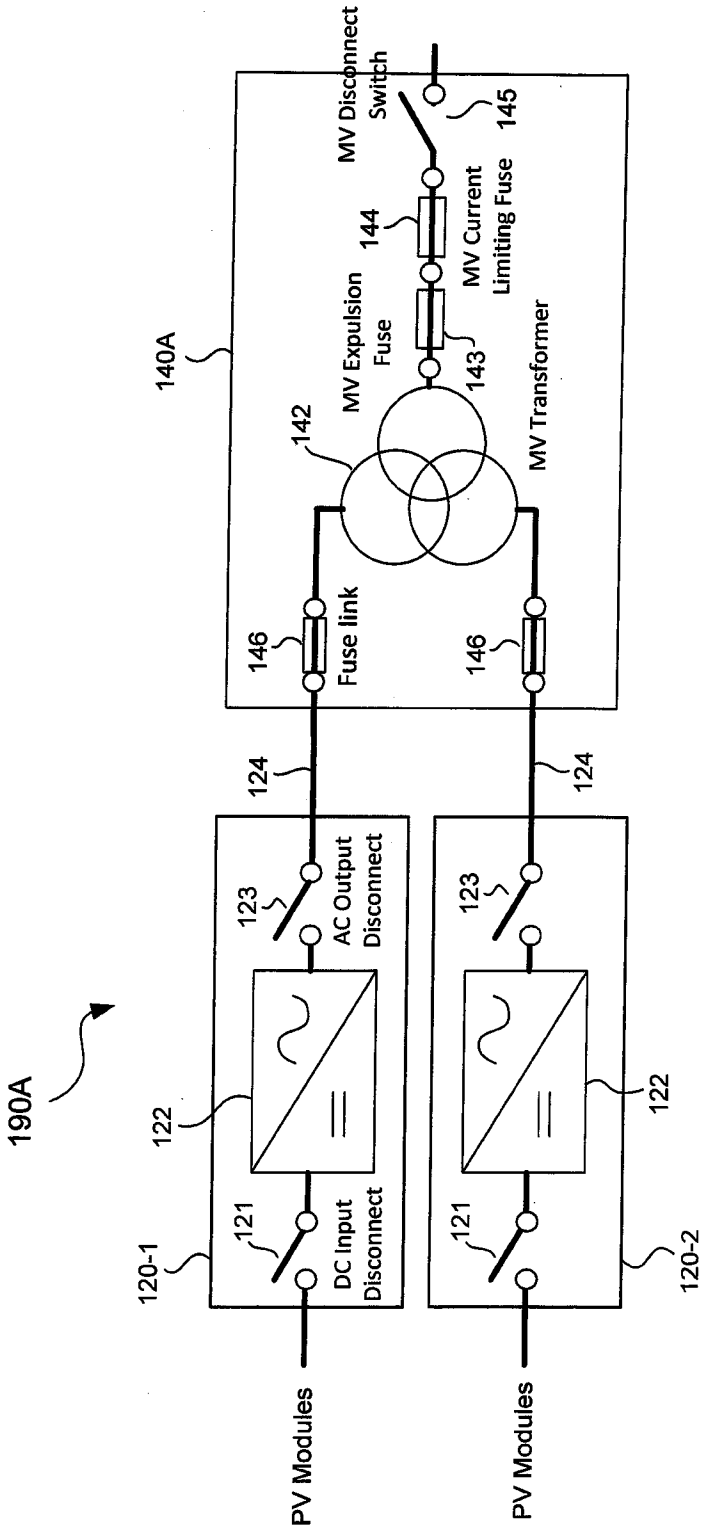

190A
140A
MV Disconnect Switch
145
144
MV Current Limiting Fuse
MV Expulsion Fuse
143
142
MV Transformer
146
Fuse link
146
124
124
123
AC Output Disconnect
123
122
122
121
DC Input Disconnect
121
120-1
120-2
PV Modules
PV Modules

FIG. 3

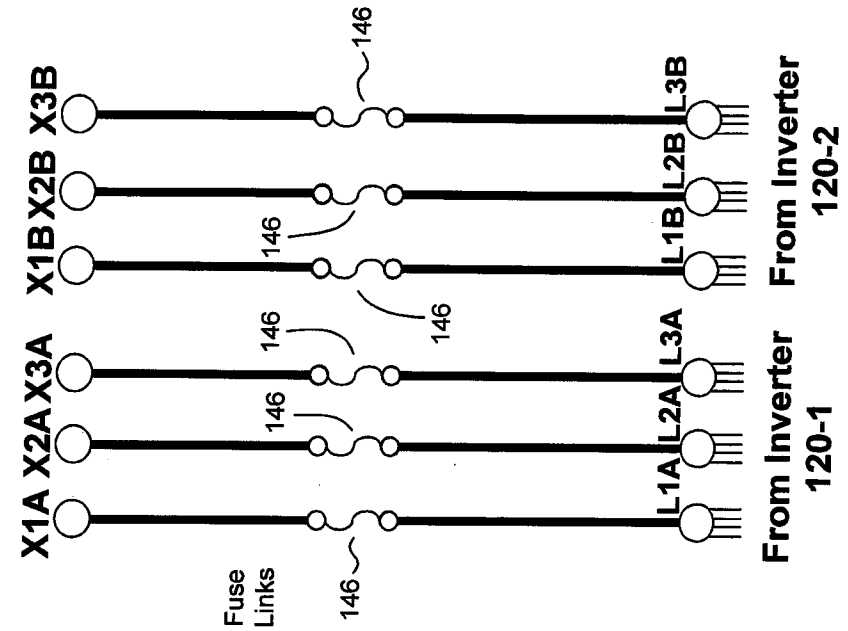

X1A
X2A
X3A
X1B
X2B
X3B
Fuse Links
146
From Inverter 120-1
From Inverter 120-2
L1A
L2A
L3A
L1B
L2B
L3B

FIG. 5

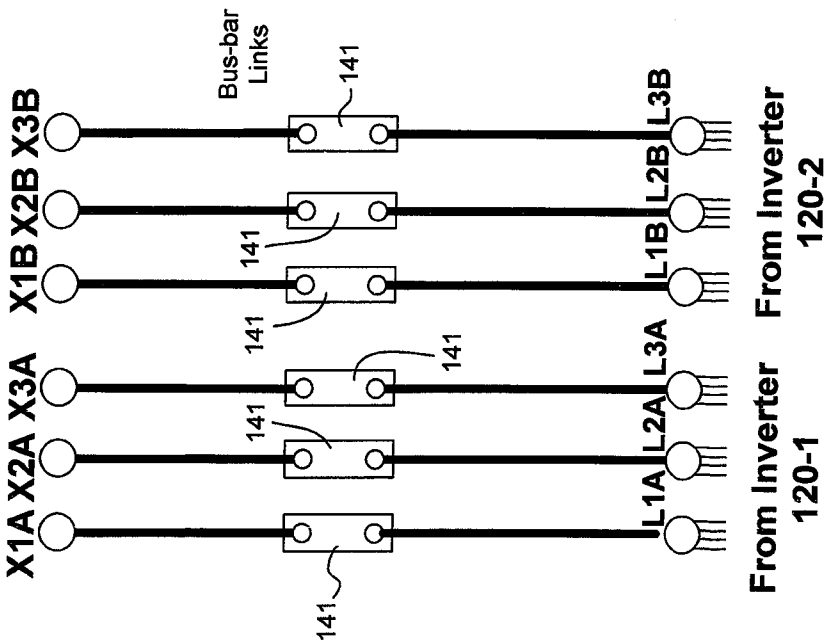

X1A
X2A
X3A
X1B
X2B
X3B
Bus-bar Links
141
From Inverter 120-1
From Inverter 120-2
L1A
L2A
L3A
L1B
L2B
L3B

FIG. 4

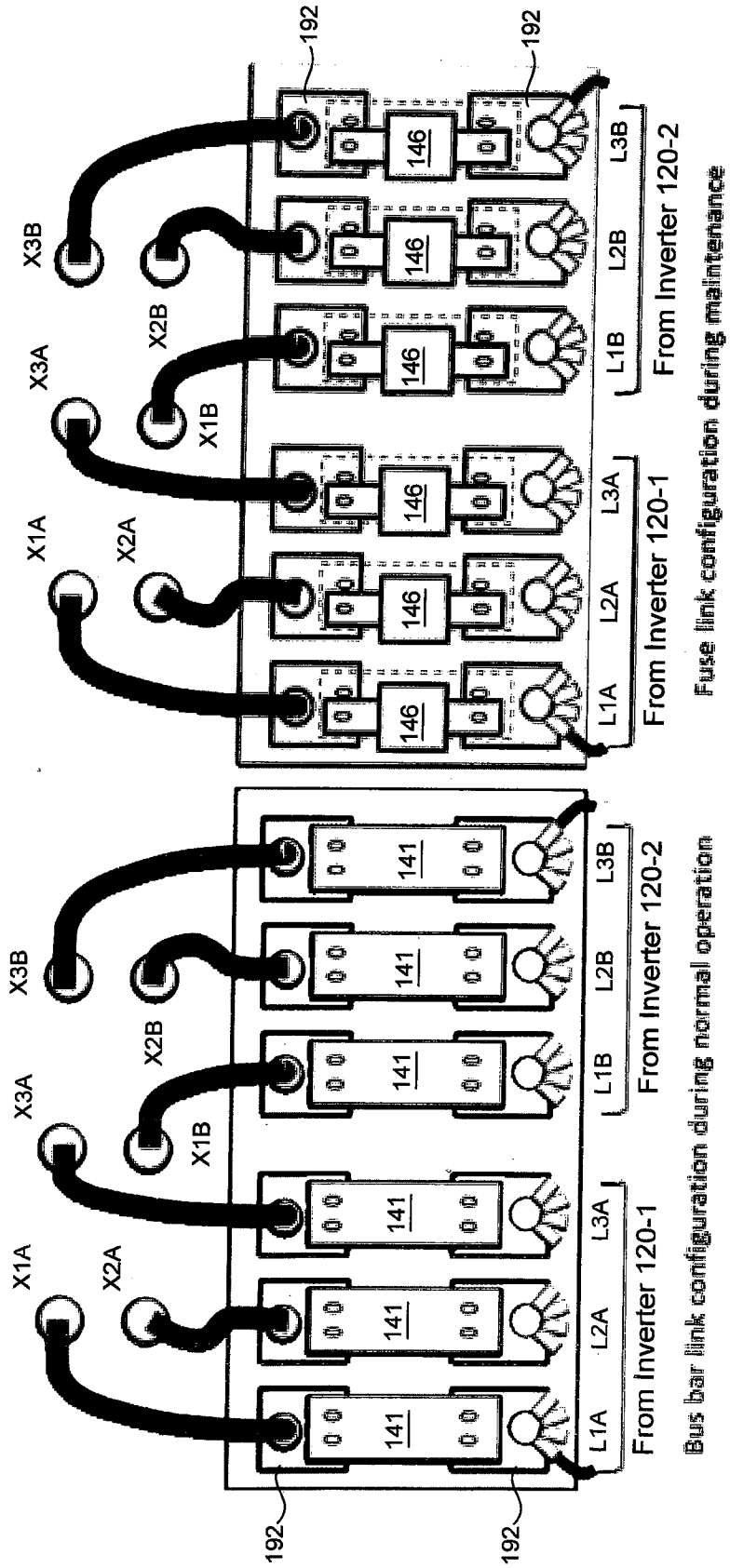

Bus bar link configuration during normal operation
From Inverter 120-1
From Inverter 120-2
L1A
L2A
L3A
L1B
L2B
L3B
X1A
X2A
X3A
X1B
X2B
X3B
141
146
192

FIG. 6

Fuse link configuration during maintenance
From Inverter 120-1
From Inverter 120-2
L1A
L2A
L3A
L1B
L2B
L3B
X1A
X2A
X3A
X1B
X2B
X3B
146
192

FIG. 7

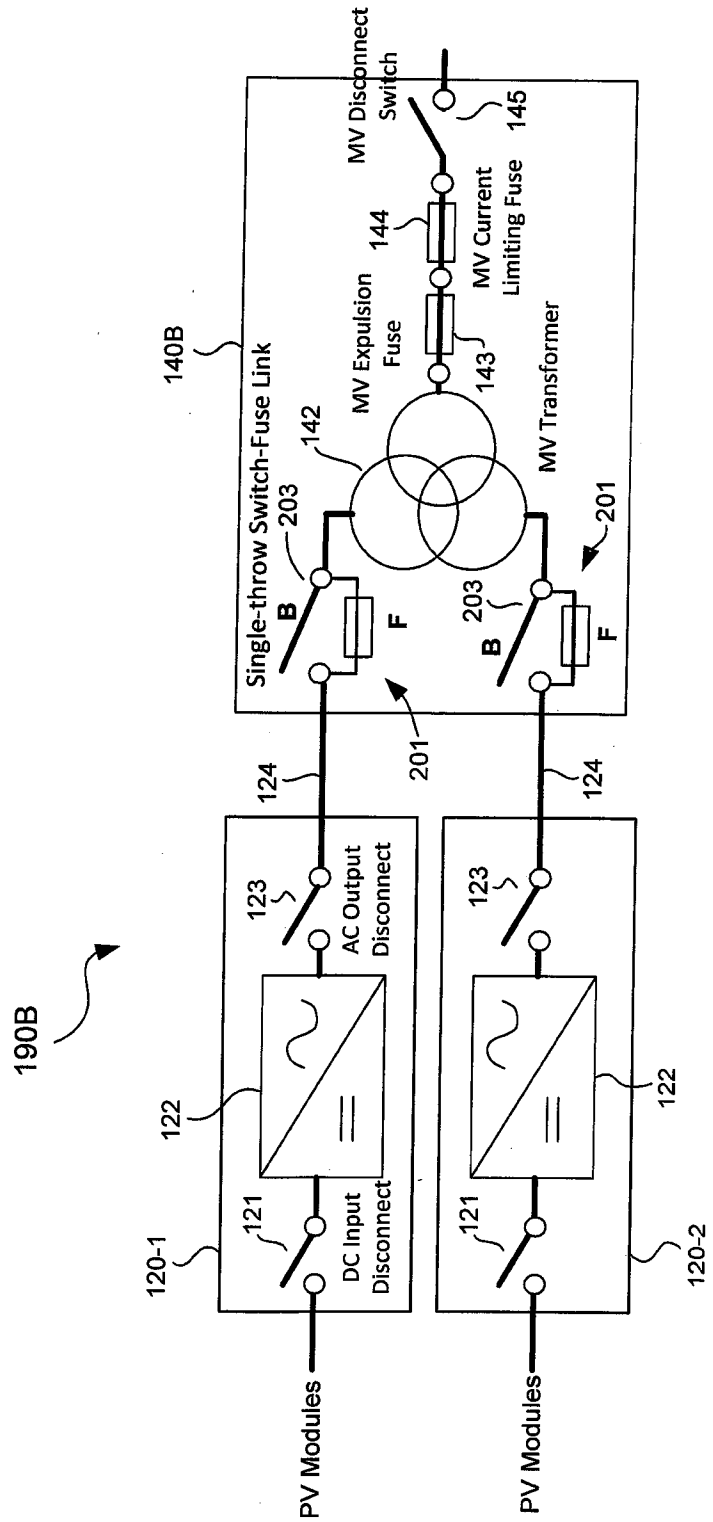

190B
140B
Single-throw Switch-Fuse Link
MV Disconnect Switch
145
MV Current Limiting Fuse
144
MV Expulsion Fuse
143
MV Transformer
142
203
201
B
F
124
123
AC Output Disconnect
122
121
DC Input Disconnect
120-1
120-2
PV Modules

FIG. 8

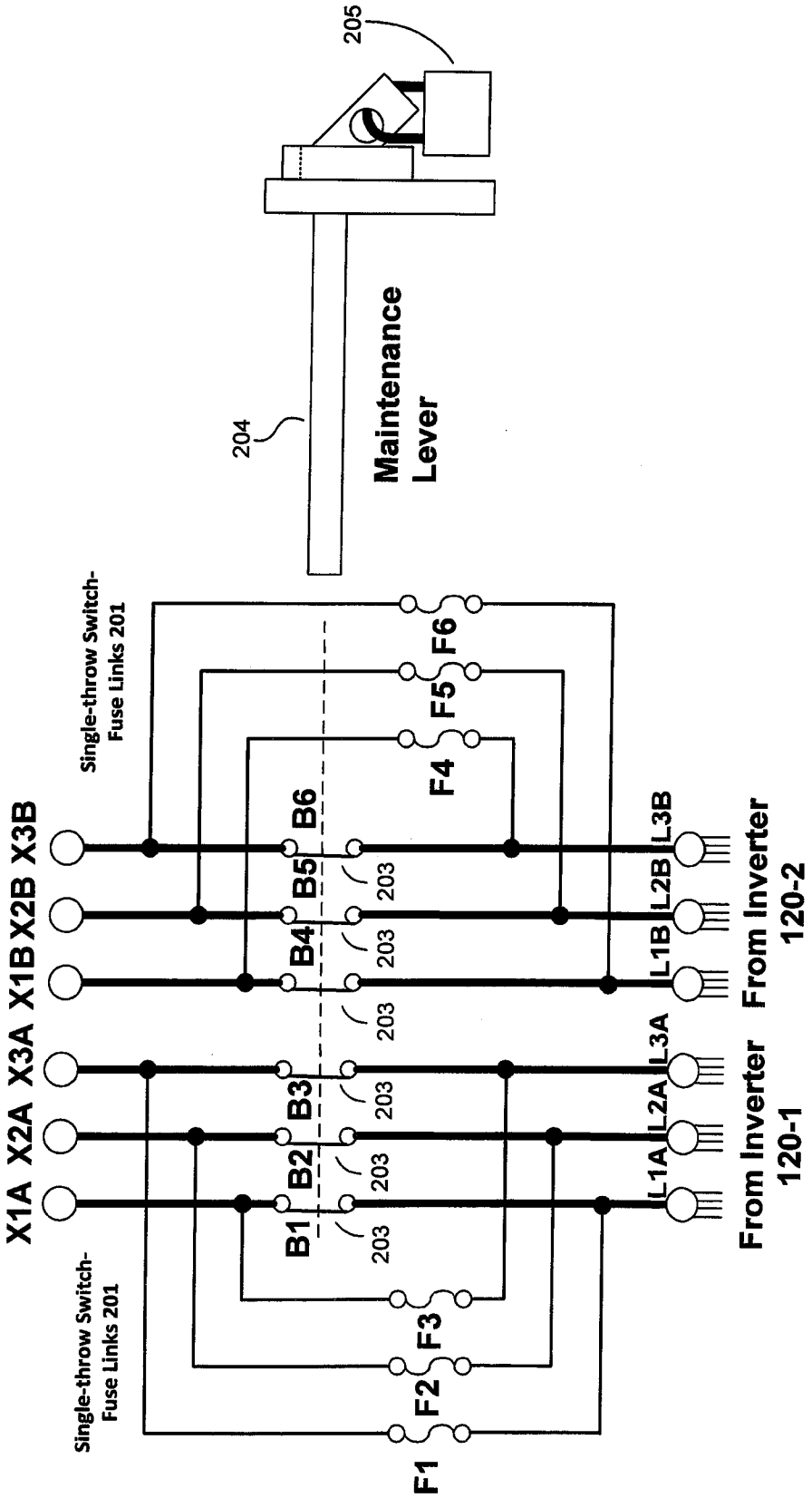

205
204
Maintenance Lever
Single-throw Switch-Fuse Links 201
F6
F5
F4
F3
F2
F1
B6
B5
B4
B3
B2
B1
203
X1A X2A X3A X1B X2B X3B
L1A L2A L3A L1B L2B L3B
From Inverter 120-1
From Inverter 120-2

FIG. 9

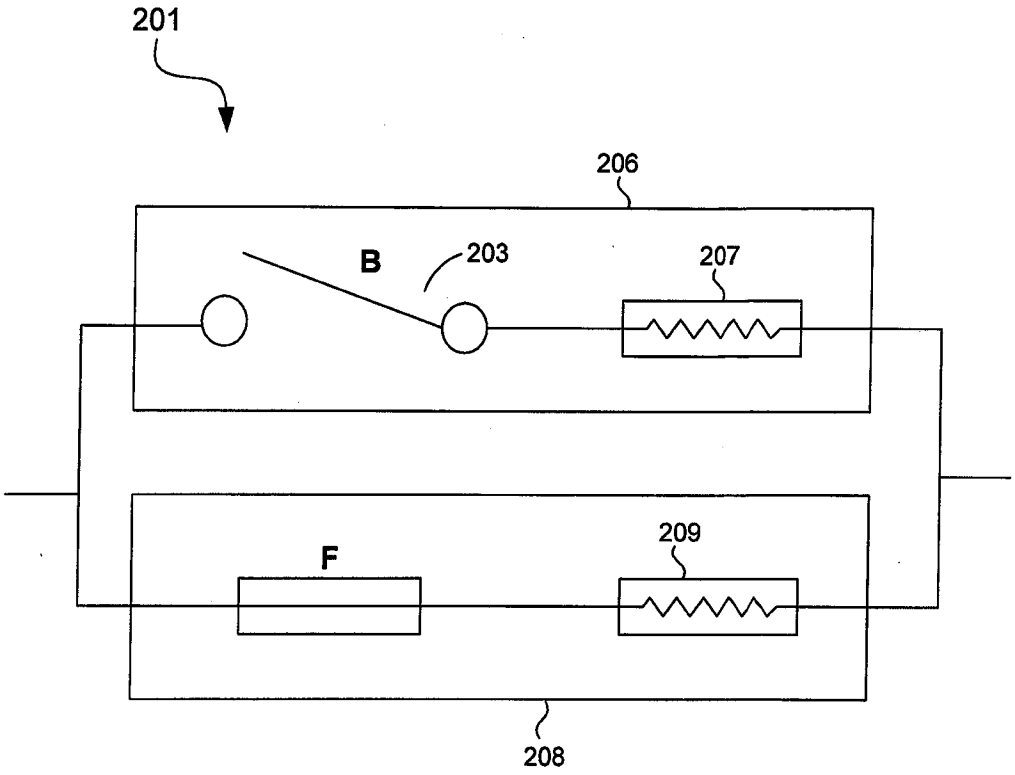


FIG. 10

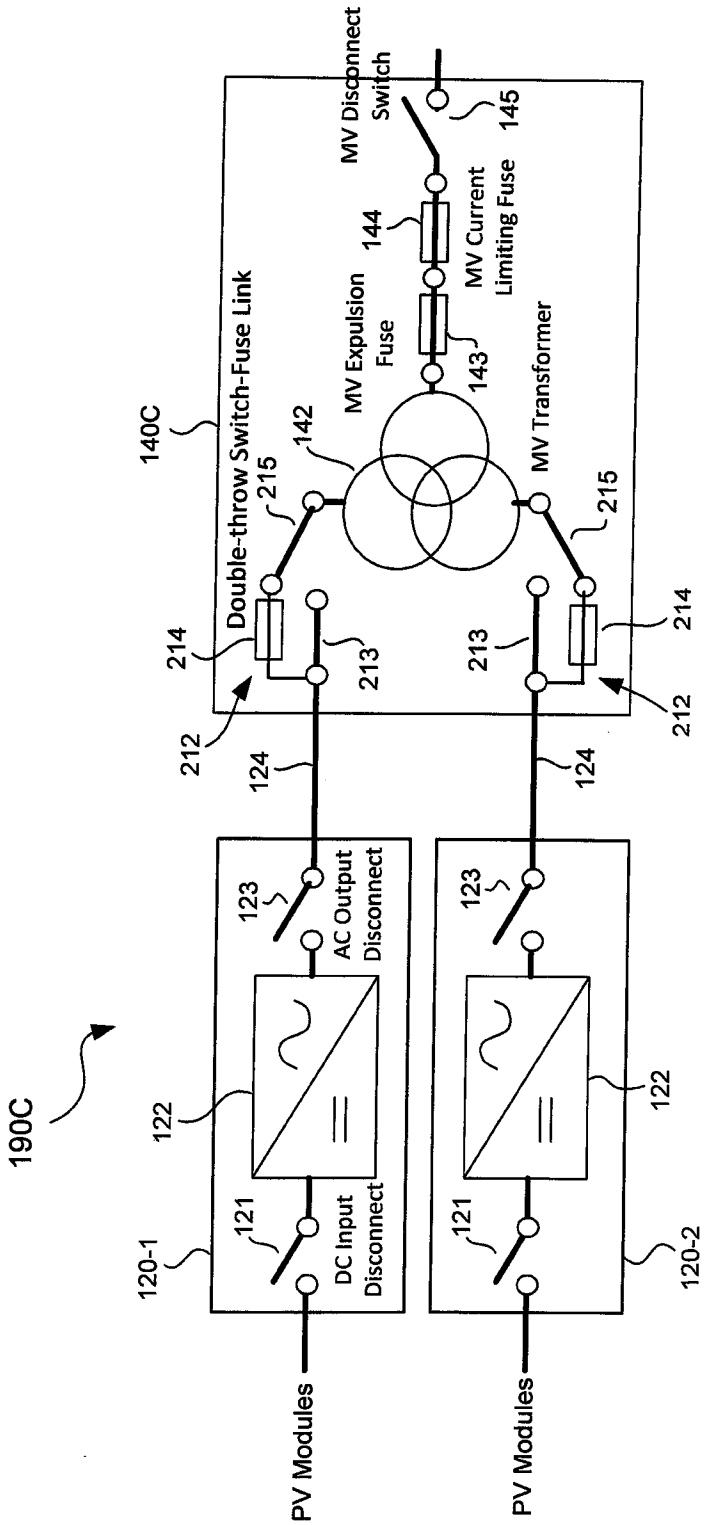

190C
140C
Double-throw Switch-Fuse Link
MV Disconnect Switch
145
MV Current Limiting Fuse
144
MV Expulsion Fuse
143
MV Transformer
142
215
214
213
212
124
123
AC Output Disconnect
122
121
DC Input Disconnect
120-1
120-2
PV Modules

FIG. 11

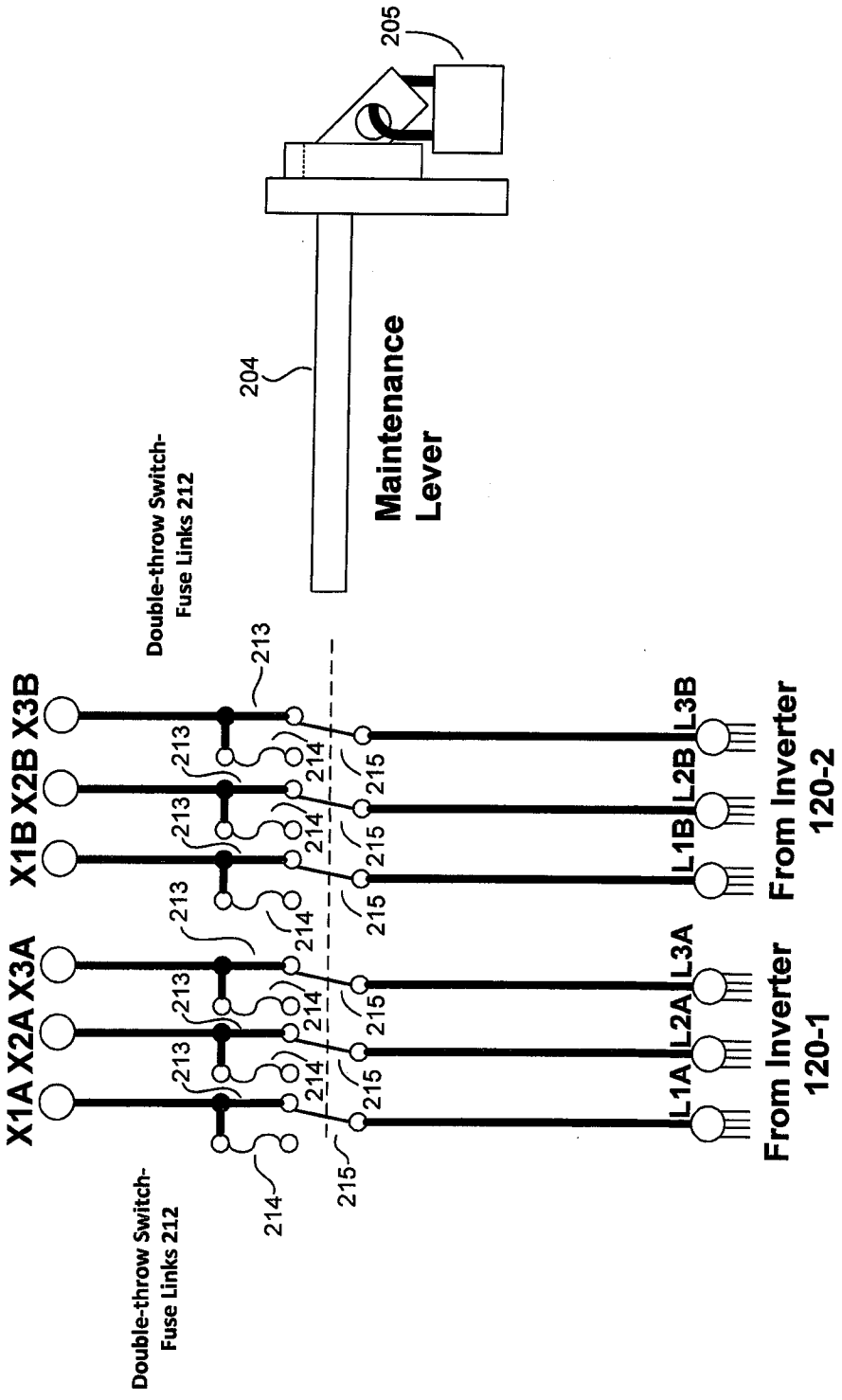

205
204
Maintenance Lever
Double-throw Switch-Fuse Links 212
213
214
215
X1A X2A X3A
X1B X2B X3B
L1A L2A L3A
L1B L2B L3B
From Inverter 120-1
From Inverter 120-2
Double-throw Switch-Fuse Links 212

FIG. 12

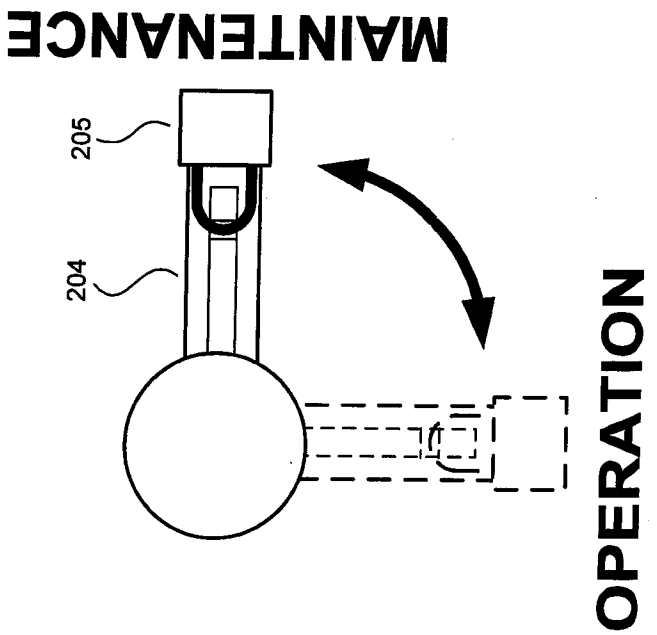

MAINTENANCE
205
204
OPERATION

FIG. 14

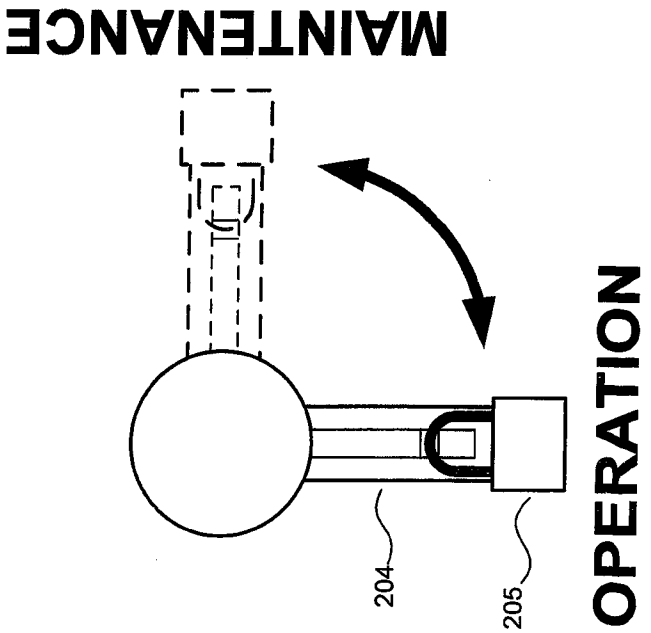

MAINTENANCE
204
205
OPERATION

FIG. 13

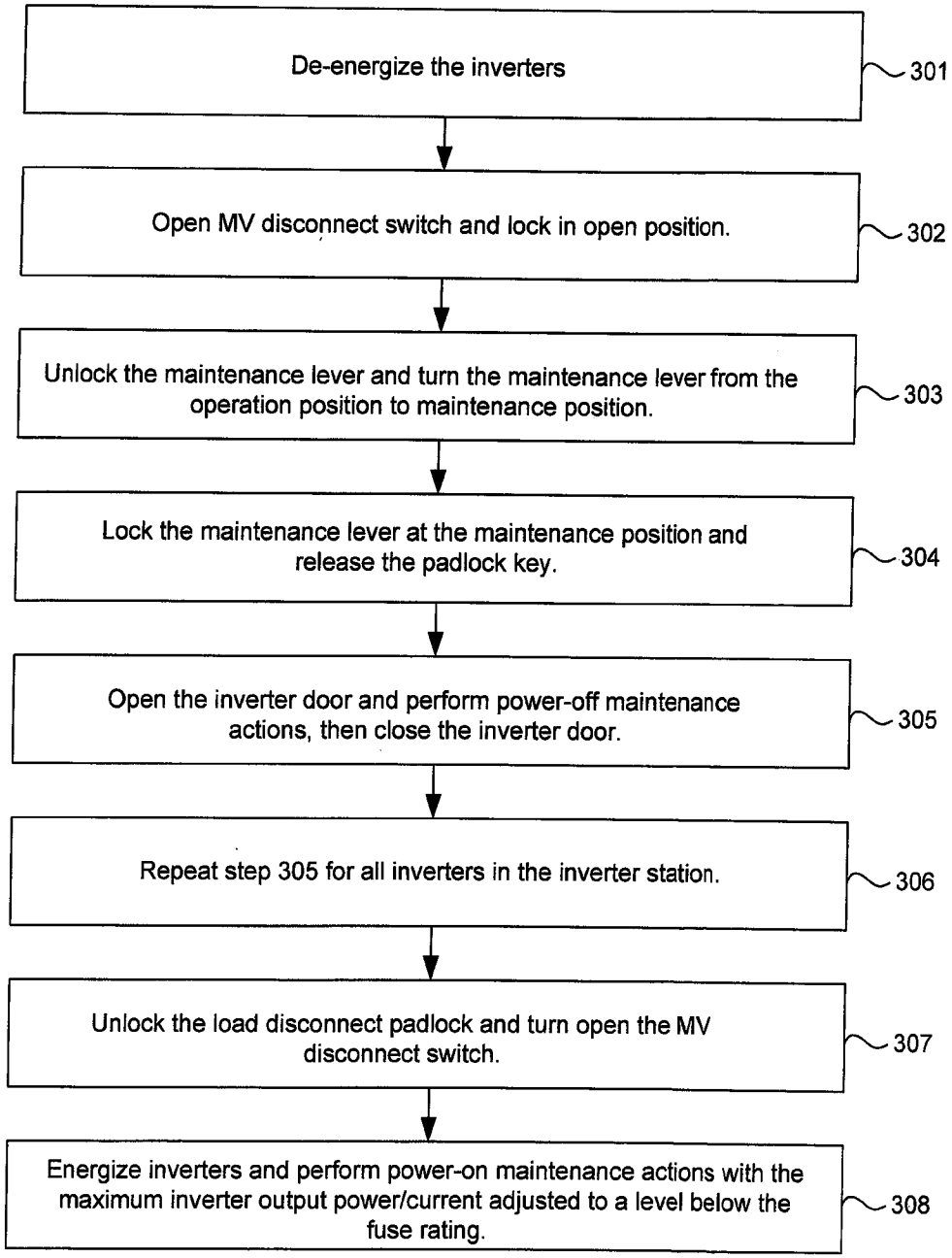

De-energize the inverters
301
Open MV disconnect switch and lock in open position.
302
Unlock the maintenance lever and turn the maintenance lever from the operation position to maintenance position.
303
Lock the maintenance lever at the maintenance position and release the padlock key.
304
Open the inverter door and perform power-off maintenance actions, then close the inverter door.
305
Repeat step 305 for all inverters in the inverter station.
306
Unlock the load disconnect padlock and turn open the MV disconnect switch.
307
Energize inverters and perform power-on maintenance actions with the maximum inverter output power/current adjusted to a level below the fuse rating.
308

FIG. 15

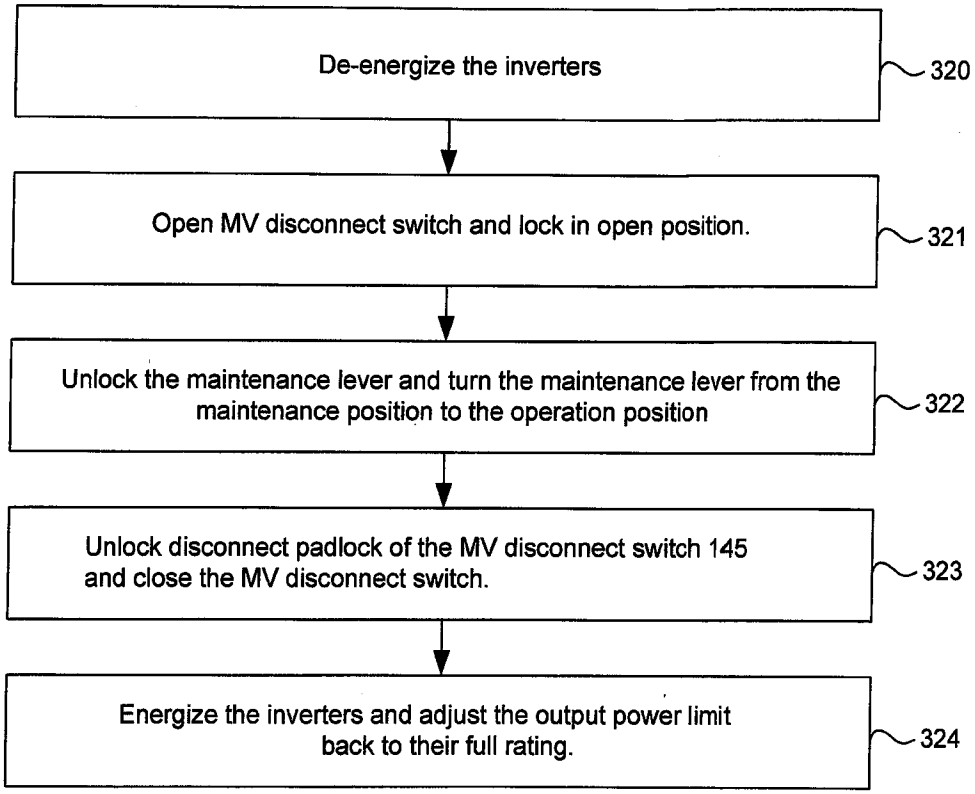

De-energize the inverters
320
Open MV disconnect switch and lock in open position.
321
Unlock the maintenance lever and turn the maintenance lever from the maintenance position to the operation position
322
Unlock disconnect padlock of the MV disconnect switch 145 and close the MV disconnect switch.
323
Energize the inverters and adjust the output power limit back to their full rating.
324

FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US12/70384

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01L 31/042 (2013.01)
USPC - 136/244; 702/58
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)
IPC(8): H01L 31/042 (2013.01)
USPC: 136/244; 702/58

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)
MicroPatent (US-G, US-A, EP-A, EP-B, WO, JP-bib, DE-C,B, DE-A, DE-T, DE-U, GB-A, FR-A); Google Scholar, IEEE, DialogPro (Derwent, INSPEC, NTIS, PASCAL, Current Contents Search, Dissertation Abstracts Online, Inside Conferences); Search terms: Solar, photovoltaic, inverter, transformer, switch, fuse, bus

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2011/0273129 A1 (COE, C. J. et al.) November 10, 2011, Figures 1 and 2, paragraphs [0019], [0020], [0055].	1-16
Y	US 3,526,778 A1 (CROCKER, L. B. et al.) September 1, 1970, column 5, lines 1-10, column 6, lines 1-20.	4, 10-16
Y	WO 95/31030 A1 (LECOURT, W. N.) November 16, 1995, Figure 7, page 1, lines 17-27, page 2, lines 11-17, page 43, lines 17-29, page 44, lines 1-8, page 45, lines 8-29, page 46, lines 1-7.	1-9, 14-16
Y	US 4,362,950 A (TURNER, J. S.) December 7, 1982, column 3, lines 18-23, lines 45-56.	2, 6

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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Date of the actual completion of the international search	Date of mailing of the international search report
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