(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 July 2010 (08.07.2010)

PCT

(10) International Publication Number
WO 2010/078303 A2

(51) International Patent Classification:
H01L 31/04 (2006.01)

(21) International Application Number:
PCT/US2009/069658

(22) International Filing Date:
29 December 2009 (29.12.2009)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/141,033 29 December 2008 (29.12.2008) US

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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

— *of inventorship (Rule 4.17(iv))*

[Continued on next page]

(54) **Title**: ELECTRICAL SAFETY SHUTOFF SYSTEM AND DEVICES FOR PHOTOVOLTAIC MODULES

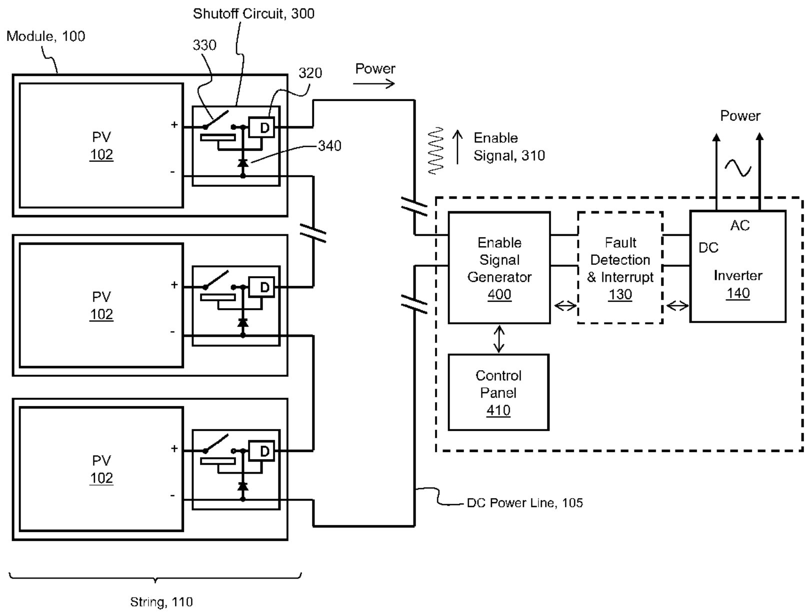

Fig. 2

(57) **Abstract**: An electrical safety shutoff system and devices for disabling electrical power output from individual photovoltaic modules in a photovoltaic array, including one or more shutoff circuits, each of which can disable electrical power output from an associated module; and at least one enable signal generator that transmits a signal to the shutoff circuits to enable power output; wherein module power output is disabled in the absence of the enable signal.

WO 2010/078303 A2

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

ATTORNEY DOCKET NO.: ATON003WO

PCT APPLICATION FOR

For

ELECTRICAL SAFETY SHUTOFF SYSTEM AND DEVICES FOR PHOTOVOLTAIC MODULES

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ELECTRICAL SAFETY SHUTOFF SYSTEM AND DEVICES FOR PHOTOVOLTAIC MODULES

RELATED APPLICATION DATA

[001] The present application claims priority to U.S. Provisional Patent Application Ser. No. 61/141,033, filed Dec. 29, 2008, which is incorporated herein by reference.

FIELD OF THE INVENTION

[002] The invention relates to an electrical safety shutoff system and associated devices that can disable the electrical output of individual photovoltaic modules, also known as solar panels, in a photovoltaic array.

BACKGROUND OF THE INVENTION

[003] Photovoltaic (PV) solar energy generation systems use photovoltaic cells (“solar cells”) to produce electricity from sunlight. They are typically implemented as arrays of individual panels, referred to as PV modules, wherein each module contains multiple cells. One difficulty with PV systems is that, whenever sunlight is incident on a PV array, the modules will be energized and cannot be turned off. This situation presents certain safety problems.

[004] **FIGURE 1** illustrates the typical layout of a PV array, with optional elements indicated by dashed lines. Individual modules **100** (of which only one is labeled) are connected in series to form one or more strings **110** having desired output voltage; multiple strings **110** are combined in parallel at one or more string-combiners **120** to aggregate power; and the outputs of the one or more string combiners **120** are fed to one or more inverters **140** which convert the direct current (DC) output of the PV modules **100** to alternating current (AC), which is then provided to a load or utility grid. The series connection of multiple modules **100** is used to achieve high voltages that minimize resistive losses in current-carrying wires comprising the DC power lines **105** which interconnect the system elements.

[005] Since the operating voltage of a typical PV array can be hundreds of volts or even up to a thousand volts, electric shock hazards involving the array are a concern. Workers assembling or performing maintenance on a high-voltage PV array must take appropriate precautions. Once an array is constructed, visitors to the site are at potential risk of electric shock if they come into contact with terminals or wiring having defective insulation. Of increasing concern is that in the event of a fire at a PV array site, firefighting personnel are placed at risk by their inability to deactivate the PV system and remove the electrical hazard. The risk of electric shock to firefighters is increased if water or other liquids are sprayed on the PV system, since these may form an electrically conductive path.

[006] Various approaches have been employed to address these problems.

[007] One category of approach ("array short-circuit") involves implementing a safety system including a switching device that can electrically short-circuit the positive and negative DC outputs of the PV array to each other in order to bring the array voltage to zero, thereby removing the hazard of electric shock when the switching device is activated.

[008] Another category of approach ("array disconnect") involves implementing a switching device that can disconnect the array from the inverter **140** and load, creating an open circuit that brings the array current to zero and removes electrical hazards from the inverter and load portions of the circuit.

[009] A shortcoming of both array short-circuit and array disconnect methods is that they disable only a portion of the PV array. In an array disconnect system, only the portion of the array located between the switching element and the inverter or load is disabled, while hazards persist in the remainder of the array. While an array short-circuit device appears to disable the entire PV system, it is only effective if all electrical interconnects are functioning properly. If one section of the array becomes disconnected due to interconnect failures or wiring disruption, that section will not be shorted and will still present an electrical hazard.

[0010] Another system for electrical disconnection uses thermally activated switches that can short-circuit portions of the array if an over-temperature condition is detected. However, this system only responds to thermal triggers. Furthermore, with this system it is difficult for personnel to know with certainty when the PV array, or any portion of it, has been disabled.

[0011] A significant potential hazard in a PV array is electrical arcing, particularly because PV systems use DC rather than AC electricity. In general, arc faults in an electrical system can be of several types. Series arcs occur when normal current flow is interrupted at failed or improper interconnections, while parallel arcs occur when a portion of the circuit is short-circuited due to failed electrical isolation. Ground faults are a special case of parallel arcs. Any of these faults may create hazards to personnel, damage the electrical system, or start a fire. In particular, a series arc occurring at a poor, intermittent, or corroded connection or at a broken wire will have increased resistance which causes heat dissipation and increased temperatures. This often accelerates deterioration until a failure occurs, sometimes violently.

[0012] Analogous to other electrical systems, arc detection circuitry can be implemented for PV arrays, as indicated by the optional fault detection and interrupt **130** in **Figure 1**. For example, Haeberlin and Real outline an approach to arc detection in “Arc Detector for Remote Detection of Dangerous Arcs on the DC Side of PV Plants” in the proceedings of the 22nd European Photovoltaic Solar Energy Conference, Milano, Italy, September 2007. They describe a system which, upon detecting a series arc in a PV array, triggers an array disconnect switch, possibly integrated within an inverter, thereby removing the load and extinguishing the arc. The system may also separately detect parallel arcs and subsequently trigger an array short-circuit switch to bring the voltage to zero and extinguish the arc.

[0013] A shortcoming of this type of system is that it requires the ability to distinguish between series and parallel arcs, which require different countermeasures. Furthermore, applying the wrong countermeasure can worsen the problem. In addition, either array short-circuit or array disconnect may result in disabling only a portion of the system, as already discussed.

[0014] More recently, various products have been introduced which include the capability to individually disconnect each module **100** in a PV array by activating a switch incorporated into the module **100** via a control signal. For example, this feature has been incorporated within such products as micro-inverters, power optimizers, and monitoring systems, designed to be installed on individual PV modules **100**. Such systems permit individual modules **100** to be disconnected, thus limiting any electrical hazard. However, if systems rely on processing of a control signal by a controller device within the module **100** in order to activate the disconnect switch, their reliability may not be adequate for safety purposes.

[0015] In view of the problems discussed in the foregoing, there exists a need for an improved method to disable the electrical output of an array of PV modules **100**.

BRIEF SUMMARY OF THE INVENTION

[0016] The invention provides a method, system, and associated devices that can be used to disable the electrical output of an array of PV modules **100**. It is an object of the invention to provide a system that can confine electrical power within individual PV modules **100** and eliminate hazards at wiring and interconnections, and to do so with greater reliability and lower cost than prior approaches.

[0017] It is an advantage of the disclosed subject matter to reduce or eliminate electrical shock hazards related to PV modules **100** and arrays.

[0018] Another advantage of the disclosed subject matter is to disable a particular module, sub-array, array, or entire system in response to user control, an electrical anomaly, or other emergency.

[0019] Yet another advantage of the disclosed subject matter is to reduce or eliminate electrical shock hazards independent of malfunctioning electrical interconnects.

[0020] An additional advantage of the disclosed subject matter is to reduce or eliminate hazards attributable to arcing faults.

[0021] **FIGURE 2** depicts an overview of a shutoff system according to the disclosed subject matter. Labels on some repeated elements are omitted for clarity, and dashed lines indicate optional elements or combinations of elements. The system consists of individual "shutoff circuits" **300**, each of which can disable the electrical output of a single module **100**; and one or more "enable signal generators" **400**, each of which transmits signals to the shutoff circuits **300** to enable electrical power output from their associated modules **100**. The shutoff circuits **300** are designed such that, in the absence of an enable signal **310**, the shutoff circuits **300** revert to a safe state in which the module **100** power is disabled. Preferably, the shutoff circuits **300** are integrated into the assemblies or the junction boxes of their associated modules **100**. The enable signal **310** is transmitted via the DC power lines **105** of the PV array, such that no additional wiring to the modules is required beyond the normal interconnections. For simplicity **Figure 2** depicts only one string **110**, but it should be understood that the system could contain a plurality of strings **110**.

[0022] Each shutoff circuit **300** contains at least a switch element **330** and a signal detector **320**. The switch element **330** is arranged such that in its normal state, the module **100** power output is disabled. The signal detector **320** detects the presence of the enable signal **310** and, if the enable signal **310** is present, causes the switch element **330** to change to a state that enables module **100** power output. The shutoff circuit **300** may be implemented as a combination of discrete devices or integrated substantially into a single device or integrated circuit.

[0023] In one embodiment of the shutoff circuit **300**, which is denoted "circuit interrupter," a normally open switch element **330** is placed in series with the PV generating capacity **102** of the module **100**, such that in the default state, the circuit is interrupted. The signal detector **320** causes the switch **330** to close to complete the circuit when an enable signal **310** is detected. In another embodiment of the shutoff circuit **301**, denoted "circuit shorter," (NOTE: 300 refers to the shutoff circuit of the circuit interrupter embodiment whereas 301 refers to the shutoff circuit of the circuit shorter embodiment; however, on the figures, 300 and 301 refer to the same diagram element and for clarity 301 has been omitted in some figures) a normally closed switch element **331** (NOTE: 330 refers to the switch of the circuit interrupter embodiment whereas 331 refers to the switch of the circuit shorter embodiment; however, on the figures, 330 and 331 refer to the same diagram element and for clarity 331 has been omitted in some figures) is placed in parallel with the PV generating capacity **102** such that in the default state, the circuit is shorted. A signal detector **321** (NOTE: 320 refers to the signal detector of the circuit interrupter embodiment whereas 321 refers to the signal detector of the circuit shorter embodiment; however, on the figures, 320 and 321 refer to the same diagram element and for clarity 321 has been omitted in some figures) opens the switch **331** when the enable signal **310** is detected. Hereafter the shutoff circuit, signal detector, and switch of the circuit interrupter versus circuit shorter embodiments (**300**, **320**, **330**) and (**301**, **321**, **331**), respectively, are understood to be interchangeable where the context does not distinguish between one and the other.

[0024] In one embodiment, the shutoff circuit **300** is passive, in the sense of requiring no independent power source and containing no logic elements. The signal detector **300** changes the state of the switch element **330** using only energy derived from the enable signal **310**.

[0025] In another embodiment, the shutoff circuit **300** is powered by its associated module **100**, and uses this power to amplify the signal detection and activate the switch element **330**.

[0026] In still another embodiment, the shutoff circuit **300** is powered by its associated module and also contains a controller **360** (not shown) that can control the switch element **330**. In this case, for example, the controller **360** (not shown) could cause the module **100** power output to be disabled even when the enable signal **310** is present.

[0027] In yet another embodiment, the shutoff circuit **300** includes both a controller **360** (not shown) and sensing elements (**370** (not shown), **371** (not shown)) with which the controller **360** (not shown) can detect arc faults or ground faults in its associated module **100,** and the controller **360** can cause the switch element **330** to disable module **100** power output in order to protect against detected faults.

[0028] Each enable signal generator **400** generates an enable signal **310** that, when detected by the shutoff circuits **300**, will enable module **100** power output. The enable signal **310** may be, for example, a high-frequency AC current or voltage. In one embodiment, the enable signal **310** is transmitted continuously in order to maintain module **100** power output. In another embodiment, the enable signal **310** is transmitted at regular intervals, and module **100** power output is disabled if the enable signal **310** is not detected by the shutoff circuit **300** within a pre-determined time. In one embodiment, the enable signal **310** may be modulated in order to encode information, which may be received by a controller **360** (not shown) within a shutoff circuit **300** or by another device. Such information could include, for example, instructions to enable or disable the power output of a particular module **100**.

[0029] For small PV arrays, only a single enable signal generator **400** is required. For larger arrays, multiple enable signal generators **400** may be used. These may be combined in a master-slave relationship.

[0030] The enable signal generator **400** includes a power supply **430** (not shown) for generating the enable signal **310**. In one embodiment, the power supply **430** (not shown) derives power from a power source external to the PV array, such as an electric grid. In another embodiment, power is derived directly from the PV array. In either case, the enable signal generator **400** may include an energy storage device **432** (not shown) such as a battery, to facilitate starting the signal generation without the external power source.

[0031] The enable signal generator **400** may contain a disconnect switch **444** (not shown) to remove the enable signal **310** from the PV array, thus shutting off the array. It may also shut off the array in response to control signals from other equipment, such as inverters **140,** fault detection systems **130**, or other devices.

[0032] Enable signal generators **400** may be integrated with other components of the PV array, such as inverters **140** and/or string combiners (**120, 121**).

[0033] These and other aspects of the disclosed subject matter, as well as additional novel features, will be apparent from the description provided herein. The intent of this summary is not to be a comprehensive description of the claimed subject matter, but rather to provide a short overview of some of the subject matter's functionality. Other systems, methods, features and advantages here provided will become apparent to one with skill in the art upon examination of the following **FIGUREs** and detailed description. It is intended that all such additional systems, methods, features and advantages that are included within this description, be within the scope of the accompanying claims.

BRIEF DESCRIPTIONS OF THE DRAWINGS

[0034] The novel features believed characteristic of the invention will be set forth in the claims. The invention itself, however, as well as a preferred mode of use, further objectives, and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

[0035] **FIGURE 1** depicts the typical layout of a photovoltaic array, including multiple parallel strings of series-connected PV modules, according to the prior art. Dashed lines indicate optional elements or combinations of elements.

[0036] **FIGURE 2** depicts a schematic diagram of a PV array incorporating a shutoff system according to the disclosed subject matter. Only one of a potential plurality of module strings is depicted. Dashed lines indicate optional elements or combinations of elements.

[0037] **FIGURE 3** depicts a schematic diagram of a PV array incorporating a safety shutoff system according to the disclosed subject matter, in which multiple enable signal generators are used to enable modules in multiple PV sub-arrays. Dashed lines indicate optional elements or combinations of elements.

[0038] **FIGURE 4** depicts a comparison of voltages along a PV module string with circuits enabled versus disabled when using shutoff circuits in the circuit interrupter embodiment.

[0039] **FIGURE 5** depicts the functional elements of a shutoff circuit in the circuit interrupter embodiment. Dashed lines indicate optional elements or combinations of elements.

[0040] **FIGURE 6** depicts an electrical schematic of a simple exemplary implementation of a shutoff circuit in the circuit interrupter embodiment.

[0041] **FIGURE 7** depicts an electrical schematic of a second exemplary implementation of a shutoff circuit, in which power from the associated PV module is used to amplify detection of the enable signal.

[0042] **FIGURE 8** depicts the functional elements of a shutoff circuit device in the circuit shorter embodiment. Dashed lines indicate optional elements or combinations of elements.

[0043] **FIGURE 9** depicts a comparison of voltages along a PV module string with circuits enabled versus disabled when using shutoff circuits in the circuit shorter embodiment.

[0044] **FIGURE 10** depicts functional elements of an enable signal generator. Dashed lines indicate optional elements or combinations of elements.

[0045] In the figures, like elements should be understood to represent like elements, even though reference labels are omitted on some instances of a repeated element, for simplicity.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0046] Although described with particular reference to disabling power output from photovoltaic modules, those with skill in the arts will recognize that the disclosed embodiments have relevance to a wide variety of areas in addition to those specific examples described below.

[0047] All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

Overview

[0048] **Figure 2** depicts a PV array incorporating a module-level shutoff system according to the disclosed subject matter. Dashed lines indicate optional elements and combinations of elements. The figure depicts only a single string **110**, but it should be understood that multiple strings **110** could be present and combined at a string combiner (**120**, **121**), which is not shown.

[0049] As shown schematically in **Figure 2**, a shutoff circuit **300** is associated with each PV module **100**. Preferably, it is incorporated within the module **100** assembly, such as within the junction box. The shutoff circuit **100** comprises at least a switch element **330** and a signal detector **320**. In one embodiment, an enable signal generator **400** couples an enable signal **310** onto the DC power lines **105** interconnecting the modules **100**. The enable signal **310** may be, for example, a high-frequency AC voltage or current. In an alternative embodiment the enable signal **310** could be delivered by a separate wired or wireless communication medium; however, this would increase the cost of implementation. The shutoff circuits **300** are configured such that the electrical output of each module **100** is enabled only when the enable signal **310** is present. In the absence of the enable signal **310**, the shutoff circuits **300** revert to a safe state in which electrical output from the modules **100** is disabled.

[0050] In one embodiment, the enable signal **310** is transmitted continuously in order to maintain module **100** power output. In another embodiment, the enable signal **310** is transmitted at regular intervals, and module **100** power output is disabled if the enable signal **310** is not detected by the shutoff circuit **300** within a pre-determined time. In one embodiment, the enable signal **310** may be modulated in order to encode information, which may be received by a controller **360** (not shown) within a shutoff circuit **300** or by another device. Such information could include, for example, instructions to enable or disable the power output of a particular module **100**.

[0051] The enable signal generator **400** may be controlled from a control panel **410**, and the control panel **410** may include a manual shutoff switch **444** (not shown) that stops the enable signal **310** and therefore disables the modules **100**. The enable signal generator **400** may also respond to control signals from other equipment, such as signals from an inverter **140**, fault detection equipment **130**, or other equipment. Similarly, the enable signal generator **400** may respond to signals from fire alarms or other safety systems. Response to these control signals allows automatic shutoff of the PV array.

[0052] The enable signal generator **400** may be a separate piece of equipment, or, as illustrated by dashed lines in **Figure 2**, may be integrated with an inverter **140** or other equipment.

[0053] **Figure 2** depicts a particular embodiment (denoted “circuit interrupter”) in which a normally open switch element **330** is in series with the PV generating capacity **102** and the switch element **330** is closed only when the enable signal **310** is detected. In another embodiment (denoted “circuit shorter”) a normally closed switch element **331** is in parallel with the PV generating capacity **102** and the switch element **331** is opened only when the enable signal **310** is detected.

[0054] As depicted in **Figure 2**, an optional PV bypass diode **340** may be included allowing current flowing in a string **110** to bypass a disconnected module **100**.

[0055] In one embodiment, a PV array may contain multiple enable signal generators **400**, which may be operated independently or in a master-slave relationship. **FIGURE 3** depicts a PV array with multiple sub-arrays **125**, wherein each sub-array has a slave enable signal generator **401** which in turn requires signals from master enable signal generator **402** in order to output its own signal, such that in the absence of a signal from the master **402** each sub-array **125** will be disabled. The various enable signal generators (**400, 401, 402)** may be integrated with other PV array equipment. For example, as indicated by dashed lines, the master **402** could optionally be integrated with an inverter **141** and the slaves **401** could optionally be integrated with string combiners **121**. The master enable signal may be delivered to the slaves **401** via the

DC power lines **106**, or may be delivered via a separate wired or wireless communication link **404**.

[0056] **FIGURE 4** further depicts the operation of the shutoff system, in a circuit interrupter embodiment. The figure compares the voltages along an exemplary string **110'** when the shutoff circuits **300** are enabled (left side – **Figure 4A**) versus disabled (right side – **Figure 4B**). The exemplary string **110'** consists of 12 modules **100'**, wherein the modules **100'** have a max power point voltage of 25 V and an open circuit voltage of 35 V, and where the negative terminal of the string **110'** is at ground potential (0 V). When the enable signal **310** is present (left side – **Figure 4A)** signal detectors **320** cause the normally open switch elements to close (**330'**) and the modules **100'** are enabled. Voltages add from the negative to the positive end of the string **110'** and voltages up to 300 V are present. In contrast, when the enable signal is not present (right side – **Figure 4B**), the switch elements are in their open state (**330''**) and modules **110'** are disabled. Current is arrested and cannot flow along the string **110'**, the wiring between the modules **100'** is essentially disconnected, and the maximum voltage difference between any two points is limited to the open circuit voltage of 35 V. Furthermore, voltage hazards are confined to within the module **100'** construction. Therefore, when the modules **100'** are disabled the hazard potential is greatly reduced. In addition, both series and parallel arcs will be interrupted in most circumstances.

[0057] A shutoff system according to the disclosed subject matter will automatically protect against hazards caused by breaking of wiring or opening of connectors during operation of the PV array. If an open circuit develops within a module string **110** or along any interconnecting wiring, the enable signal **310** will be blocked and therefore the modules **100** beyond the open circuit point will be shut off.

Circuit Interrupter

FUNCTIONAL ELEMENTS – NON-POWERED

[0058] **FIGURE 5** depicts the functional elements of the shutoff circuit **300** in the circuit interrupter embodiment. Optional elements are shown with dashed lines.

[0059] The shutoff circuit **300** is connected to the PV generating capacity **102** of its associated module **100** through the “PV + In” and “PV - In" terminals (**305**, **306**) and is connected to the PV array via the “PV + Out” and “PV - Out" terminals (**307**, **308**). Note that the polarity refers to the relative voltage and not to the direction of positive current flow through the shutoff circuit **300**, which is from “-” to “+”.

[0060] A normally-open switch element **330** is in series with either the “+” or “-” leg of the circuit. The switch element **330** may be, for example, a mechanical relay or a solid-state device such as a transistor. In particular, a field-effect transistor (FET) may be advantageous since it can be switched with low current to its control input. The switch element **330** should be designed to withstand the inductive voltages that may be created when it opens and disrupts the string **110** current. Therefore, the switch element **330** may preferentially be designed to open slowly enough to limit inductive voltages to acceptable levels, and/or may include a bypass element such as a diode to suppress transient voltage spikes.

[0061] A signal detector **320** is placed in series with either the “+” or “-” leg of the circuit. The signal detector **320** detects the enable signal **310** and causes the switch element **330** to close when the enable signal **310** is present. The signal detector **320** may be implemented, for example, as an inductive or capacitive filter or resonant circuit, or in another manner. In one embodiment, passive (unamplified) detection of the enable signal **310** causes the circuit to drive the control gate of switch element **330** to enable module **100** power output.

[0062] A PV bypass element **340**, such as a diode, may be included to allow the module **100** to be electrically bypassed when the switch **330** is open or when the module **100** is non-functioning, e.g. due to shading. In this case the signal detector **320** must be positioned within the portion of the circuit that will remain in series with the rest of the array when the PV bypass **340** is activated, to ensure that the enable signal **310** can be sensed. Note that the PV bypass **340** could also be implemented as a switch element with a control terminal. A signal bypass **345**, such as a capacitor, may be included in parallel with the PV bypass **340** to permit passage of the enable signal **310**.

FUNCTIONAL ELEMENTS – POWERED

[0063] The elements described so far constitute an embodiment in which control of the switch element **330** is powered only by the enable signal **310**. In other embodiments, the shutoff circuit **300** includes a power supply **350** that draws power from the associated PV module **100** in order to operate active components. For example, the power supply **350** could consist of a resistive divider, a zener diode, or a voltage regulator integrated circuit, together with a filter capacitor.

[0064] In one such embodiment, a driver circuit **325** is used to amplify the output of the signal detector **320** and operate the switch element **330**. For example, the driver **325** may include an operational amplifier.

[0065] In another embodiment, a controller **360**, such as a microcontroller, may be included. The controller **360** may analyze the enable signal **310** received by the signal detector **320** and may either enable or disable the switch element **330** via the driver **325** according to internal logic. In one embodiment, the enable signal **310** may be modulated in order to encode information, which may be received by the controller **360**. Such information could include, for example, instructions to enable or disable the power output of a particular module **100**.

[0066] The controller **360** may also contain a communication mechanism, such as a wireless link, allowing the shutoff circuit **300** to be either enabled or disabled in response to a remote signal. In one embodiment, the wireless communication link could be used to deliver the enable signal **310**, instead of delivering it via the DC power line.

[0067] In yet another embodiment, current sense elements **(370**, **371)** are included in series with the "+" and "-" legs of the circuit, and the sensed currents are analyzed by the controller **360**. The current sense elements **(370**, **371**) permit the detection of ground faults or arc faults within the module **100**, through analysis of the sensed signals using logic within the controller **360**. The controller **360** may therefore cause the module **100** to shut off due to a locally detected fault. Similarly, voltage sense elements (not shown) could be included in addition to or instead of the current sense elements (**370**, **371**).

[0068] Note that, in embodiments containing a controller **360**, individual modules **100** can be disabled according to logic within their associated controllers **360**, without shutting down the entire array or string **110**, provided that PV bypass elements (e.g. **340**) are included.

[0069] When the PV module **100** is used to power the driver **325** that controls the switch element **330**, there is the possibility for oscillatory behavior. For example, if a PV module **100** is shaded, it may be driven into reverse bias by excessive current flowing from the remainder of the string **110**, thereby removing power to the active components of the module's associated shutoff circuit **300**. As a result, the driver **325** will not operate and the switch **330** will revert to the normally open position. However, the reverse bias condition would then be lifted, the PV power generation capacity would be restored, and the driver **325** would be able to close the switch **330**, restarting the cycle. In one embodiment, the effect of such oscillations is reduced by incorporating circuitry that lowers the frequency of restart events by decreasing the speed of the circuit response. In another embodiment, the effect of such oscillations is reduced by using the controller **360** to manage restart events, for example by introducing time delays, pro-actively disabling module power output in response to detected under-voltage conditions, or through other methods.

EXEMPLARY IMPLEMENTATIONS

[0070] **FIGURE 6** depicts a circuit schematic for a simple exemplary implementation of the shutoff circuit **300** in a circuit interrupter embodiment containing only the switch element **330** and the signal detector **320**.

[0071] Q1 is an enhancement-mode FET which constitutes the switch element **330**. L1, C1, R1, and D1 form the signal detector **320**. The enable signal **310** is a high-frequency AC current imposed on the DC power line **(105, 106)** interconnecting the modules **100**. The enable signal **310** generates an AC voltage across L1, which is rectified by D1 and charges C1, creating a DC voltage at the gate of Q1. This turns on Q1, permitting current to flow out of the module **100**. If the enable signal **310** is removed, C1 discharges through R1 and Q1 is turned off when its gate voltage falls below the threshold.

[0072] The size of inductor L1 and the frequency and magnitude of the enable signal **310** must be chosen to develop sufficient voltage to turn on FET Q1. Typically 5-10 V are required for this type of device. For example, this may be achieved with an inductor of ~1 mH and an enable signal **310** of ~100 kHz and ~10 mA. Using a higher frequency and/or a greater current magnitude would permit the use of a smaller and therefore less expensive inductor, while lower frequencies or current magnitudes require a larger and more expensive inductor. Therefore, the enable signal **310** frequency is preferably on the order of 100 kHz or higher.

[0073] The time constant of the device is controlled by R1, C1, and L1. In particular, by choosing values appropriately, the device can be designed such that the switching speed of Q1 is limited by L1. When the enable signal **310** is removed, Q1 will begin to turn off, but the subsequent reactive voltage developed across L1 may charge C1 and therefore slow down the switching of Q1. This can be used to prevent the device from turning off too quickly.

[0074] **FIGURE 7** depicts an exemplary implementation of a shutoff circuit **300** in a circuit interrupter embodiment that includes a power supply **350** and powered components. The switch element **330** and signal detector **320** are similar to those of **Figure 6**, however here operational amplifier U1 serves as a driver for the gate of Q1, amplifying the detected enable signal **310**. This permits choosing smaller values of the inductor L1 or of the frequency or magnitude of the enable signal **310**. U1 is powered from the PV module **100**; its positive rail is powered from the "PV + In" input **305**, while its negative rail is powered from the simple power supply **350** formed by zener diode D3, resistors R5 and R9, and capacitor C3.

[0075] The circuit implementations of **Figure 6** and **Figure 7** are meant only to be exemplary. Other implementations may be used to achieve the functions of the shutoff circuit **300** as outlined with reference to **Figure 5**.

Circuit Shorter

[0076] **FIGURE 8** depicts the functional elements of a shutoff circuit **301** in a circuit shorter embodiment. Dashed lines indicate optional elements. In contrast to the circuit interrupter embodiment, the switch element **331** is now a normally-closed switch placed in parallel with the PV generating capacity, and the switch **331** is opened when the enable signal **310** is detected by signal detector **321**. Other elements are substantially the same as discussed in reference to **Figure 5**. The normally-closed switch element **331** could be implemented, for example, as a mechanical relay or a solid-state device such as a transistor. In particular, it could be implemented as a depletion-mode FET.

[0077] In one embodiment, the normally-closed switch element **331** brings the voltage across the input terminals (**305**, **306**) to zero when it is closed. In this case, module **100** power is not available to power the functions of controller **360** or driver **326** while module **100** is in its disabled state. Therefore, signal detector **321** must derive enough energy from the enable signal **310** to drive switch **331** to its open state in order to enable module **100** power output. In an alternative embodiment, these limitations are lifted by, for example, placing a voltage limiting device (such as a diode) in series with switch element **331**, in order to prevent the module **100** voltage from falling all the way to zero and therefore permitting power supply **350** to function when the module **100** is in its disabled state. The voltage should be kept low to minimize power dissipation in the voltage limiting device.

[0078] **FIGURE 9** compares the voltages along an exemplary PV module string **110'** incorporating shutoff circuits **301** in the circuit shorter embodiment, when the shutoff circuits **301** are enabled (left side – **Figure 9A**) versus disabled (right side – **Figure 9B**). As discussed in reference to **Figure 4**, for illustration an exemplary string of 12 modules **100'** is shown wherein the modules **100'** operate at a max power point of 25 V and wherein the negative terminal of the string **110'** is at ground potential (0 V). When the modules **100'** are enabled (left side – **Figure 9A**), the switch elements are in an open state (**331'**), voltages add from the negative to the positive end of the string, and voltages up to 300 V are present. When the modules **100'** are disabled (right side – **Figure 9B**), switch elements are in their closed state (**331''**), each module **100'** is shorted and the voltage at all points of the string **110'** is near zero. Most electrical hazards are eliminated, and both series and parallel arcs will be interrupted in most circumstances.

Enable Signal Generator

[0079] In one embodiment, the enable signal generator **400** imposes the enable signal **310** on the DC power lines (**105**, **106**) interconnecting modules **100** in the array, in order to enable module **100** power output.

[0080] **FIGURE 10** depicts the functional elements of the enable signal generator **400**, with optional elements indicated by dashed lines.

[0081] Power from the PV array is fed through the enable signal generator **400** via the four +/- in/out terminals (**421**, **422**, **423**, **424**).

[0082] A signal generator **440** generates the enable signal **310**, which is applied to either the "+" or "-" leg of the circuit via a driver **442** and signal coupling elements **446**. For example, the signal may be a high-frequency AC voltage or current. Preferably, the frequency is on the order of 100 kHz or higher. In one embodiment, the enable signal **310** is generated continuously, while in another embodiment, it is generated at regular intervals. In another embodiment, the enable signal **310** may be modulated in order to encode information to be transmitted.

[0083] The signal coupling element **446** may be implemented as, for example, a bypass capacitor, a transformer, or a semiconductor device such as a transistor.

[0084] A switch **444**, positioned either locally or remotely, provides for the interruption of the enable signal **310** in order to disable the PV modules **100**. The placement of the switch **444** between driver **442** and signal coupling **446** indicated in **Figure 10** is only exemplary. Other placements of switch **444** could also serve to disable the generation or application of enable signal **310**.

[0085] Filter elements **450** on one or both legs of the circuit may be used to block high-frequency signals and thus prevent the enable signal **310** from interfering with other equipment installed on the PV array, such as inverters **140**, as well as to prevent high-frequency signals from such other equipment from reaching the modules and enabling them spuriously.

[0086] A controller element **460**, such as a microcontroller, may be included. The controller **460** may implement the signal generator **440** function in software. In addition, it may process control signals received from other equipment, such as inverters **140**, fault detectors **130**, or other safety systems, in order to automatically shut down the PV array under certain conditions. The controller **460** also may be used in a slaved enable signal generator **401** to respond to signals from a master **402**.

[0087] A power supply **430** is included within the enable signal generator **400** in order to operate the controller **460**, signal generator **440**, and driver **442**. This power supply **430** may derive power from the PV array itself and/or from an external source, such as a utility power grid to which the array is connected, or any other external power source. With the shutoff system of disclosed subject matter in place, a power source is required in order to start the PV array, since the initial default state of the modules is "off" until the enable signal **310** is generated. Therefore, the enable signal generator **400** may include an energy storage device **432**, such as a rechargeable battery, in order to start the PV array in the absence of an external power source.

[0088] In an alternative embodiment, the enable signal generator **400** uses a wireless transmission device to deliver the enable signal **310** to the shutoff circuits **300**, rather than imposing an enable signal **310** on the DC power lines.

Combination with a Monitoring Device

[0089] The safety shutoff system and devices disclosed herein could be implemented in conjunction with a module-level monitoring system and devices such as disclosed in U.S. Provisional Patent Application number 61/102,933, "Photovoltaic Module Performance Monitoring System, Method, and Storage Medium" and Patent Cooperation Treaty application PCT/US09/59716 "Photovoltaic Module Performance Monitoring System And Devices," in order to realize certain benefits, including sharing of components and enabling of additional features due to synergistic operation.

Embodiment for Modules with AC Output

[0090] The preceding discussion focuses on modules having DC electrical output. It will be recognized that the disclosed subject matter may also be applied to photovoltaic modules which include micro-inverters producing AC outputs.

[0091] Although particularly described with reference to a small number of modules, module strings, shutoff circuits, enable signal generators, string combiners, inverters, and the like, this disclosure is intended to include any number of these components.

[0092] Further, although example circuits and schematics to implement the elements of the disclosed subject matter have been provided, one skilled in the art, using this disclosure, could develop additional hardware and/or software to practice the disclosed subject matter and each is intended to be included herein.

[0093] In addition to the above described embodiments, those skilled in the art will appreciate that this disclosure has application in a variety of arts and situations and this disclosure is intended to include the same.

WHAT IS CLAIMED IS:

1. A system for disabling electrical power output from one or more photovoltaic modules in a photovoltaic array, comprising:

one or more shutoff circuits, each of which can disable electrical power output from an associated module; and

at least one enable signal generator which generates an enable signal and transmits said signal to one or more of said shutoff circuits, wherein said shutoff circuits disable electrical power output from said associated modules in the absence of said enable signal.

2. The system of claim 1, wherein one or more electrical hazards are confined substantially within said modules in the absence of said enable signal.

3. The system of claim 1, wherein said shutoff circuits are integrated substantially within the assemblies or junction boxes of said associated modules.

4. The system of claim 1, wherein said enable signal is transmitted via power lines interconnecting said modules.

5. The system of claim 1, wherein said enable signal is transmitted via a wireless communications medium.

6. The system of claim 1, wherein the electrical output of said modules is DC.

7. The system of claim 1, wherein said modules incorporate micro-inverters and the electrical output of said modules is AC.

8. The system of claim 1, wherein said shutoff circuits are integrated substantially into a single device or integrated circuit.

9. The system of claim 1, wherein said shutoff circuits comprise at least:

a switch element, wherein said switch element has a normal state that disables electrical output from said associated module; and

a signal detector, wherein said signal detector causes said switch element to change to another state that enables electrical output from said associated module when said signal detector detects said enable signal.

10. The system of claim 0, wherein:

said module has a photovoltaic generating capacity; and said switch element is normally open and is placed substantially in series with said photovoltaic generating capacity of said module, such that in the absence of said enable signal said module's electrical output is interrupted.

11. The system of claim 0, wherein:

said module has a photovoltaic generating capacity; and

said switch element is normally closed and is placed substantially in parallel with said photovoltaic generating capacity of said module, such that in the absence of said enable signal the electrical output of said module is substantially shorted.

12. The system of claim 0, wherein energy necessary to change said switch element from said normal state to said other state is derived from said enable signal.

13. The system of claim 9, wherein said shutoff circuits further comprise a power supply, wherein said power supply derives power from said associated module.

14. The system of claim 13, wherein said shutoff circuits further comprise a driver circuit, wherein said driver circuit changes the state of said switch element using energy derived from said power supply, and wherein said driver circuit is connected to said signal detector.

15. The system of claim 13, wherein said shutoff circuits further comprise a controller, wherein said controller derives power from said power supply and controls said switch element using a driver circuit.

16. The system of claim 15, further comprising sensing elements, wherein said sensing elements sense at least one of a current or voltage of said associated module, and wherein said controller processes one or more signals from said sensing elements to identify one or more fault conditions, and wherein said controller controls said switch element in response to said fault conditions.

17. The system of claim 15, wherein said enable signal is modulated to encode information to be received by said controller.

18. The system of claim 17, wherein said information includes commands to enable or disable electrical output from said associated module.

19. The system of claim 1, wherein said enable signal is a high-frequency AC current or voltage.

20. The system of claim 1, wherein said enable signal is transmitted continuously.

21. The system of claim 1, wherein said enable signal is transmitted at regular intervals, and wherein electrical power output of said associated module is disabled if said enable signal is not detected by a signal detector within a pre-determined time.

22. The system of claim 1, additionally comprising at least one master enable signal generator, wherein said master enable signal generator controls at least one of said enable signal generators.

23. The system of claim 22, wherein said master enable signal generators control said enable signal generators via a wireless communications medium.

24. The system of claim 1, wherein said enable signal generator includes a power supply, wherein said power supply derives power from at least one of:

said photovoltaic array;

an external power source;

an electric utility grid; and

an energy storage device contained within said enable signal generator.

25. The system of claim 1, wherein said enable signal generator includes a disconnect switch which interrupts transmission of said enable signal to said shutoff circuits.

26. The system of claim 1, wherein said enable signal generator is controlled by an inverter or a fault detection system.

27. The system of claim 1, wherein said enable signal generator is integrated substantially within a string combiner, an inverter, or a fault detection system.

28. A device for disabling electrical power output from an associated photovoltaic module in a photovoltaic array, comprising:

a switch element, wherein said switch element has a normal state that disables output from said associated module; and

a signal detector, wherein said signal detector causes said switch element to change to a state which enables output from said associated module when said signal detector receives an enable signal from an external enable signal generator.

29. The device of claim 28, wherein said enable signal is transmitted over one or more power lines connecting said associated module to the photovoltaic array.

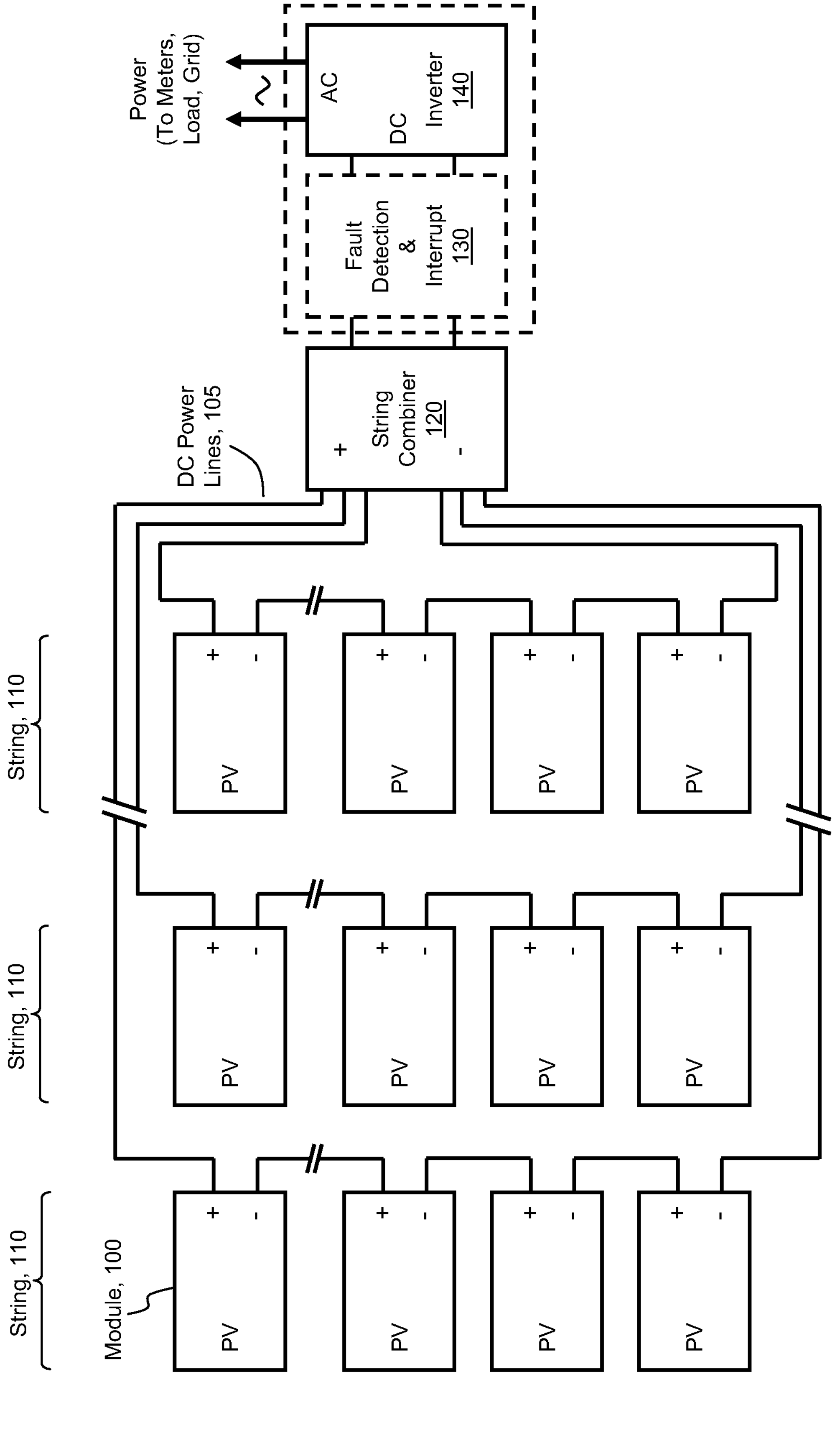
30. The device of claim 28, wherein said signal detector causes said switch element to change state using energy derived from said enable signal.

31. The device of claim 28, further comprising a power supply which derives power from said associated module.

32. The device of claim 31, further comprising a driver circuit powered by said power supply, wherein said driver circuit causes said switch element to change state in response to said signal detector.

33. The device of claim 32, further comprising a controller which controls said driver circuit.

34. The device of claim 33, further comprising sensing elements which sense at least one of a voltage or current of said associated module, wherein said controller processes signals from said sensing elements to identify fault conditions, and wherein said controller controls said switch element in response to said fault conditions.



PRIOR ART

Fig. 1

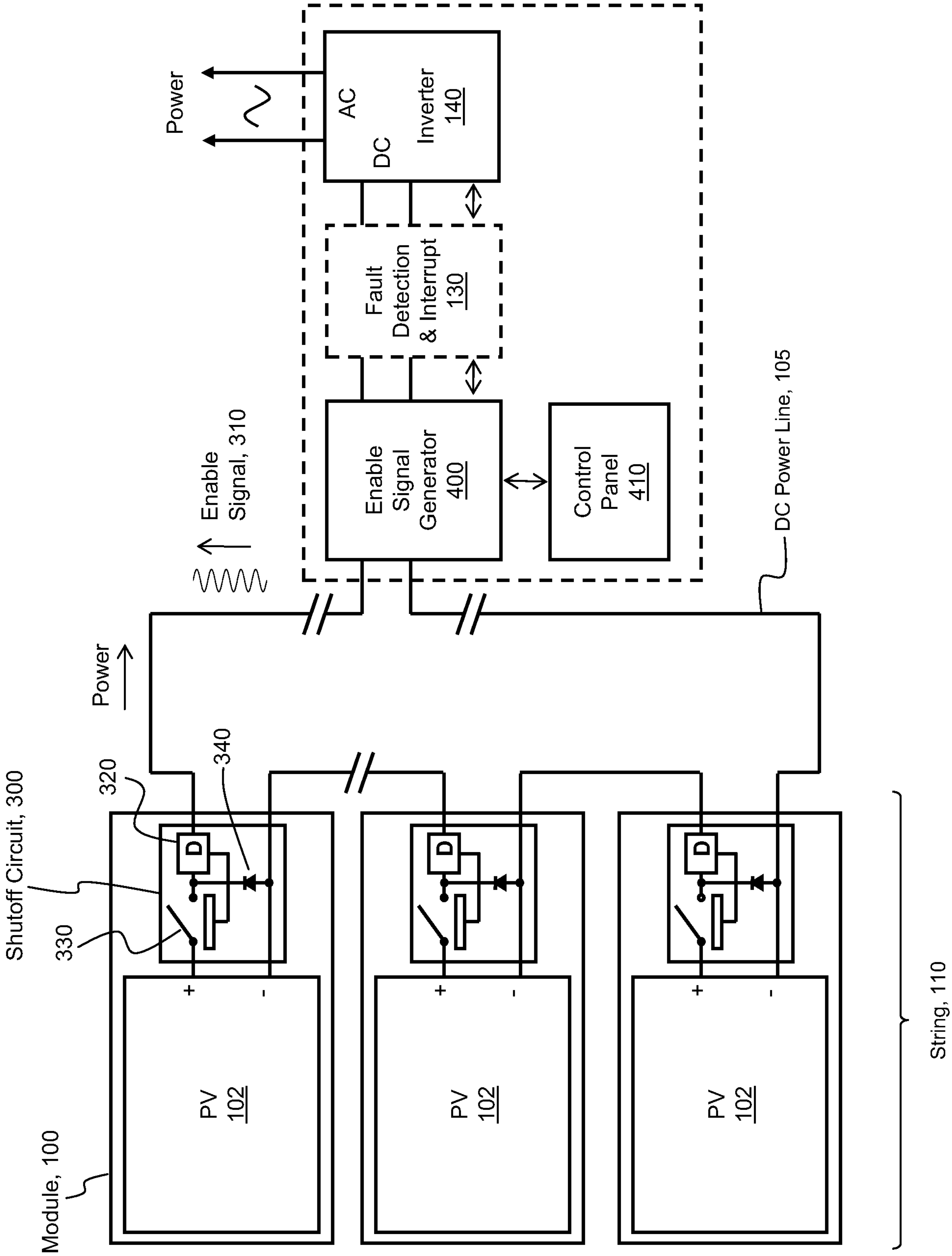

Power
AC
DC
Inverter
140
Fault
Detection
& Interrupt
130
Enable
Signal, 310
Enable
Signal
Generator
400
Control
Panel
410
DC Power Line, 105
Power
Shutoff Circuit, 300
320
340
330
D
+
-
PV
102
Module, 100
String, 110

Fig. 2

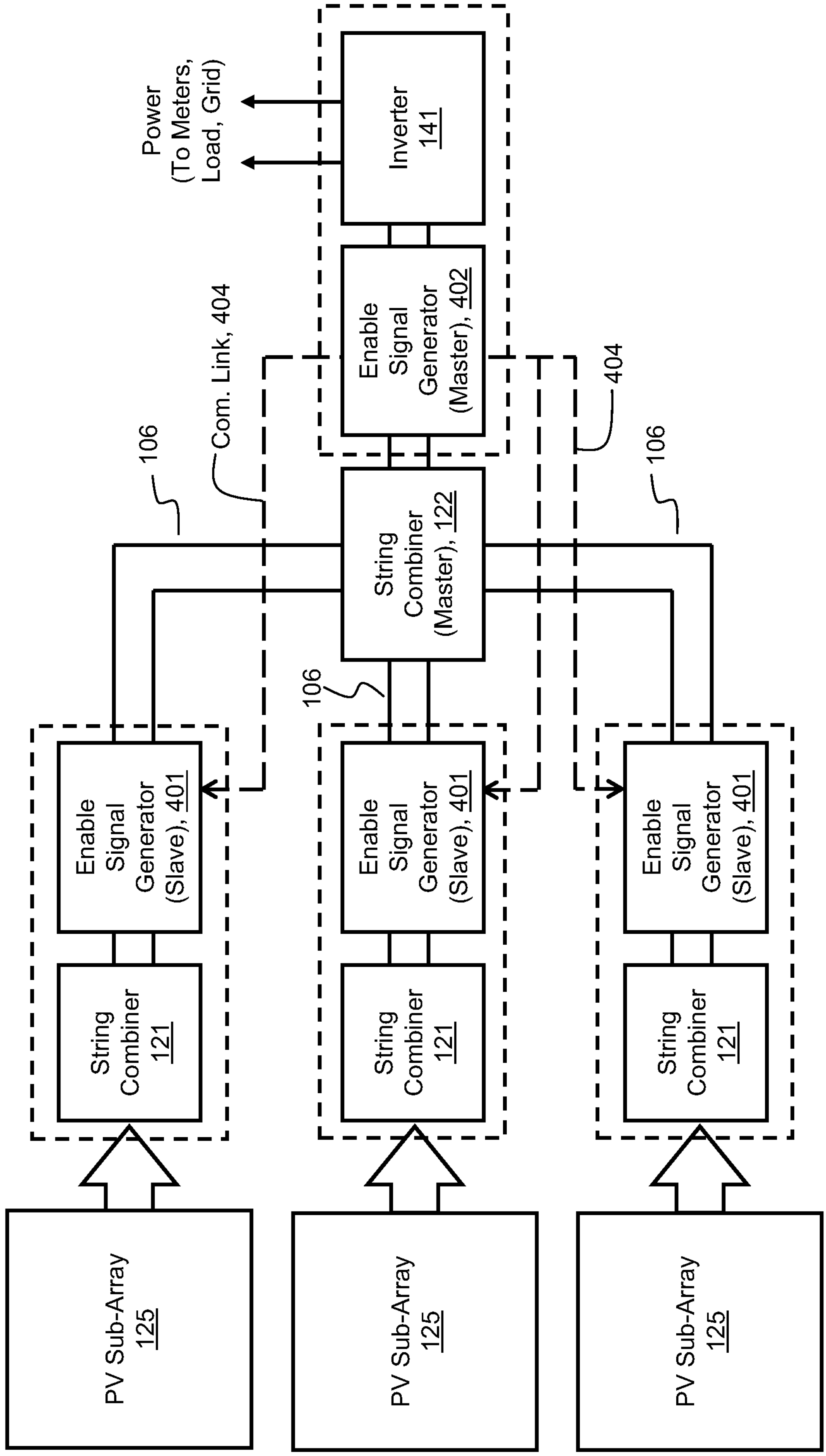

Power
(To Meters,
Load, Grid)
Inverter
141
Enable
Signal
Generator
(Master), 402
Com. Link, 404
404
106
106
106
String
Combiner
(Master), 122
Enable
Signal
Generator
(Slave), 401
String
Combiner
121
PV Sub-Array
125

Fig. 3

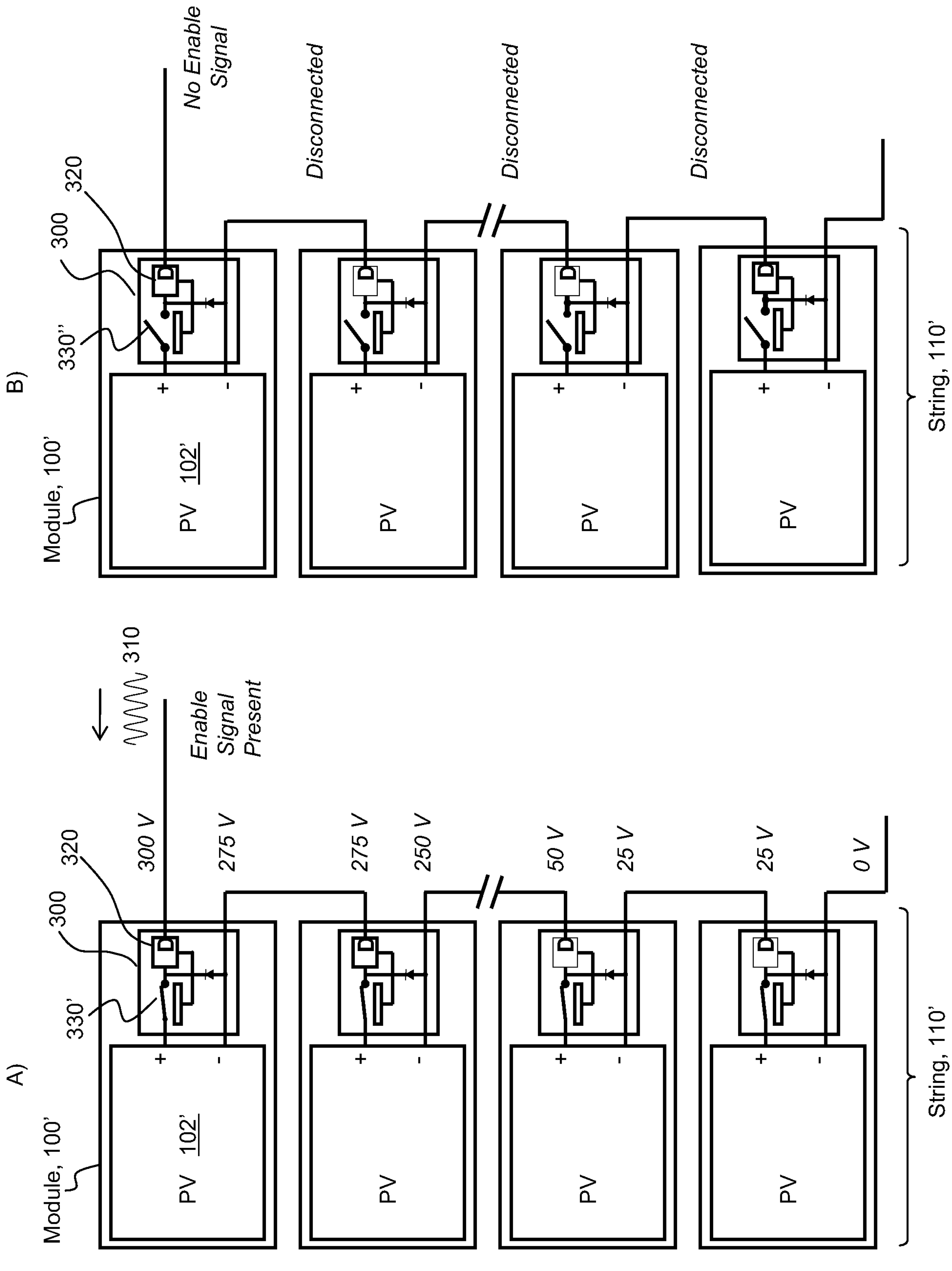

A)
Module, 100'
PV 102'
PV
PV
PV
330'
300
320
300 V
275 V
275 V
250 V
50 V
25 V
25 V
0 V
310
Enable Signal Present
String, 110'
B)
Module, 100'
PV 102'
PV
PV
PV
330''
300
320
No Enable Signal
Disconnected
Disconnected
Disconnected
String, 110'

Fig. 4

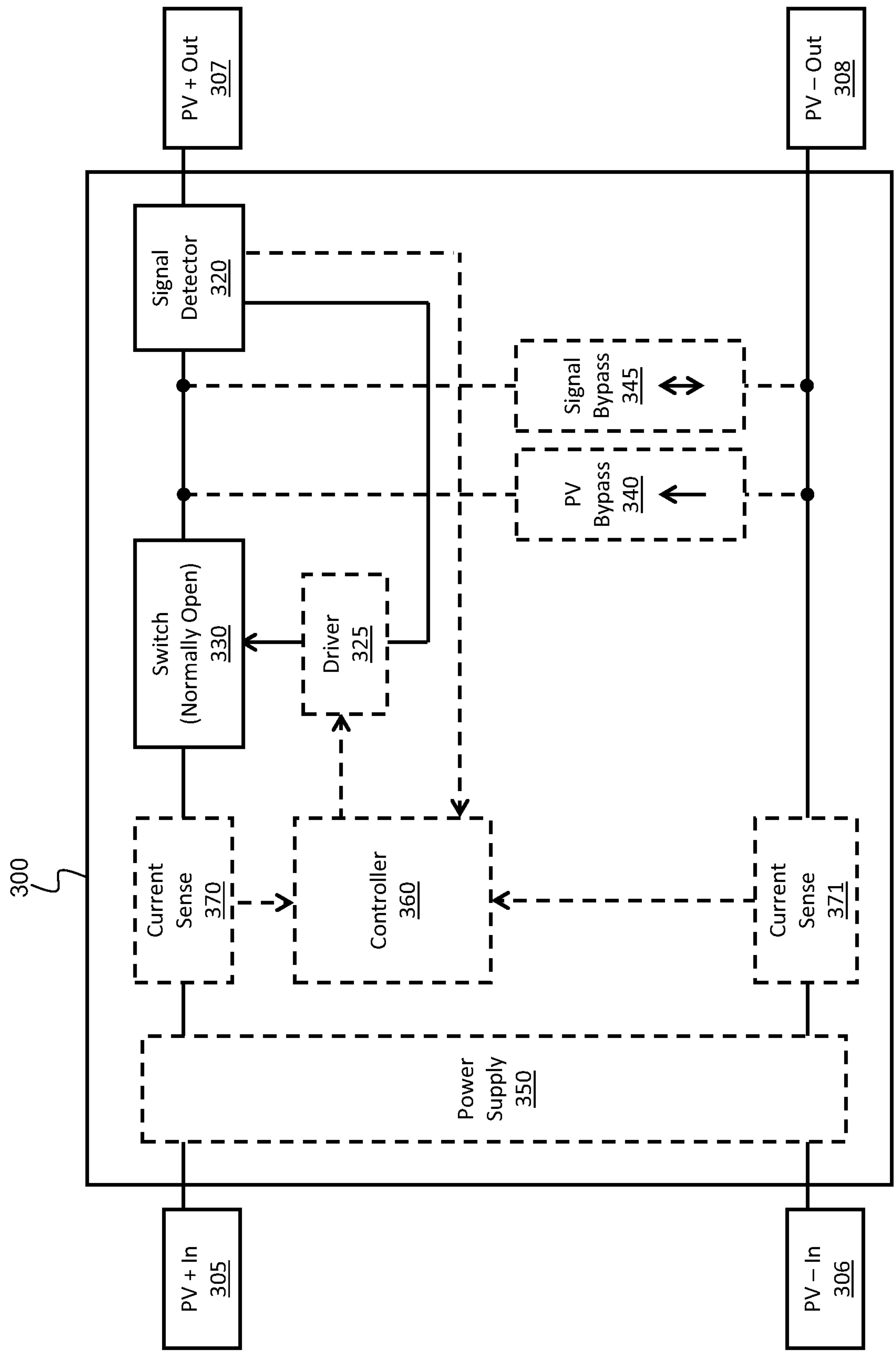

300
PV + Out
307
PV – Out
308
Signal
Detector
320
Signal
Bypass
345
PV
Bypass
340
Switch
(Normally Open)
330
Driver
325
Current
Sense
370
Controller
360
Current
Sense
371
Power
Supply
350
PV + In
305
PV – In
306

Fig. 5

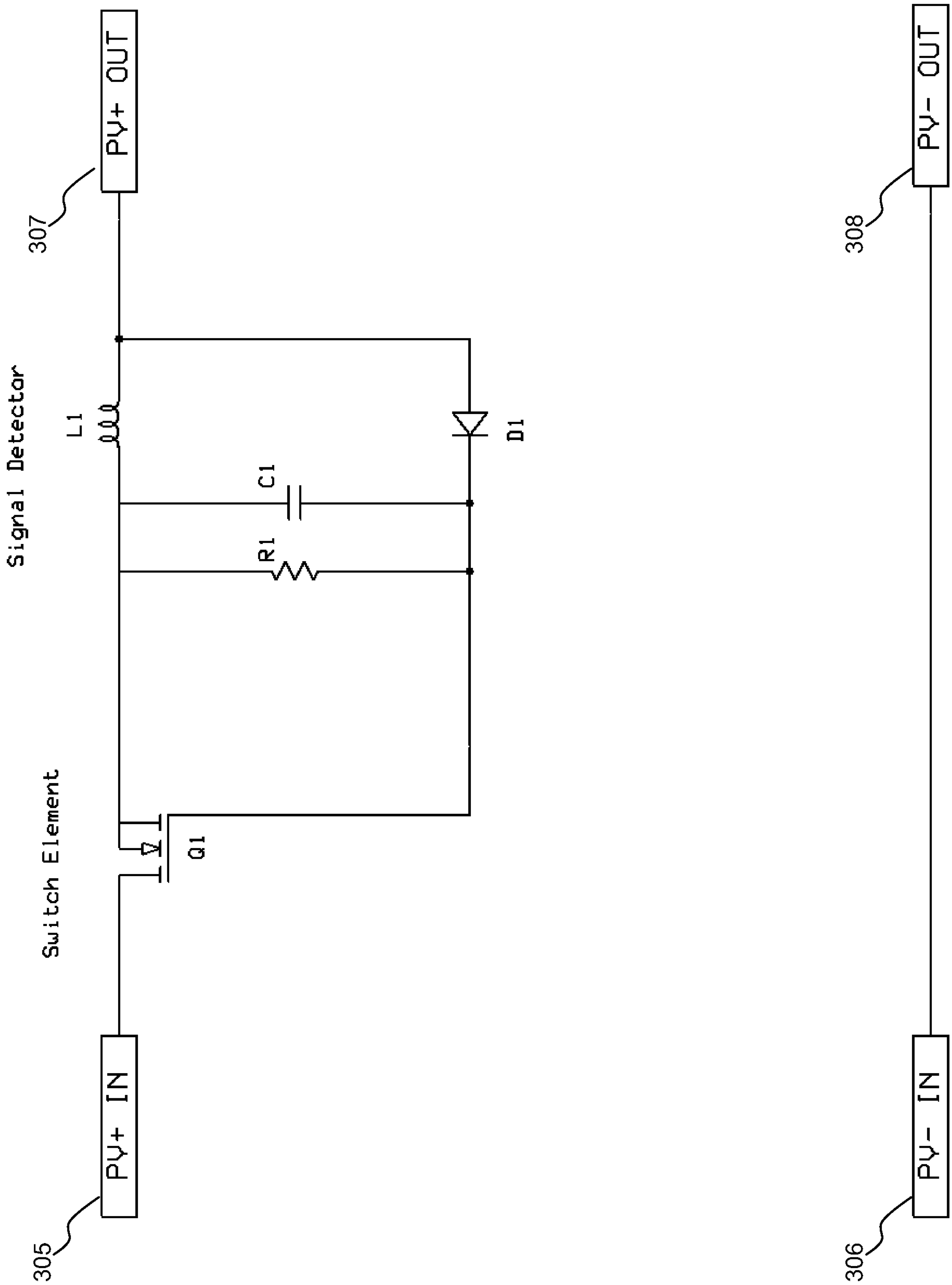

PV+ OUT
307
PV- OUT
308
Signal Detector
L1
D1
C1
R1
Switch Element
Q1
PV+ IN
305
PV- IN
306

Fig. 6

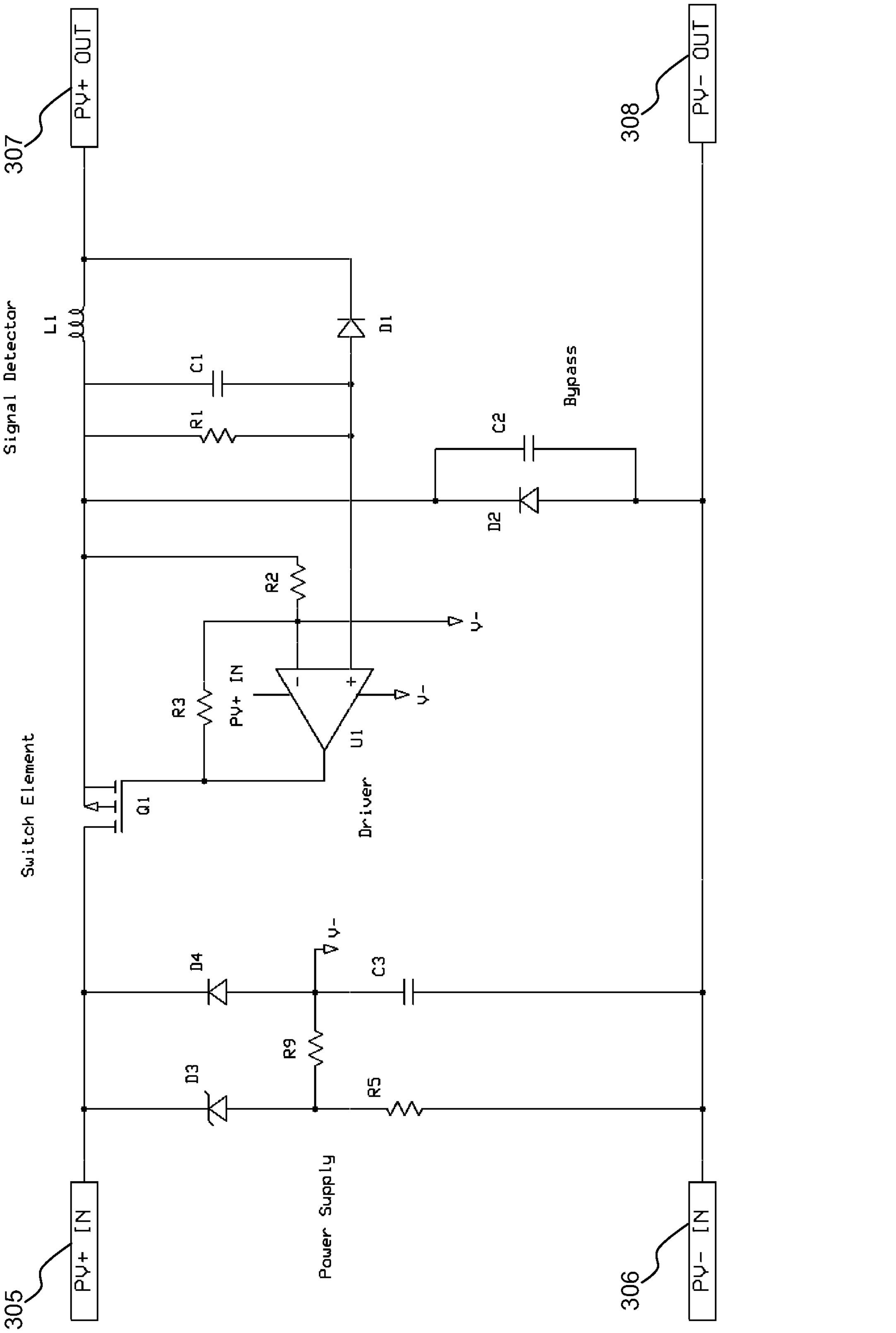

307
PV+ OUT
308
PV- OUT
Signal Detector
L1
C1
R1
D1
Bypass
C2
D2
R2
V-
R3
PV+ IN
U1
V-
Switch Element
Q1
Driver
D4
V-
C3
R9
D3
R5
Power Supply
305
PV+ IN
306
PV- IN

Fig. 7

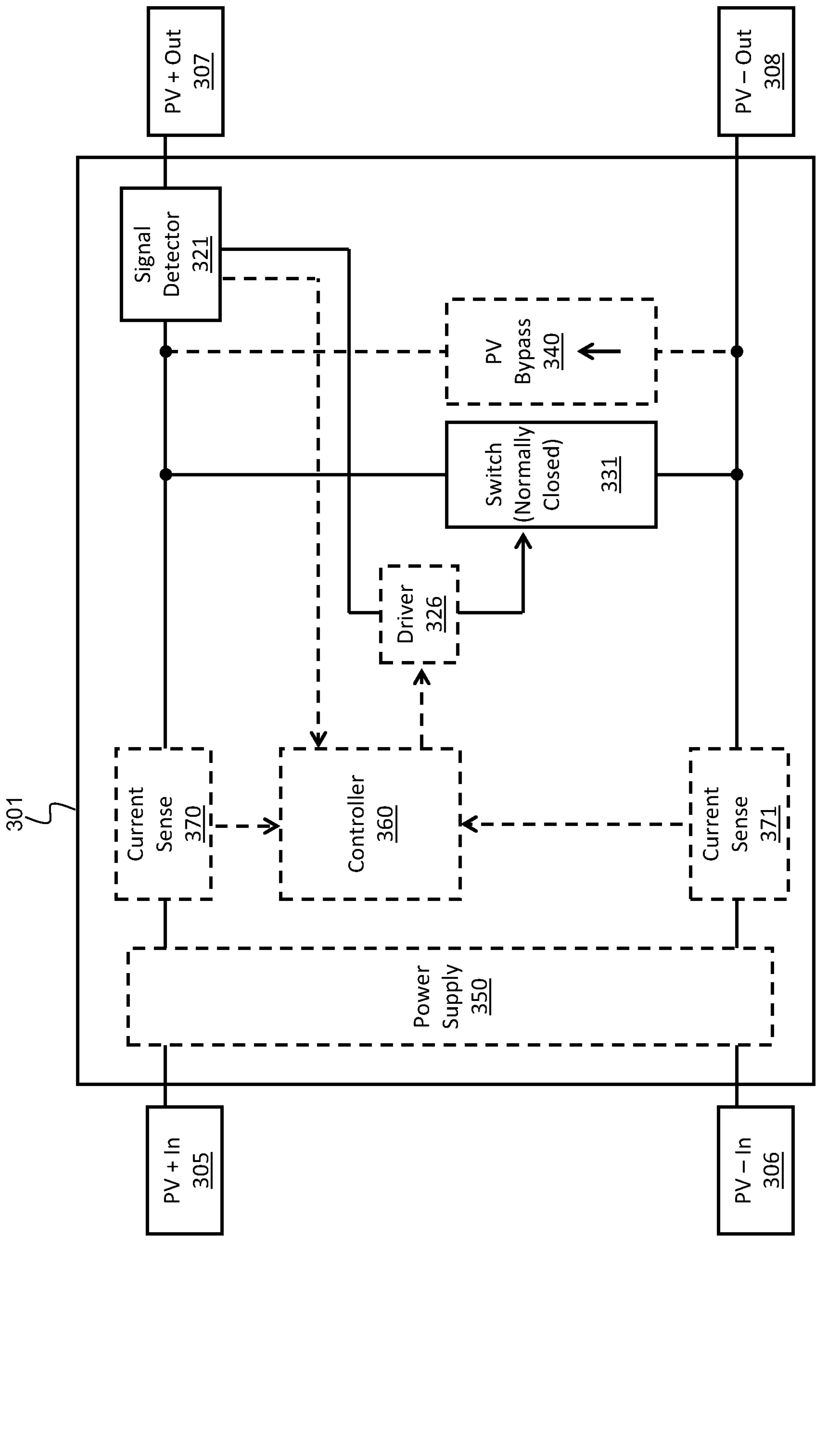

PV + Out
307
PV – Out
308
Signal
Detector
321
PV
Bypass
340
Switch
(Normally
Closed)
331
Driver
326
301
Current
Sense
370
Controller
360
Current
Sense
371
Power
Supply
350
PV + In
305
PV – In
306

Fig. 8

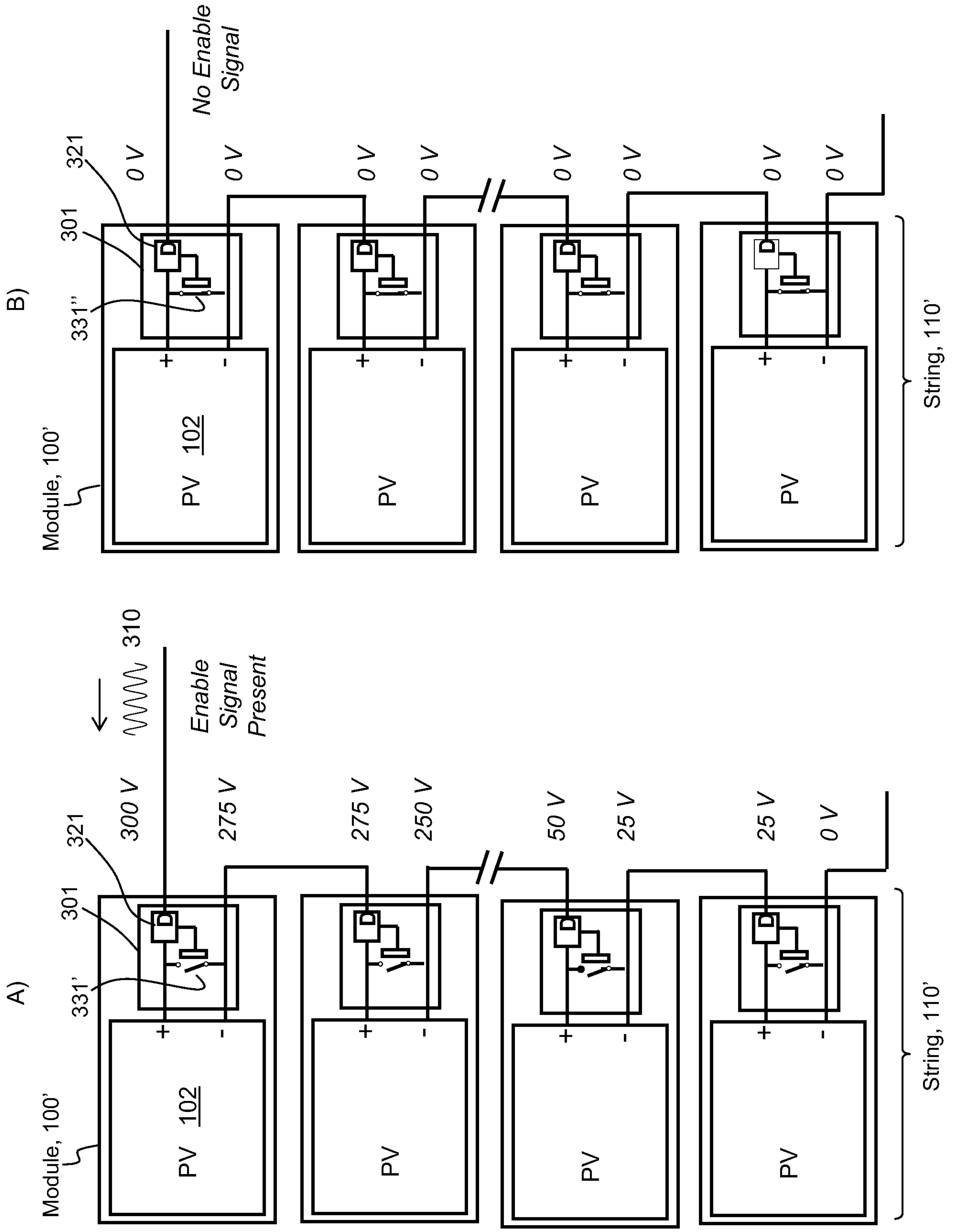

A)
Module, 100'
331'
301
321
300 V
275 V
275 V
250 V
50 V
25 V
25 V
0 V
310
Enable Signal Present
PV 102
PV
PV
PV
String, 110'
B)
Module, 100'
331''
301
321
0 V
0 V
0 V
0 V
0 V
0 V
0 V
0 V
No Enable Signal
PV 102
PV
PV
PV
String, 110'

Fig. 9

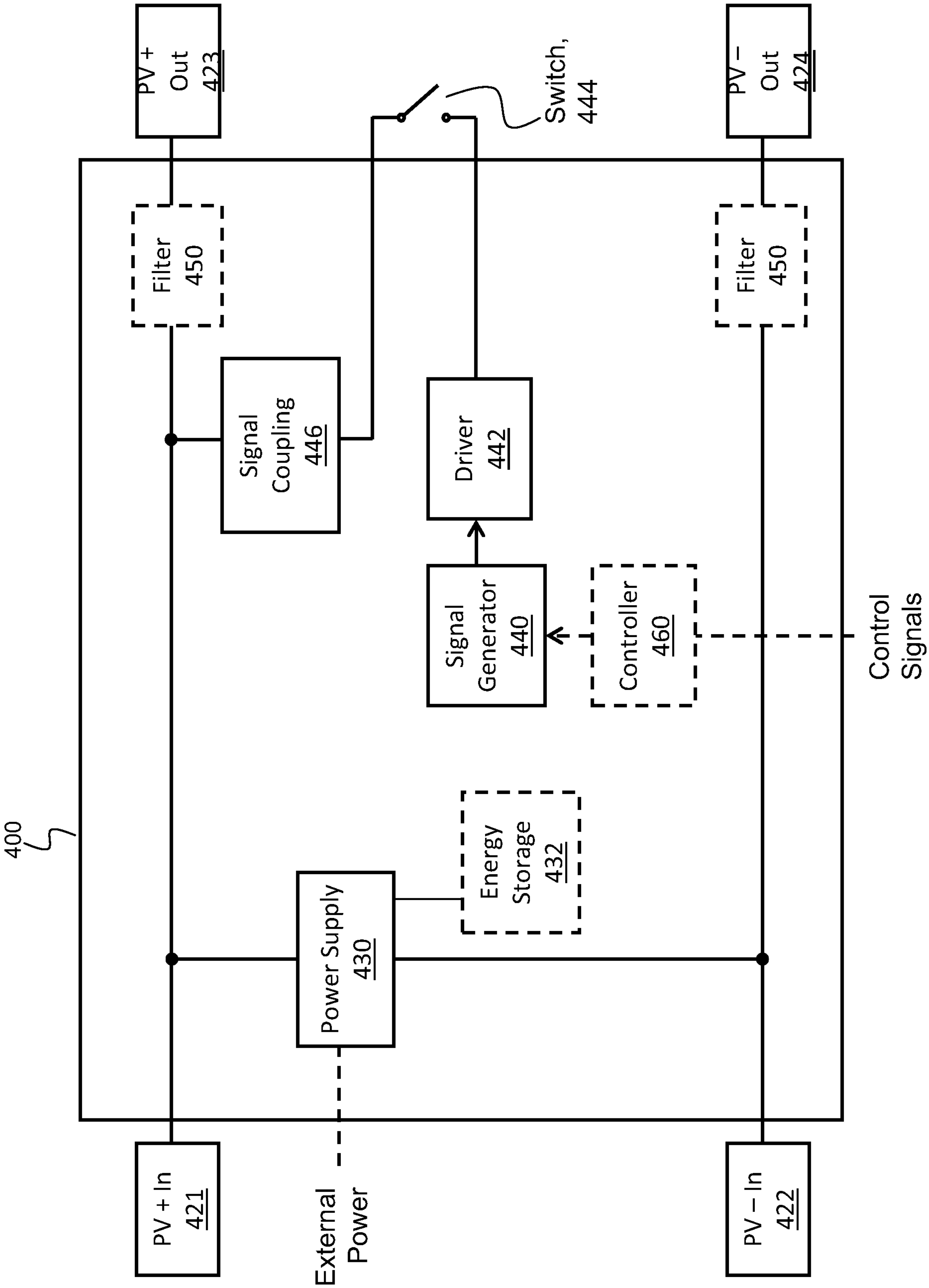

400
PV + In
421
External
Power
PV – In
422
Power Supply
430
Energy
Storage
432
Signal
Coupling
446
Driver
442
Signal
Generator
440
Controller
460
Control
Signals
Filter
450
Filter
450
PV +
Out
423
Switch,
444
PV –
Out
424

Fig. 10