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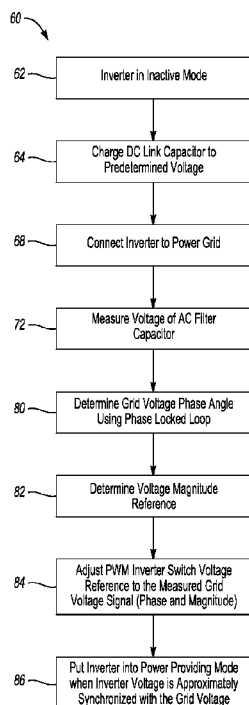
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(54) Title: GRID-FORMING INVERTER SYNCHRONIZATION FOR CONNECTION TO A POWER GRID

(57) Abstract: An illustrative example embodiment of a grid-forming inverter system includes an inverter including a plurality of switches, the inverter being configured to be selectively connected to a power grid; and an electronic controller including a voltage magnitude module that is configured to determine a voltage magnitude reference based on a voltage of the power grid when the inverter is in an inactive mode wherein the inverter is not operating to provide power, a phase locked loop module that is configured to determine a reference angle based on a phase angle of the voltage of the power grid when the inverter is in the inactive mode, and wherein the controller uses the voltage magnitude reference and the reference angle to set an initial voltage of the inverter to be approximately synchronized with the voltage of the power grid when the inverter switches from the inactive mode into a power providing mode.

**Fig-2**



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GRID-FORMING INVERTER SYNCHRONIZATION FOR CONNECTION TO A POWER GRID

STATEMENT REGARDING GOVERNMENT SUPPORT

5 This invention was made with government support under Contract No. DE-EE0003954 awarded by the United States Department of Energy. The government has certain rights in this invention.

TECHNICAL FIELD

10 The present disclosure relates to electrical power control systems. More particularly, but without limitation, the present disclosure relates to synchronizing a grid-forming inverter with a power grid to facilitate connection between the inverter and the power grid.

BACKGROUND

15 There are a variety of applications for microgrids to provide power in addition to or at least temporarily in place of conventional utility company power grids. For example, microgrids are useful in remote locations where the traditional utility power grid is inaccessible or for supplying power during a power outage to buildings that are on the microgrid.

20 Many microgrid configurations generate DC or variable AC voltages and therefore require a grid-forming inverter to interface with the utility grid, which typically has well-regulated voltage and frequency. The grid-forming inverter assists in regulating voltage and frequency. Paralleling the grid forming inverter with the power grid or other grid-forming inverter is typically only
25 possible when a paralleling control algorithm is employed. Some such algorithms are based on the known P-Q droop controller. Some known grid-forming inverters include an additional interface switch, which monitors phase angle and magnitude differences between the inverter and the external power grid. The switch typically only closes when the voltage discrepancy is within a preset threshold in order to avoid or minimize transient current.

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While synchronization switches are useful, they introduce additional cost and reliability issues. It would be beneficial to be able to provide grid-forming inverter synchronization without requiring such a switch.

5 SUMMARY

An illustrative example embodiment of a grid-forming inverter system includes an inverter including a plurality of switches, the inverter being configured to be selectively connected to a power grid; and an electronic controller including a voltage magnitude module that is configured to determine a voltage magnitude reference based on a voltage of the power grid when the inverter is in an inactive mode wherein the inverter is not operating to provide power, a phase locked loop module that is configured to determine a reference angle based on a phase angle of the voltage of the power grid when the inverter is in the inactive mode, and wherein the controller uses the voltage magnitude reference and the reference angle to set an initial voltage of the inverter to be approximately synchronized with the voltage of the power grid when the inverter switches from the inactive mode into a power providing mode.

In an example embodiment having one or more features of the system of the previous paragraph, the inverter includes an AC filter capacitor, the voltage magnitude reference is based on a voltage across the AC filter capacitor, and the reference angle is based on the voltage across the AC filter capacitor.

In an example embodiment having one or more features of the system of either of the previous paragraphs, the controller includes a frequency droop module that determines an angular frequency of the voltage of the power grid, the controller includes an integrator that determines a phase angle for the initial voltage of the inverter during the power providing mode, and the integrator uses the reference angle when determining the phase angle for the initial voltage of the inverter.

In an example embodiment having one or more features of the system of any of the previous paragraphs, the controller includes a pulse width modulation signal generator, and the controller sets the initial voltage through pulse signals controlling the plurality of switches.

In an example embodiment having one or more features of the system of any of the previous paragraphs, the controller includes a voltage droop module that provides a reference voltage based on a power measurement associated with the inverter, and the proportional integrator uses the voltage magnitude reference, the reference voltage from the voltage droop module and
5 a measured voltage when determining a magnitude of the initial voltage of the inverter.

An illustrative example embodiment of a method of synchronizing a grid-forming inverter with a power grid, in which the grid-forming inverter has a plurality of switches, includes: connecting the inverter to the power grid while the inverter is in an inactive mode wherein the inverter is not
10 operating to provide power; determining a voltage magnitude reference based on a voltage of the power grid when the inverter is in the inactive mode; using a phase locked loop module to determine a reference angle based on a phase angle of the voltage of the power grid when the inverter is in the inactive mode; setting an initial voltage of the inverter based on the voltage magnitude reference and the reference angle; and switching the inverter from the inactive mode
15 into a power providing mode when the initial voltage of the inverter is approximately synchronized with a voltage of the power grid.

In an example embodiment having one or more features of the method of the previous paragraph, the inverter includes an AC filter capacitor, the voltage magnitude reference includes
20 determining a voltage across the AC filter capacitor, and the reference angle is based on the voltage across the AC filter capacitor.

An example embodiment having one or more features of the method of any of the preceding paragraphs includes setting the initial voltage based on pulse width modulation signals that
25 control the plurality of switches.

In an example embodiment having one or more features of the method of any of the preceding paragraphs, the inverter includes a DC link capacitor associated with the plurality of switches. The method includes charging the DC link capacitor to a preselected voltage prior to connecting
30 the inverter to the power grid.

An example embodiment having one or more features of the method of any of the preceding paragraphs includes using a frequency droop module to determine an angular frequency of the voltage of the power grid; and using an integrator to determine a phase angle for the initial

voltage of the inverter during the power providing mode, wherein the integrator uses the reference angle when determining the phase angle for the initial voltage of the inverter.

An example embodiment having one or more features of the method of any of the preceding paragraphs includes using a voltage droop module to provide a reference voltage based on a power measurement associated with the inverter; and using a proportional integrator to determine a magnitude of the initial voltage of the inverter, wherein the proportional integrator uses the voltage magnitude reference, the reference voltage from the voltage droop module and a measured voltage when determining the magnitude of the initial voltage of the inverter.

Various features and advantages associated with at least one disclosed embodiment will become apparent to those skilled in the art from the following detailed description. The drawings that accompany the detailed description can be briefly described as follows.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 schematically illustrates an example embodiment of a grid-forming inverter system designed according to an embodiment of this invention.

Figure 2 is a flow chart diagram that summarizes an example synchronizing control process.

DETAILED DESCRIPTION

Embodiments of this invention provide an ability to synchronize a grid-forming inverter with a power grid without requiring a synchronization switch. Eliminating a requirement for such a hardware switch may reduce costs and improve reliability of microgrid systems that include a grid-forming inverter. One feature of the example embodiment of this description includes monitoring the power grid voltage and phase angle using a phase locked loop while the grid-forming inverter is inactive to facilitate matching the inverter output to the grid voltage when the inverter is enabled.

Figure 1 schematically illustrates a grid-forming inverter system 20 that is useful as part of a microgrid power system, for example. An inverter 22 includes a plurality of switches that may be controlled using known techniques to provide power having selected voltage and frequency

characteristics. The inverter 22 can be used to provide power in a manner consistent with power supplied by a main grid 24, which may be operated by a utility company. An electronic controller 26 includes at least one computing device that controls operation of the grid-forming inverter system 20.

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The electronic controller 26 can comprise a control unit or computational device having one or more electronic processors (e.g., a microprocessor, a microcontroller, an application specific integrated circuit (ASIC), etc.) and associated memory. The controller 26 may be realized in a single device or different functions of the controller may be embodied in, or hosted in, different devices collectively operating to provide the required control functionality. A set of instructions could be provided on a memory or tangible storage medium associated with the one or more devices used as the controller 26, which when executed, cause the controller 26 to implement the control techniques mentioned in this description. The set of instructions could be embedded in a portion of the one or more devices used as the controller 26 as software, firmware or specifically configured hardware or circuitry. Alternatively, the set of instructions could be provided as software in a separate memory or storage device that is accessible by the processor portion of the controller. Given this description those skilled in the art will realize a configuration of the controller 26 that will meet their particular needs.

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The illustrated controller 26 includes a power calculation module 30, a frequency droop module 32, an integrator 33, a voltage droop module 34, a proportional integrator 36, a voltage magnitude module 38 and a pulse width modulation (PWM) signal generator 40 that are collectively useful according to known techniques for controlling switches 44 of the inverter 22 to provide power from an associated microgrid. The controller 26 also includes features or capabilities that are useful for synchronizing the inverter 22 with the power grid 24 schematically shown at 50 (a mode selection feature schematically represented by switches 50 for selecting when the output of the PWM signal generator 40 is used for synchronization) and a phase locked loop module 52. The switches 50 are shown in the position that schematically represents synchronization mode.

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Figure 2 is a flow chart diagram 60 that summarizes an example approach to synchronizing the grid-forming inverter with the power grid 24. At 62, the grid-forming inverter is in an inactive mode in which the inverter 22 is not operating for providing power to any load and the switches 50 are in the condition or position shown in Figure 1. At 64 the voltage of a DC link capacitor 66

is charged to a predetermined voltage for protecting the switches 44 from an inrush of current. At 68 a connector, such as a conventional circuit breaker 70, connects the inverter 22 to the power grid 24. The previously established DC link voltage protects the switches 44.

5 At 72, a voltage transducer 74 provides the controller 26 an indication of the voltage across an AC filter capacitor 76. At 80 the phase locked loop module 52 tracks the grid voltage phase angle θ_0 and provides it to the PWM signal generator 40. At 82 the voltage magnitude module 38 provides an initial voltage magnitude reference value V_0 to the PWM signal generator 40. The reference angle θ_0 and the voltage magnitude reference V_0 provide initial grid voltage phase
10 and magnitude measurements to facilitate synchronization.

While still in the inactive mode, at 84 the PWM inverter voltage reference is adjusted to match the power grid voltage as indicated by the reference angle θ_0 and the voltage magnitude reference V_0 . When the inverter voltage is sufficiently synchronized with the grid voltage, the
15 inverter is switched into a power providing mode at 86 to begin inverter operation. In one embodiment, the PWM generator 40 provides fast pulses to control the switches 44 to control an average voltage of the inverter. Initiating the power providing mode in the illustration includes changing the position of the schematic switches 50 from the 0 position shown in Figure 1 to the 1 position. At 88 the frequency droop module 32 determines an angular frequency ω . The
20 integrator 33 determines the corresponding phase angle θ using the reference angle θ_0 as an initial value to bring the inverter voltage in phase with the grid voltage. The voltage droop module 34 determines a voltage magnitude reference. The proportional integrator 36 controls the terminal voltage according to the voltage magnitude reference V_0 to minimize any voltage magnitude difference between the inverter 22 and the grid 24 when the inverter begins to
25 provide power, which is in parallel with the power grid 24 in this example instance.

In the power providing mode the frequency droop module 32 and the voltage droop module 34 begin to operate according to a known technique so that the inverter 22 works in parallel with the grid 24.

30 Implementing the synchronization strategy summarized in Figure 2 ensures that the grid-forming inverter 22 can be connected to the grid 26 without an additional hardware synchronizing switch. The cost of the grid-forming inverter system 20 decreases and the reliability of the system increases without such a switch.

The preceding description is illustrative rather than limiting in nature. Variations and modifications to the disclosed examples may become apparent to those skilled in the art that do not necessarily depart from the essence of the contribution to the art provided by the disclosed
5 embodiments. The scope of legal protection can only be determined by studying the following claims.

CLAIMS

We claim:

- 5 1. A grid-forming inverter system, comprising:
 an inverter including a plurality of switches, the inverter being configured to be
selectively connected to a power grid; and
 an electronic controller including
 a voltage magnitude module that is configured to determine a voltage magnitude
10 reference based on a voltage of the power grid when the inverter is in an inactive mode
 wherein the inverter is not operating to provide power,
 a phase locked loop module that is configured to determine a reference angle
 based on a phase angle of the voltage of the power grid when the inverter is in the
inactive mode, and
15 wherein the controller uses the voltage magnitude reference and the reference
 angle to set an initial voltage of the inverter to be approximately synchronized with the
 voltage of the power grid when the inverter switches from the inactive mode into a power
 providing mode.
- 20 2. The system of claim 1, wherein
 the inverter includes an AC filter capacitor;
 the voltage magnitude reference is based on a voltage across the AC filter capacitor;
and
 the reference angle is based on the voltage across the AC filter capacitor.

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3. The system of claim 1, wherein
the controller includes a frequency droop module that determines an angular frequency of the voltage of the power grid;
the controller includes an integrator that determines a phase angle for the initial voltage
5 of the inverter during the power providing mode; and
the integrator uses the reference angle when determining the phase angle for the initial voltage of the inverter.

10 4. The system of claim 1, wherein
the controller includes a pulse width modulation signal generator; and
the controller sets the initial voltage through pulse signals controlling the plurality of switches.

15 5. The system of claim 1, wherein
the controller includes a voltage droop module that provides a reference voltage based on a power measurement associated with the inverter;
the proportional integrator uses the voltage magnitude reference, the reference voltage from the voltage droop module and a measured voltage when determining a magnitude of the
20 initial voltage of the inverter.

6. A method of synchronizing a grid-forming inverter with a power grid, the grid-forming inverter including a plurality of switches, the method comprising:

25 connecting the inverter to the power grid while the inverter is in an inactive mode wherein the inverter is not operating to provide power;

determining a voltage magnitude reference based on a voltage of the power grid when the inverter is in the inactive mode;

using a phase locked loop module to determine a reference angle based on a phase angle of the voltage of the power grid when the inverter is in the inactive mode;

30 setting an initial voltage of the inverter based on the voltage magnitude reference and the reference angle; and

switching the inverter from the inactive mode into a power providing mode when the initial voltage of the inverter is approximately synchronized with a voltage of the power grid.

7. The method of claim 6, wherein
the inverter includes an AC filter capacitor;
the voltage magnitude reference includes determining a voltage across the AC filter
capacitor; and
5 the reference angle is based on the voltage across the AC filter capacitor.

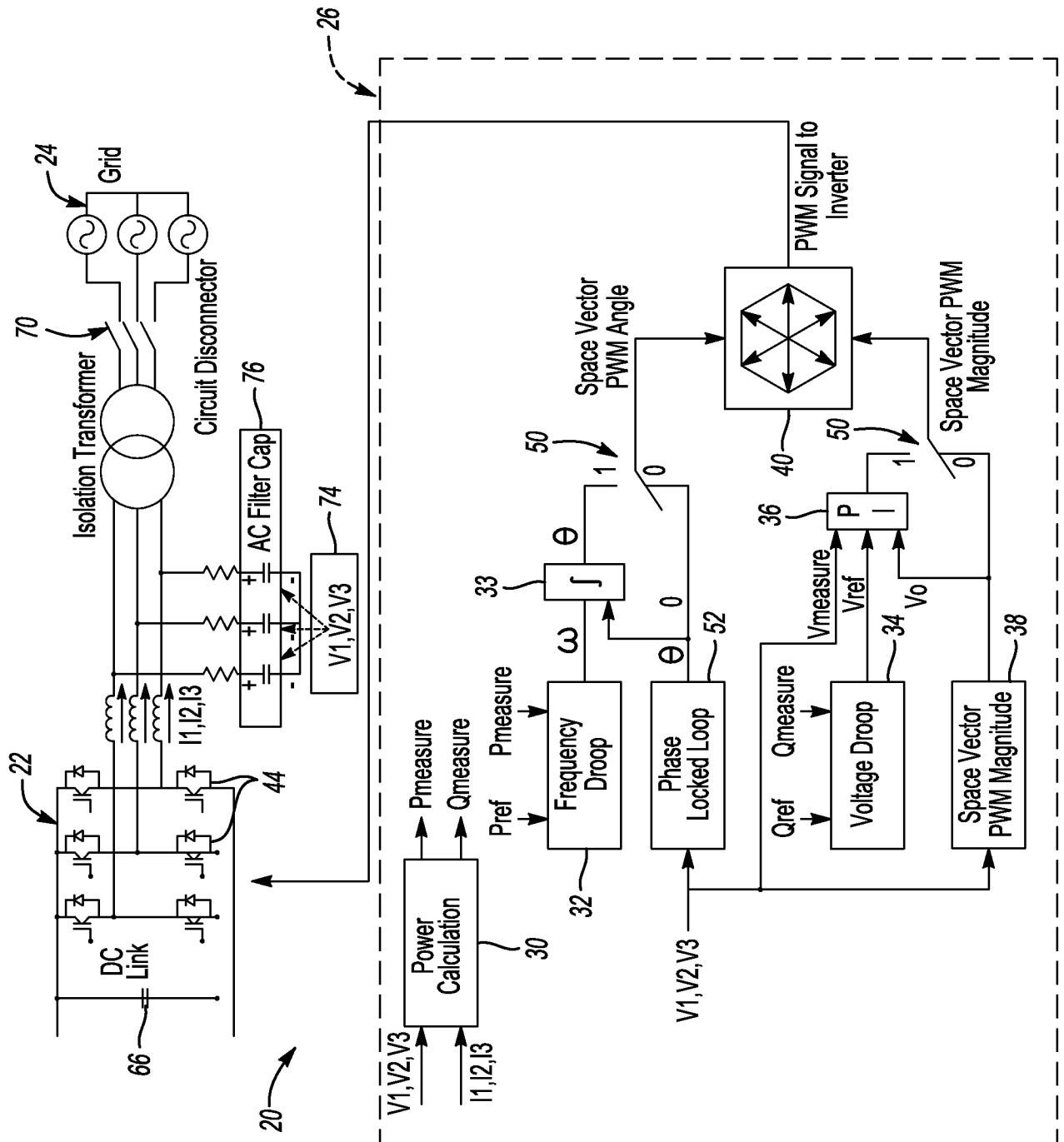
8. The method of claim 6, comprising
setting the initial voltage based on pulse width modulation signals that control the
plurality of switches.

9. The method of claim 6, wherein
the inverter includes a DC link capacitor associated with the plurality of switches; and
the method comprises charging the DC link capacitor to a preselected voltage prior to
connecting the inverter to the power grid.

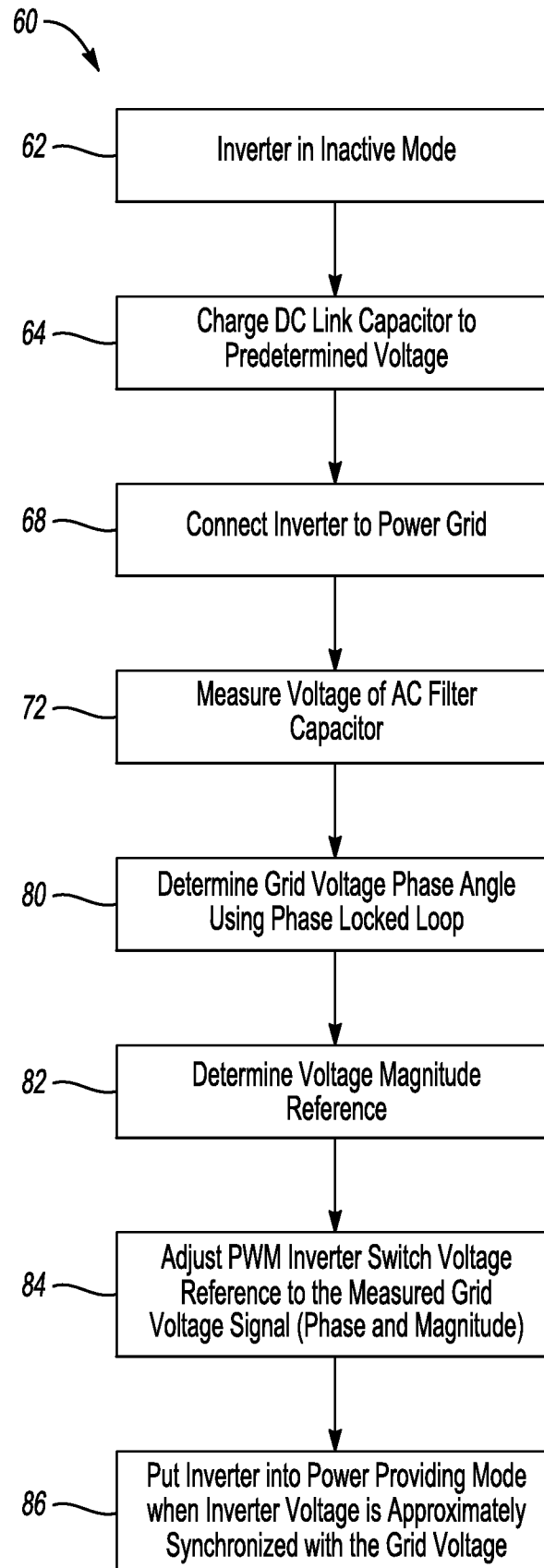
10. The method of claim 6, comprising
using a frequency droop module to determine an angular frequency of the voltage of the
power grid;
using an integrator to determine a phase angle for the initial voltage of the inverter
20 during the power providing mode, wherein the integrator uses the reference angle when
determining the phase angle for the initial voltage of the inverter.

11. The method of claim 6, comprising
using a voltage droop module to provide a reference voltage based on a power
25 measurement associated with the inverter; and
using a proportional integrator to determine a magnitude of the initial voltage of the
inverter, wherein the proportional integrator uses the voltage magnitude reference, the
reference voltage from the voltage droop module and a measured voltage when determining the
magnitude of the initial voltage of the inverter.

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2/2

**Fig-2**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/56539

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H02M 7/42 (2015.01)

CPC - H02J 3/40, H02M 7/42, Y02E 10/563

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)- H02M 7/42 (2015.01)

CPC-H02J 3/40, H02M 7/42, Y02E 10/563

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

IPC(8)- H02M7/42,7/48,7/53 (2015.01)

CPC-H02J3/40,3/42,3/44; H02M7/42,7/48,7/53, Y02E10/563; USPC - 363/95,97,98,131-134

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatBase, Proquest Dialog, Google Scholar, Google Patents,

Search terms used: inverter, switches, power, utility, grid, PLL, phase locked loop, phase, reference, angle, synchronize, inactive, off, offline, idle, mode, frequency droop, integrator, frequency droop, voltage droop

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y — A	US 8,395,919 B2 (SCHROEDER et al.) 12 March 2013 (12.03.2013) Fig 6, 8, abstract, col 4, ln 10-25, col 6, ln 17-36, col 7, ln 1-9	1, 2, 4, 6-9 3, 5, 10, 11
Y — A	US 7,183,667 B2 (COLBY et al.) 27 February 2007 (27.02.2007) Fig 1B, 2A, abstract, col 3, ln 54-67, col 5, ln 54-62, col 6, ln 4-20	1, 2, 4, 6-9 3, 5, 10, 11
A	US 2013/0073109 A1 (CHENG et al.) 21 March 2013 (21.03.2013) Fig 1-3, abstract, para [0019], [0020]	3, 5, 10, 11

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

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“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

“&” document member of the same patent family

Date of the actual completion of the international search

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