US 20130322139A1

(19) **United States**

(12) **Patent Application Publication**

LEE et al.

(10) **Pub. No.: US 2013/0322139 A1**

(43) **Pub. Date: Dec. 5, 2013**

(54) INPUT AC VOLTAGE CONTROL BI-DIRECTIONAL POWER CONVERTERS

(71) Applicant: **The University of Hong Kong**, Hong kong (HK)

(72) Inventors: **Chi Kwan LEE**, Hong Kong (CN); **Shu Yuen Ron HUI**, Hong Kong (CN)

(21) Appl. No.: **13/907,350**

(22) Filed: **May 31, 2013**

Related U.S. Application Data

(60) Provisional application No. 61/654,628, filed on Jun. 1, 2012.

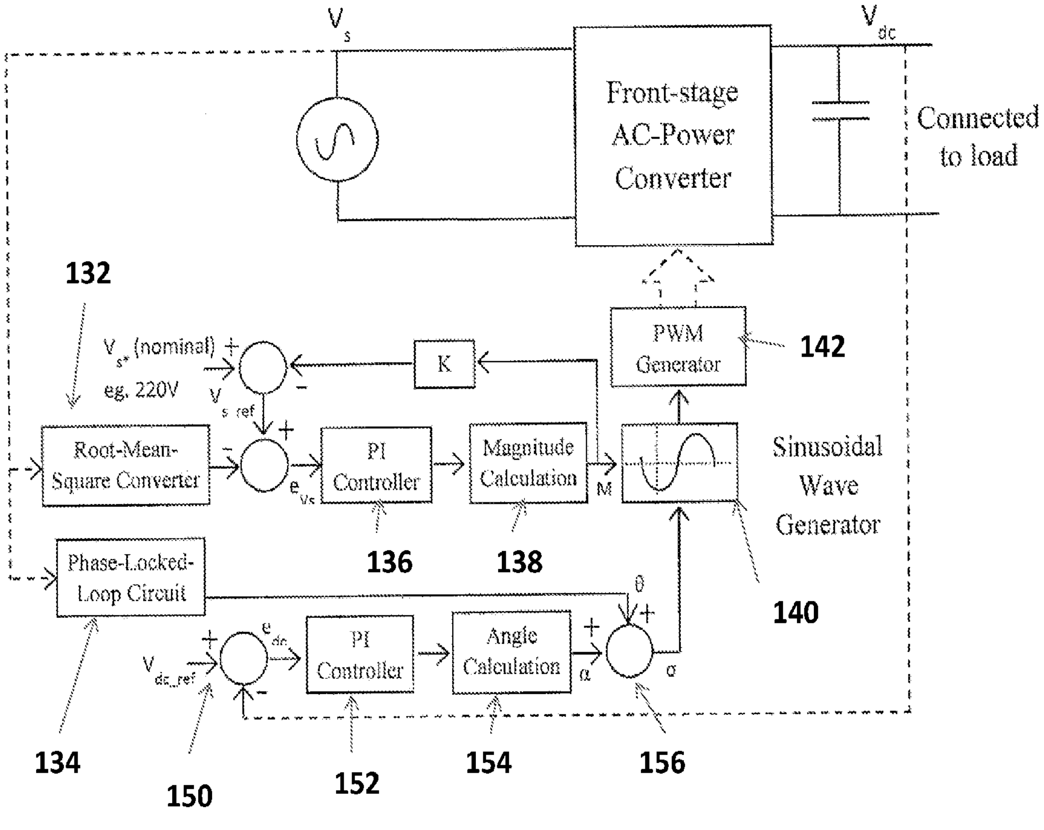
Publication Classification

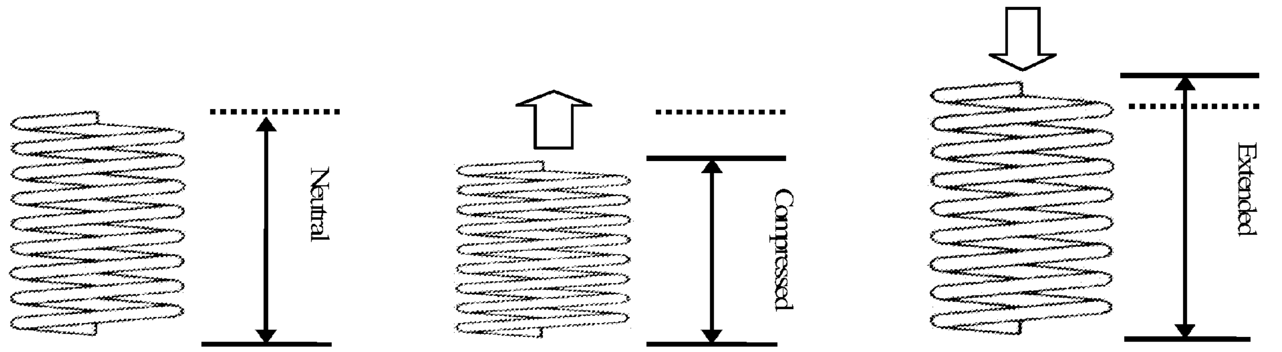
(51) **Int. Cl.**
H02M 7/68 (2006.01)

(52) **U.S. Cl.**
CPC ***H02M 7/68*** (2013.01)
USPC **363/84**

(57) **ABSTRACT**

A family of power converters has input ac voltage regulation instead of output dc voltage regulation. The bi-directional converters control power flows and maintain the input ac voltage at or close to a certain reference value. These bi-directional power converters handle both active and reactive power while maintaining the input ac voltage within a small tolerance. Use of these converters is favorable for future power grid maintenance in that they (i) ensure the load demand follows power generation and (ii) provide distributed stability support for the power grid. The converters can be used in future smart loads that help stabilize the power grid.

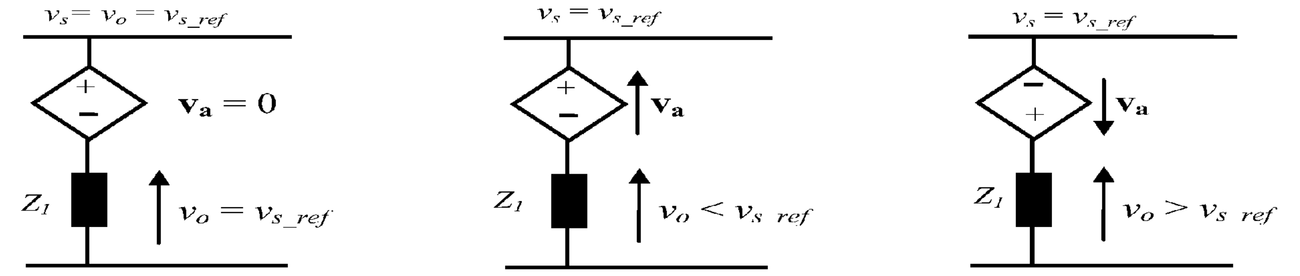




(a-1)
Neutral position

(b-1)
Mechanical push (upward force)

(c-1)
Mechanical pull (downward force)



(a-2)
Neutral position

(b-2)
Voltage boosting function

(c-2)
Voltage reduction function

FIG. 1
(Prior Art)

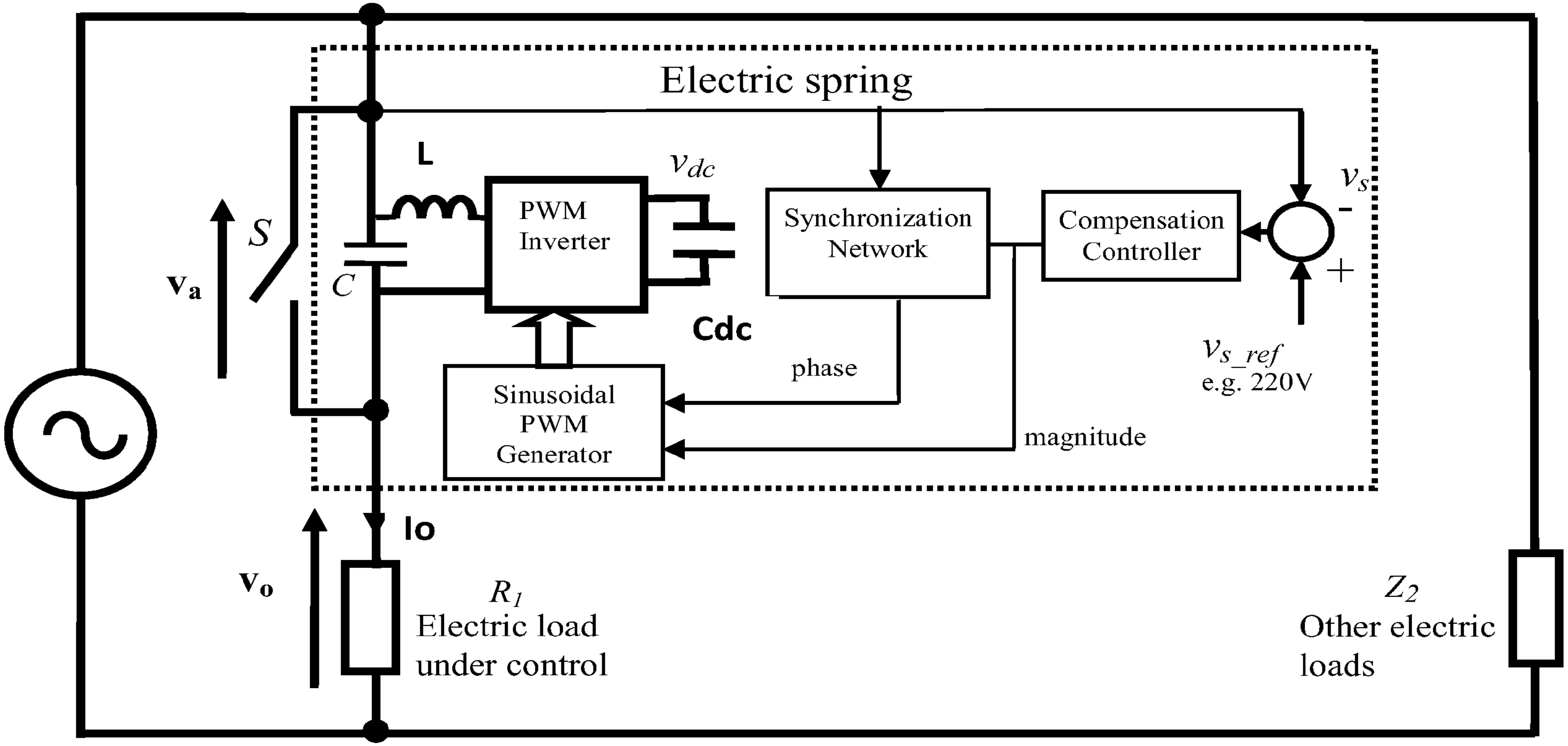
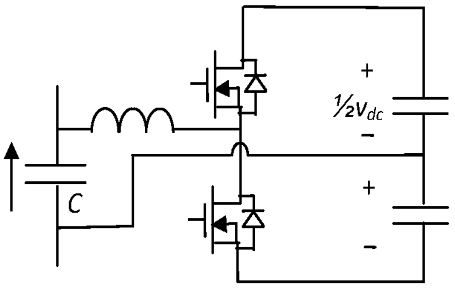
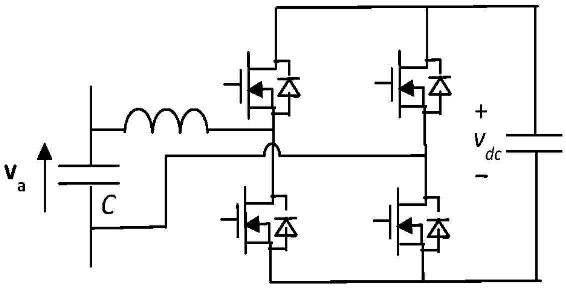


FIG. 2
(Prior Art)



A. Half-bridge inverter



B. Full-bridge inverter

FIG. 3
(Prior Art)

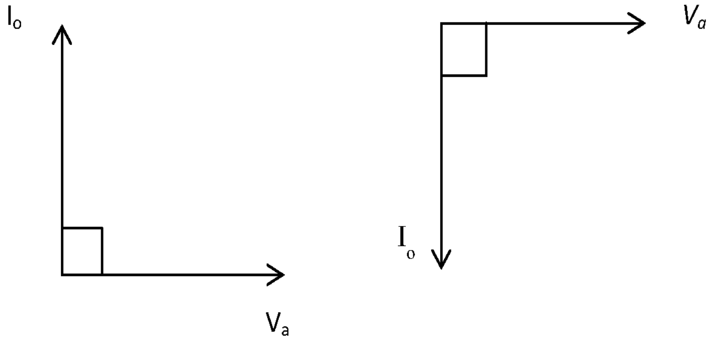
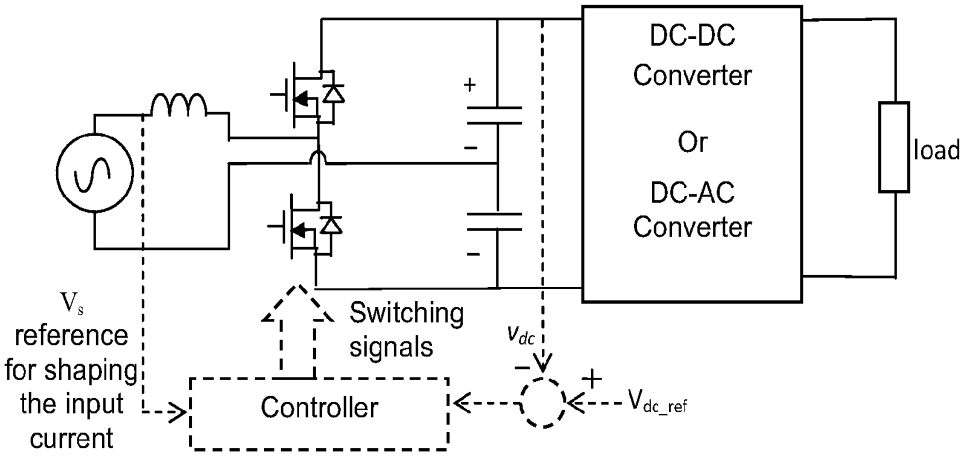
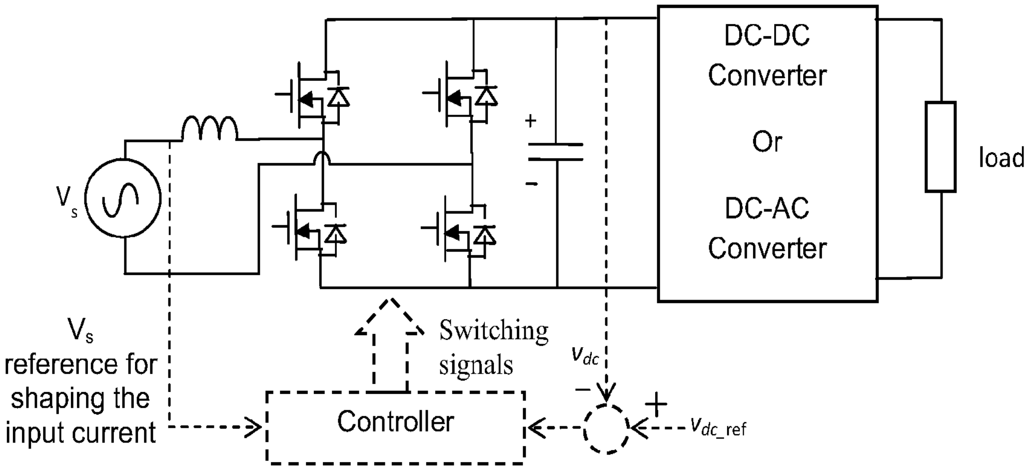


FIG. 4
(Prior Art)

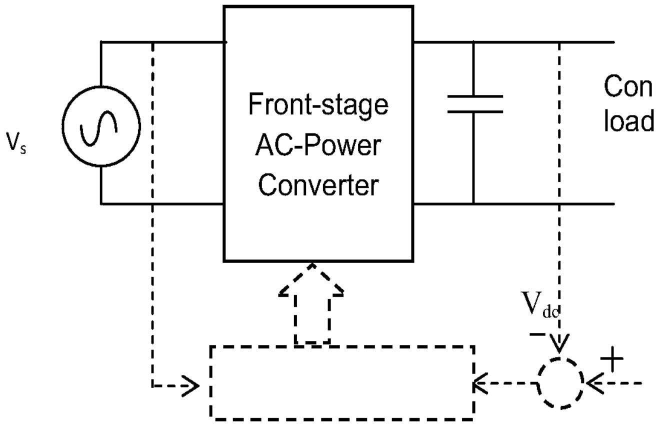


A. Typical Half-bridge ac-dc converter with “output voltage”

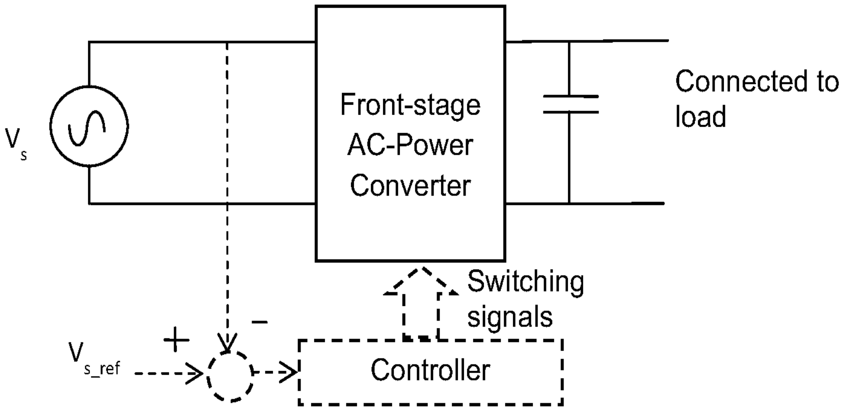


B. Typical Full-bridge inverter with “output voltage” control

FIG. 5
(Prior Art)



A. “Output-voltage” control in traditional ac-dc power conversion.



B. Proposed “input voltage” control in ac-dc power conversion

FIG. 6

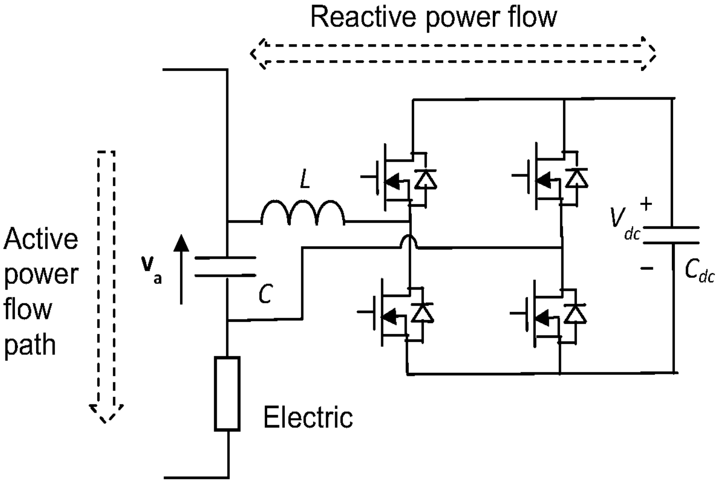

Reactive power flow
Active power flow path
v_a
L
C
Electric
V_{dc}
+
−
C_{dc}

FIG. 7A

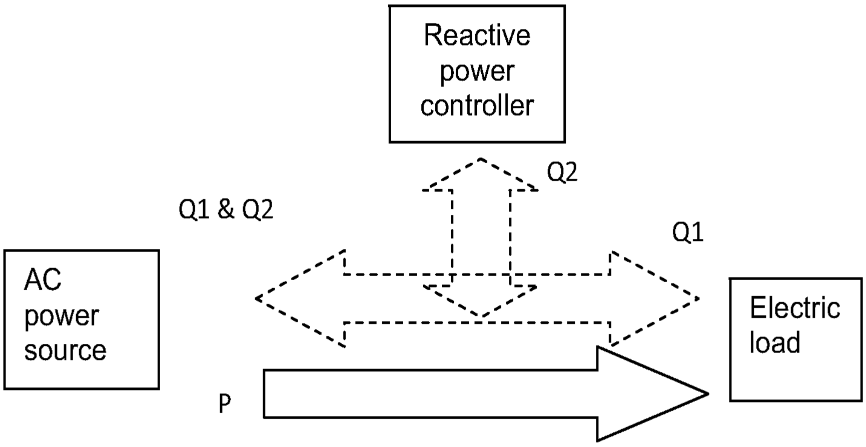

Reactive power controller
Q2
Q1 & Q2
Q1
AC power source
Electric load
P

FIG. 7B

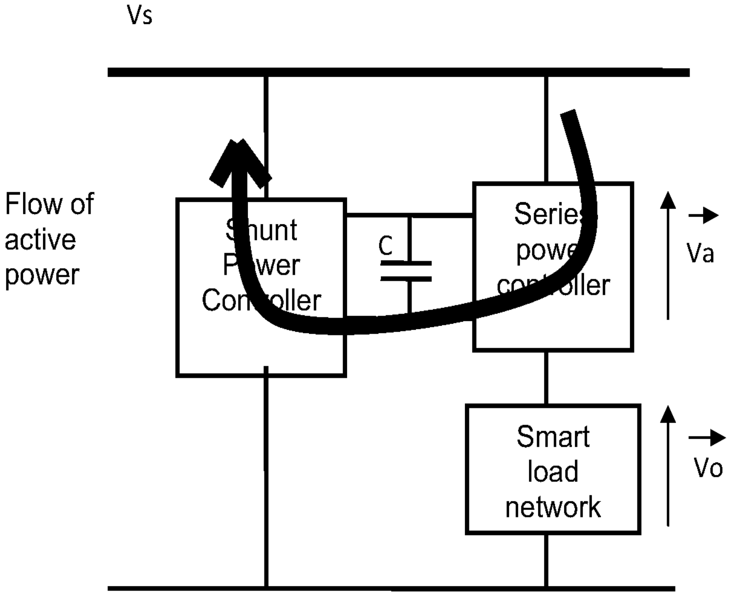

Vs
Flow of active power
Shunt Power Controller
C
Series power controller
Va
Smart load network
Vo

FIG. 8

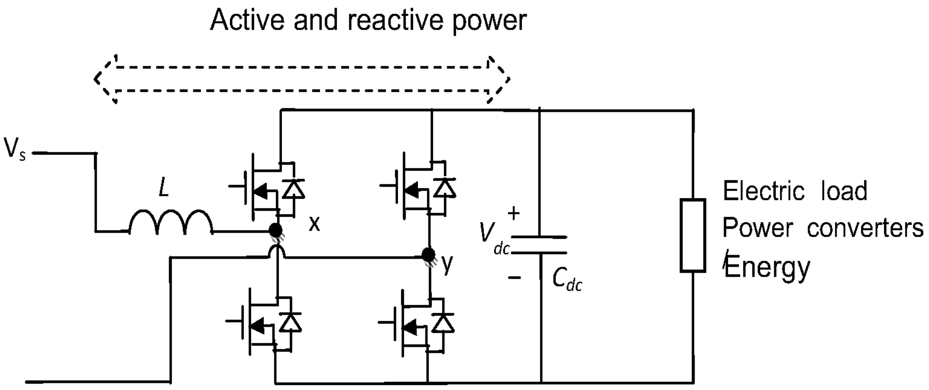

Active and reactive power
V_s
L
x
y
V_{dc}
+
–
C_{dc}
Electric load
Power converters
/Energy

FIG. 9A

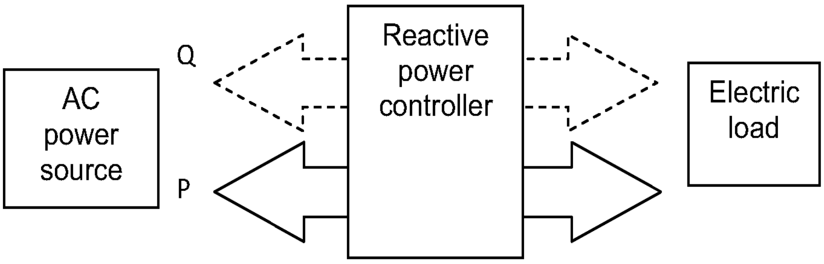

AC
power
source
Q
P
Reactive
power
controller
Electric
load

FIG. 9B

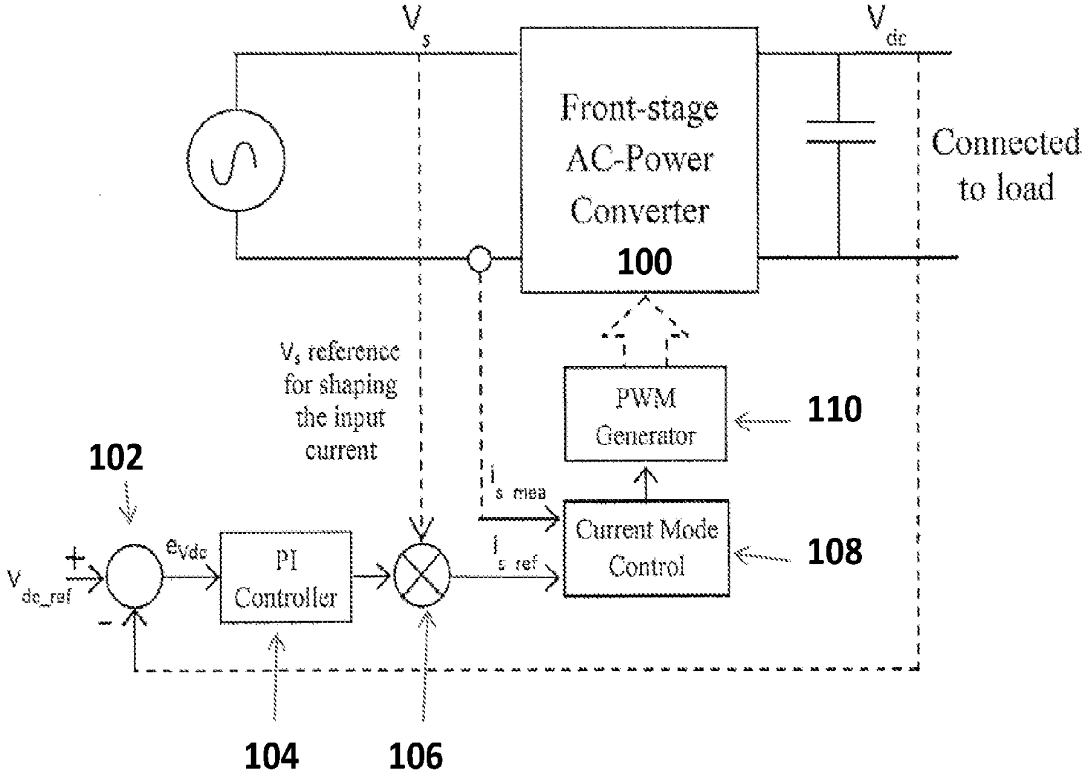


FIG. 10
(Prior Art)

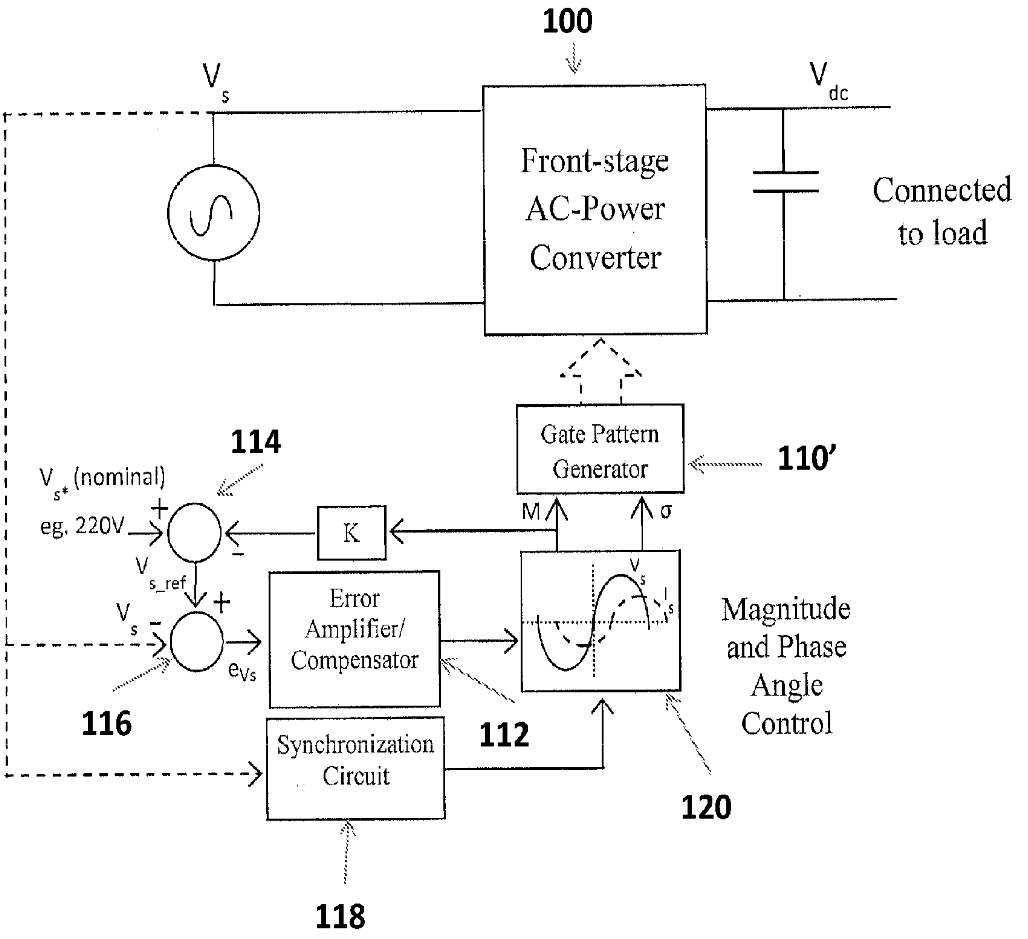

100
V_s
V_{dc}
Front-stage AC-Power Converter
Connected to load
Gate Pattern Generator
110'
114
V_{s*} (nominal)
eg. 220V
+
-
K
M
σ
V_{s_ref}
+
V_s
-
e_{Vs}
Error Amplifier/ Compensator
V_s
I_s
Magnitude and Phase Angle Control
116
112
Synchronization Circuit
120
118

FIG. 11

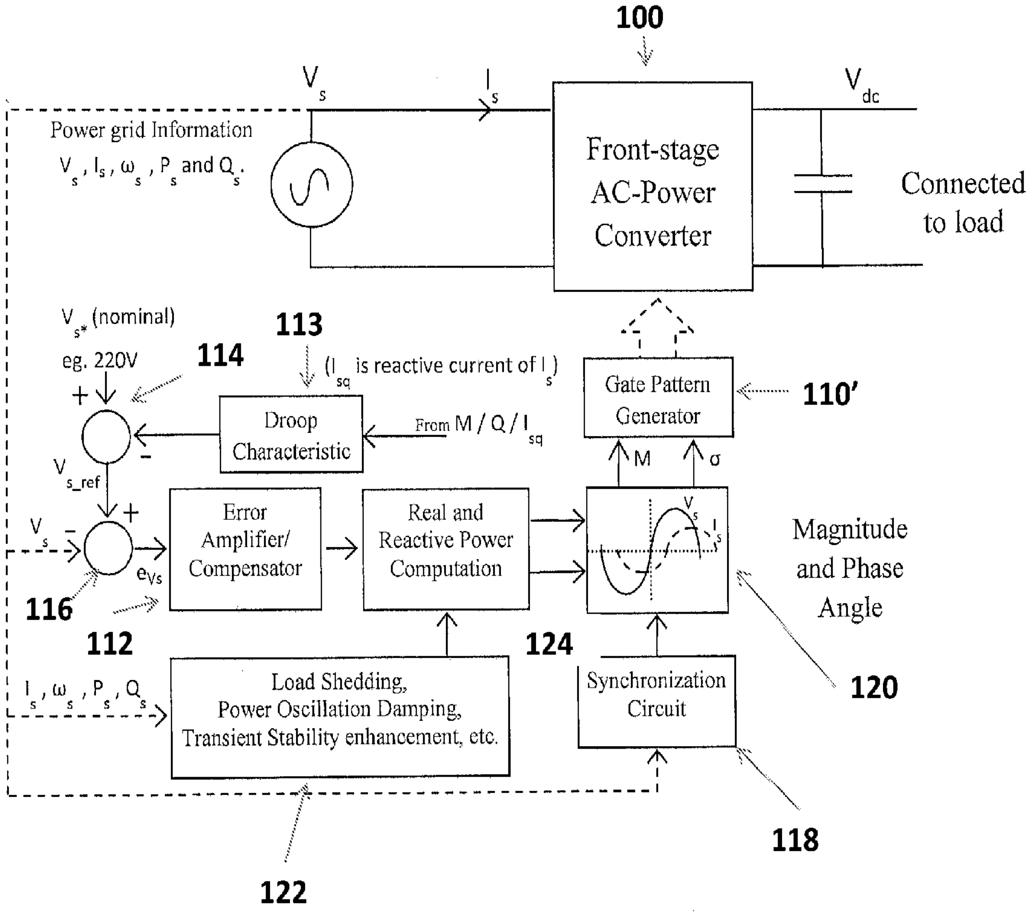

100
Vs
Is
Vdc
Power grid Information
Vs, Is, ωs, Ps and Qs.
Front-stage AC-Power Converter
Connected to load
Vs* (nominal)
eg. 220V
113
114
(Isq is reactive current of Is)
+
-
Droop Characteristic
From M / Q / Isq
Gate Pattern Generator
110′
M
σ
Vs_ref
Vs
eVs
Error Amplifier/ Compensator
Real and Reactive Power Computation
Magnitude and Phase Angle
116
112
124
Is, ωs, Ps, Qs
Load Shedding, Power Oscillation Damping, Transient Stability enhancement, etc.
Synchronization Circuit
120
118
122

FIG. 12

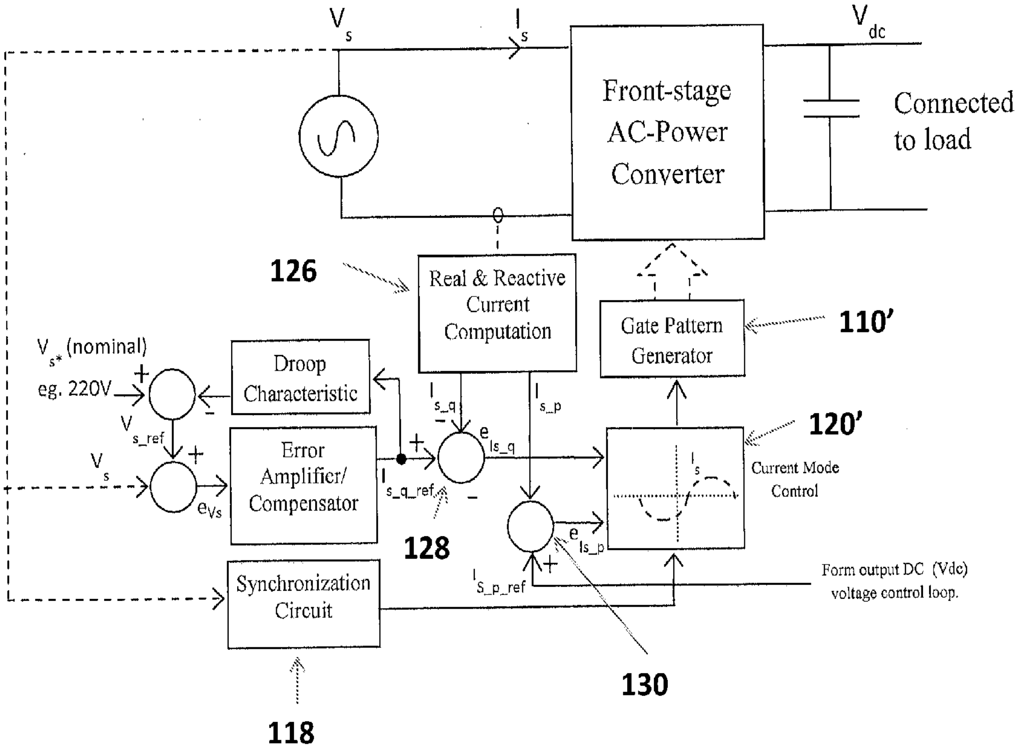

V_s
I_s
Front-stage AC-Power Converter
V_{dc}
Connected to load
126
Real & Reactive Current Computation
Gate Pattern Generator
110'
V_{s*} (nominal)
eg. 220V
Droop Characteristic
V_{s_ref}
V_s
e_{Vs}
Error Amplifier/ Compensator
I_{s_q}
I_{s_p}
e_{Is_q}
$I_{s\_q\_ref}$
128
e_{Is_p}
$I_{S\_p\_ref}$
120'
I_s
Current Mode Control
Form output DC (Vdc) voltage control loop.
Synchronization Circuit
118
130

FIG. 13

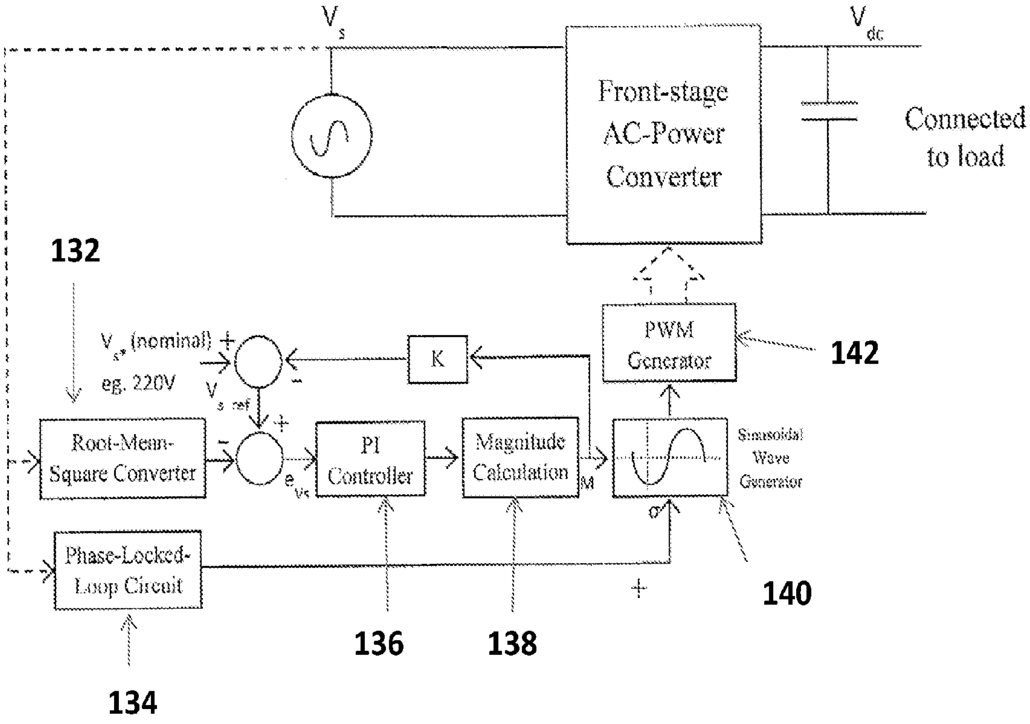

V_s
V_{dc}
Front-stage AC-Power Converter
Connected to load
132
V_{s*} (nominal) +
eg. 220V
$V_{s\ ref}$
+
−
−
K
PWM Generator
142
Root-Mean-Square Converter
e_{Vs}
PI Controller
Magnitude Calculation
M
Sinusoidal Wave Generator
σ
Phase-Locked-Loop Circuit
+
140
136
138
134

FIG. 14

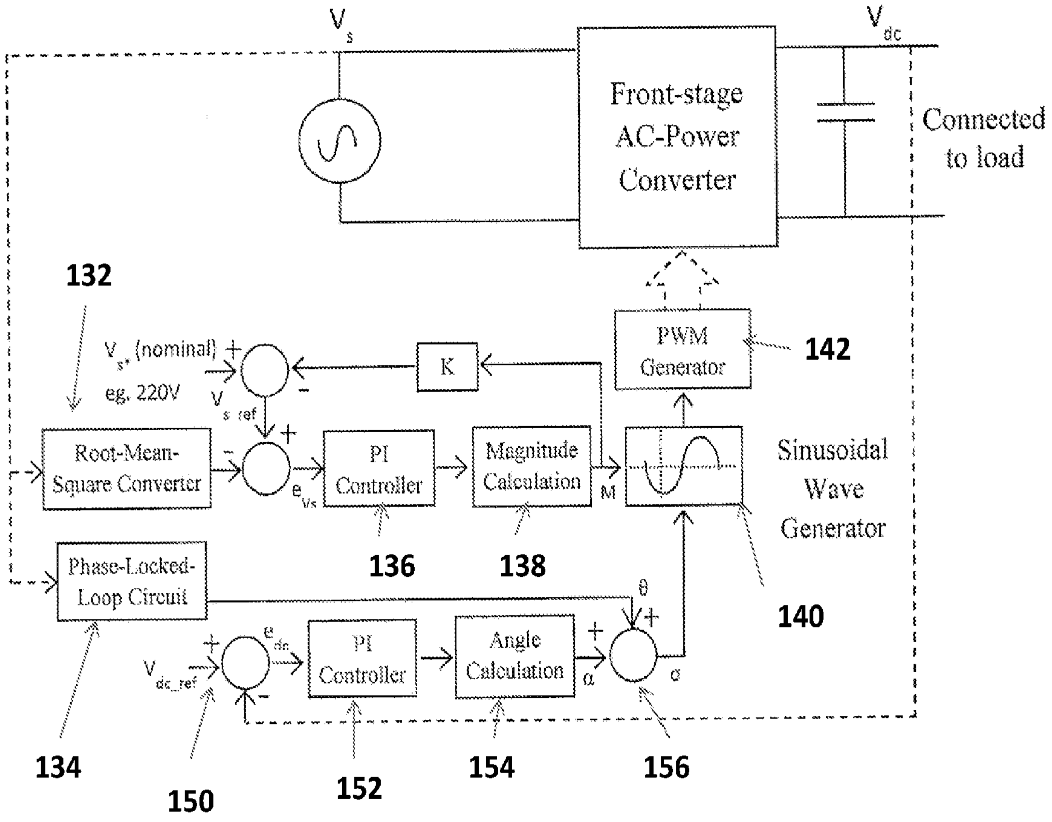

V_s
V_dc
Front-stage AC-Power Converter
Connected to load
132
V_s* (nominal) eg. 220V
V_s_ref
+
-
K
PWM Generator
142
Root-Mean-Square Converter
e_Vs
PI Controller
Magnitude Calculation
M
Sinusoidal Wave Generator
136
138
140
Phase-Locked-Loop Circuit
θ
V_dc_ref
e_dc
PI Controller
Angle Calculation
α
σ
134
150
152
154
156

FIG. 15

INPUT AC VOLTAGE CONTROL BI-DIRECTIONAL POWER CONVERTERS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of U.S. patent application Ser. No. 61/654,628, filed Jun. 1, 2012 which is hereby incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] 1. Technical Field

[0003] The subject matter disclosed herein relates to input ac voltage regulation and power flow control of bi-directional AC-DC power converters and bi-directional AC-AC converters.

[0004] 2. Description of Related Art

[0005] The increasing awareness of climate change has prompted many governments worldwide to impose policies that call for the introduction of renewable energy sources. Presently power generation is “centralized” and “unidirectional,” By monitoring the voltage and frequencies of the power grid, the utility companies can determine the amount of electricity needed by the load centers (such as a city) and can generate the required amount of electric power from the power plants. A balance of power generation and load is an essential condition for the stability of the power system. Although the difference between power generation and load demand can be absorbed by energy storage, energy storage is either expensive (such as batteries) or dependent on locations (such as water reservoirs). For existing power systems, the control paradigm is to have “the power generation follow the load demand” in order to maintain power system stability.

[0006] In future power grids, renewable energy sources such as solar panels and wind power generators will be installed in a “distributed” manner and the power flow could be “bidirectional,” i.e., the power can be supplied to the grid from these generators or taken from the grid by these generators. These distributed renewable power sources, both known or unknown to the utility companies, make it very difficult for the power companies to control the power balance. Therefore, there is a need for a shift of the control paradigm for a future power grid with substantial penetration of intermittent renewable energy. In the new paradigm “the load demand has to follow power generation.”

[0007] In order to achieve power balance, various methods have been proposed previously. Scheduled load shedding has been a traditional method in load power control. However, such a method is not useful for maintaining dynamic power balance in real-time. Smart loads with ON/OFF control for electric loads, such as refrigerators and air-conditioning systems [1-3], have been proposed for real-time power balance. See, the articles [1] S. C. Lee et al., “Demand Side Management With Air Conditioner Loads Based on the Queuing System Model,” IEEE Transactions on Power Systems, Volume: 26, Issue: 2, 2011, pages 661-668; [2] G. C. Heffner et al., “Innovative approaches to verifying demand response of water heater load control,” IEEE Transactions on Power Delivery, Volume: 21, Issue: 1, 2006, pages 388-397; and [3] A. Brooks et al., “Demand Dispatch,” IEEE Power and Energy Magazine, Volume: 8, Issue: 3, 2010, pages 20-29. However, shutting down electrical appliances is intrusive and may cause inconvenience to and opposition from consumers.

[0008] Recently, an electric spring concept based on the three centuries old Hooke’s law has been proposed and practically embedded in electric loads to regulate the line or mains voltage in the power grid. See, [4] S. Y. R. Hui et al., “Power Control Circuit and Method for Stabilizing a Power Supply,” U.S. patent application Ser. No. 61/389,489, filed on 4 Oct. 2010 (Patent Application Publication No. US2012/0080420 A1). The electric spring concept refers to the use of a power converter together with its load to form a “smart load” unit that can provide regulation of the mains voltage. With the use of an input voltage control (instead of the traditional output voltage control), reactive power converters (i.e. power converters that handle reactive power only and not active power) have been used to fulfill the electric spring concept. The electric spring implementation based on the use of a controlled voltage source connected in series with an electric load is described in the above-identified Hui article and is shown in FIG. **1**. The controlled voltage source can be realized with a reactive power converter. The power converter can be a power inverter in which a large capacitor C_{dc} is used as a controllable dc voltage source (V_{dc}) as shown in FIG. **2**. The power inverter can then be switched in a sinusoidal pulse-width modulated (PWM) manner to generate a switched PWM voltage waveform with a strong fundamental voltage and some high-frequency voltage harmonics. The high-frequency voltage harmonics are filtered by the inductive-capacitive (LC) filter so that only the sinusoidal fundamental voltage (V_a) is generated across the capacitor of the LC filter as the voltage output of the electric spring. It should be noted that in the control scheme shown in FIG. **2** the electric spring uses “input voltage control.” The control variable is the input voltage of the reactive power converter, which is the mains voltage (V_s) at the location of the installation of the equipment. The output voltage of the reactive power control (V_o) is allowed to fluctuate for the regulation of the mains voltage V_s. In order to ensure that the power converter works as a reactive power controller, the vector relationship of V_a and I_o is perpendicular when Io is not zero as shown in FIG. **4**.

[0009] The International Electrotechnical Commission Regulation IEC 61000-3-2 requires offline electric equipment of 20 W or above to comply with electromagnetic compatibility requirements. For equipment fed by ac mains, the input power factor must be kept at or above 0.9. In modem electric equipment such as switched mode power supplies for computers and servers, power factor corrected (PFC) ac-dc power converters are commonly used to ensure that the input voltage and input current are in phase (i.e. unity power factor if the input current is sinusoidally shaped). In this regard, the power inverters (half-bridge or full-bridge inverters in FIG. **3**) can be used as ac-dc power converters as shown in FIG. **5**.

[0010] In existing ac-dc power conversion applications, it is always assumed that the mains voltage is sinusoidal and stable at its nominal rms value (such as 230V), because most developed countries have well regulated mains voltage that is kept to its nominal value with a +/−6% tolerance in developed countries and +/−10% in other regions. Therefore, traditional ac-dc power converters normally assume a fairly stable ac mains supply. For this reason, no input-voltage control (except that in the Hui et al. article and application, which is by the present inventors) has been reported. Traditional ac-dc power converters adopt the “output-voltage control” because they are used for regulating the output dc voltage. For the power factor corrected (PFC) converters in FIG. **5**, the mains voltage is sensed so that the power converter can be switched to force the input current of the power converter to follow the sinusoidal shape of the mains voltage and be in phase with the mains voltage. In this way, near unity power factor can be achieved. The magnitude of the input current is controlled to maintain a fairly constant output de voltage (Vdc) through an "output-voltage control" feedback loop. For a 220V-240V rms mains supply, typical Vdc is controlled at a dc voltage of about 400V. Because the input voltage and current of this PFC converter are in phase, the PFC power converter with its output load emulates a pure resistor. Therefore, the PFC converter fed load system consumes active power. Also, power flow is unidirectional from the mains to the load. However, in future power grids with substantial renewable energy sources of an intermittent nature, the assumption that the mains voltage can be stable within the +/−6% is questionable.

SUMMARY OF THE INVENTION

[0011] The present invention is directed a method and apparatus for stabilizing a power grid that includes substantial intermittent energy sources by using bidirectional reactive power controller arrangements.

[0012] In an illustrative embodiment an ac-dc power converter, which may be found on a number of consumer products connected to the mains, is modified so that it has input voltage control, which in turn allows it to act as a smart load and to stabilize the grid. Naturally the grid is too powerful for any one converter to balance it, so it is contemplated that the converters will be implemented in a vast number of products so that the overall effect will be a stabilized grid.

[0013] The distinctive feature of the invention with respect to the traditional ac-dc power conversion method is illustrated in FIG. **6**. In a traditional schematic, there is no input voltage control because the existing mains voltage in is well regulated. As previously explained, the distributed and intermittent nature of renewable energy sources may cause power imbalance between power generation and load demand, leading to the possibility of power instability such as fluctuation in the mains voltage. The mains voltage in future power grids may not be stable. Therefore, "input voltage control" is proposed for ac-dc power converters with both active and reactive power flow control. The principle applies to both single-phase and multi-phase systems.

[0014] In the Hui published patent application, the electric load is connected in series with filter capacitor C of the power converter (FIG. **7**A). The corresponding power flow diagram is shown in FIG. **7**B. Active power does not flow through the power converter. Since the dc bulk capacitor of the power converter in FIG. **7**A does not consume active power, the power converter in FIG. **7**A only handles reactive power.

[0015] There is also one version of the reactive power controller arrangements in Hui that can handle both active and reactive power as shown in FIG. **8**. It should be noted that this power converter circulates active power through the power converter, and that the active power does not come from the electric load. This is in fact a limitation in the proposal described in Hui. This means that active power cannot be transferred from the electric load back to the a.c. mains supply in the proposal of Hui. However, according to the present invention, the electric load is connected to the d.c. bulk capacitor such that the power converter in FIG. **9**A handles both active and reactive power. The power flow diagram of this embodiment of the invention is shown in FIG. **9**B. Both active and reactive power components have to go from the mains to the load through the power converter in the present invention. A comparison of the power flow diagram in FIG. **7**B with that in FIG. **9**B, highlights the major differences between the present invention and that of the Hui publication. Since the power converter in this proposal can handle both active and reactive power, the input voltage and current can be in any phase relationship.

[0016] The present invention is particularly useful for electric loads with energy storage elements. For example, electric vehicles have batteries and, if necessary, active power can be transferred from the batteries to the a.c. mains supply.

[0017] The present invention proposes a new approach in order to utilize the electric spring concept in stabilizing future power grids. Similar to the electric spring implementation described in Hui, this new realization has some of the same electric spring features. These include:

[0018] (i) the use of "input voltage control" in the power converter with the mains voltage as input,

[0019] (ii) the use of a power converter such as a power inverter (i.e. ac-dc power converter), and

[0020] (iii) the provision of input voltage regulation functions (i.e. the regulation of the mains voltage).

However, unlike the approach in Hui, the present invention has the following differences as illustrated in FIG. **7**B and FIG. **9**B using a single-phase system as an example (the principle also applies to multi-phase systems).

[0021] (i) The electric load is connected to the bulk d.c. capacitor of the power converter (while the electric load in Hui is connected in series with the filter capacitor of the power converter).

[0022] (ii) Electric loads can include a second power converter stage, an energy storage device and the output load.

[0023] (iii) The power converter can handle BOTH active and reactive power (while the power converter in Hui can only handle reactive power).

[0024] (iv) Active and reactive power can flow in BOTH directions, i.e. from the mains to the power converter and vice versa.

[0025] (v) The vectors of the input voltage and input current of the power converter are NOT necessarily fixed at perpendicular positions. They can be in any phase relationship.

[0026] (vi) The control parameter in the power converter can also include the mains frequency ωs to improve the power grid stability.

[0027] (vii) The output voltage of the power converter is regulated when the power converter ONLY provides reactive power compensation to the power grid.

[0028] (viii) The output voltage of the power converter is allowed to fluctuate when the power converter provides active power compensation to the power grid.

BRIEF DESCRIPTION OF DRAWINGS

[0029] The foregoing and other features of the present invention will be more readily apparent from the following detailed description and drawings of illustrative embodiments of the invention wherein like reference numerals refer to like parts throughout the various figures unless otherwise specified and in which:

[0030] FIGS. **1**A, **1**B and **1**C illustrate the electric spring concept for neutral, boosting and reduction functions;

[0031] FIG. **2** is a block diagram of a prior art reactive power converter in the form of an inverter;

[0032] FIGS. **3**A and **3**B are schematic diagrams of prior art half-bridge and full-bridge inverters, respectively, which can be used as reactive power converters;

[0033] FIG. **4** s a diagram illustrating the vector relationship between voltage and current in the reactive power controller of FIG. **2** when the current I_o is not zero;

[0034] FIGS. **5**A and **5**B are schematic diagrams of single-phase examples of prior art ac-dc power converters based on half-bridge and full-bridge power inverters, respectively, with "output voltage" regulation;

[0035] FIGS. **6**A and **6**B are schematic diagrams of, respectively, a prior art ac-dc power converter with output-voltage control and an ac-dc power converter with input voltage control according to the present invention;

[0036] FIG. **7**A is a schematic diagram of a single phase power converter using an electric spring with reactive power control as in the Hui publication;

[0037] FIG. **7**B is a power flow diagram of the power converter of FIG. **7**A;

[0038] FIG. **8** is block diagram illustrating one version of the electric spring in the Hui publication with a series power controller absorbing active power and a shunt power controller feeding the active power back to the mains power lines.;

[0039] FIG. **9**A is a schematic diagram of a single phase power converter using an electric spring with both active and reactive power control in accordance with an embodiment of the present invention;

[0040] FIG. **9**B is a power flow diagram of the power converter of FIG. **9**A;

[0041] FIG. **10** is a block diagram of an output-voltage control in a prior art ac-dc power conversion with well-regulated mains voltage;

[0042] FIG. **11** is a block diagram of an ac-dc power converter with input-voltage control according to an embodiment of the present invention where the mains voltage may not be stable due to intermittent renewable energy sources on the grid;

[0043] FIG. **12** is a block diagram of an ac-dc power converter with an input-voltage control according to another embodiment of the present invention with auxiliary control signals to improve transient and dynamic power system stability;

[0044] FIG. **13** is a block diagram of an ac-dc power converter with an input-voltage control according to a further embodiment of the present invention using a current mode control method:

[0045] FIG. **14** is a block diagram of an ac-dc power converter with input-voltage control according to a still further embodiment of the present invention; and

[0046] FIG. **15** is a block diagram of an ac-dc power converter with input-voltage control according to a yet another embodiment of the present invention.

DETAILED DESCRIPTION

[0047] The main objective of using a bi-directional ac-dc power converter with flexible control of the vector relationships of the input voltage and input current of the ac-dc power converter is to provide a new mechanism of regulating the mains voltage. This objective is achieved with the help of an input voltage control loop (FIG. **5**). An electric load with this front end bidirectional ac-dc power converter and the input voltage control can be considered as a new form of "smart load" that can help stabilize the mains voltage in future power grids that may be subject to disturbance and fluctuation caused by the intermittent nature of renewable power sources. The converter in this proposal can also perform load demand response, such as load shedding, or even provide active power compensation/injection to the power grid to improve the power balance.

[0048] The bidirectional ac-dc power converters concerned in this invention not only include standard power converters constructed with converter legs comprising power switches in 2-level or N-level totem-pole arrangements, but also include other variants of ac-dc power converters such as the Z-inverters. The principle applies to both single-phase and multi-phase systems.

[0049] FIG. **10** shows the traditional "output-voltage control" scheme of bi-directional ac-dc power converters **100**. No input voltage control is used traditionally because in existing power systems with no or limited intermittent renewable power generation, tight mains voltage (V_s) regulation can be assumed. As shown in FIG. **10** the dc output voltage V_{dc} is compared to a reference voltage in comparator **102**. The difference signal is applied to PI Controller **104**, whose output is multiplied with the input mains voltage V_s in a multiplier **106**. The input current I_{s_mea} is measured and applied to current mode control **108**. The output of multiplier **106** is the current reference signal I_{s_ref}, which is also applied to Current Mode Control **108**. The output of the Current Mode Control **108** drives the Pulse-Width Modulation Generator **110** which sets the pulse width and frequency in the AC power Converter **100**. The input current (Is) is switched and shaped by the AC power Converter into the required sinusoidal shape with magnitude and phase angle according to the $_{Is\_ref}$.

[0050] FIG. **12** shows a version of the new input-voltage control scheme for bi-directional ac-dc power converters **100** with both active and reactive power flow control. The mains voltage (V_s) at which this power converter is installed is sensed as a feedback variable (shown in dashed lines). From this sensed voltage signal, the phase angle and/or the frequency of the ac mains voltage can be obtained from circuit **118**. The sensed mains voltage is compared with a mains voltage reference (V_{s_ref}) in comparator **116**. The mains voltage reference can be derived with the Droop Characteristic circuit **113** based on the magnitude of the PWM signal (M), the reactive power (Q) and the input current (I_s). As depicted in FIG. **11**, the Droop Characteristic circuit can comprise a feedback gain K applied to signal M, and a comparison of that signal to the nominal mains signal V_s in comparator **114** to derive the mains voltage reference (V_{s_ref}). The difference signal e_{Vs} is applied to an error amplifier/compensator **112**. As shown in FIG. **11** the output of this circuit is applied to Magnitude and Phase Angle circuit **120**. Further, a Synchronization circuit **118** receives the mains signal V_s and its output is also applied to circuit **120**. Circuit **120** generates at least two control variables, namely the magnitude (M) and the phase angle (σ) of the PWM, which are applied to the Gate Pattern Generator **110'**, which in turn drives the front-stage ac-dc power converter **100**, with the objective of controlling the active and reactive power of the bidirectional ac-dc power converter so that the mains voltage Vs will be regulated to a certain mains voltage reference V_{s_ref}. The more complex version shown in FIG. **12** includes a control circuit **122** whose output depends on the input current (Is), angular frequency (ωs), active power (P_s) and reactive power (Q_s). The output of circuit **122** and the Error Amplifier/Compensator **112** are combined in Real and Reactive Power Computation circuit **124**. The two outputs of circuit **124** are applied to Magnitude and Phase Angle circuit **120** along with the output of Synchronization circuit **118**. The result is the magnitude control signal (M) and the phase angle (σ).

[0051] For a single-phase bidirectional ac-dc power converter, this PWM voltage applied to converter **100** from gate pattern generator **110'** is the voltage between points x and y (i.e. V_{xy}) in FIG. **9**A. Beside the magnitude control signal (M) of V_{xy}, the control loop also provides the phase angle (σ) which is the angle between V_s and V_{xy}. With the control of V_{xy} and σ, the magnitude and phase angle of input current (i.e. the input inductor current) can be controlled. Therefore, both active and reactive power can be controlled to regulate the mains voltage to the mains voltage reference value at the location of the installation.

[0052] Another input voltage control scheme is shown in FIG. **13**. In this control scheme, both the input voltage (V_s) and the input current (Is) are sensed. Information, such as input voltage (V_s), input current (Is), angular frequency (ω_s), phase angle between Vs and Is, active power (P) and reactive power (Q), are thus obtained. With the knowledge of P and Q and the help of a synchronous circuit **118**, the magnitude (M) and angle (σ) control signals for the ac-dc power converter **100** can be derived with the objective of regulating the input mains voltage Vs to follow its reference V_{s_ref}.

[0053] FIG. **11** and FIG. **12** show two control schemes that generate control signals for the PWM voltage of the bi-directional ac-dc power converter. These two schemes control the input current indirectly, by directly controlling the PWM voltage of the ac-dc power converter. The alternative control scheme as shown in FIG. **13** uses a direct current control. The direct current control scheme in FIG. **13** is similar to that of the indirect current control schemes in terms of the use of voltage and droop control. However, the magnitude and angle control variables which this scheme generates are for the direct control of the input current. In FIG. **13**, the instantaneous input current is sensed in circuit **126** and fed into a current control loop for comparison with the current reference $I_{s\_q\_ref}$ generated at the output of the error circuit **112** by the input voltage control scheme. This input current (I_s) is switched and shaped by the bi-directional power converter into the required sinusoidal shape with magnitude and phase angle according to the input voltage control with the objective of regulating the input ac voltage. In particular, quadrature phase current I_{s_q} is compared to $I_{s\_q\_ref}$ in comparator **128**. The in-phase current I_{s_p} is compared to the reference current $I_{s\_p\_ref}$ from the output of the dc voltage control loop in comparator **130**. The outputs of the comparators **128**, **130** are directed to the Current Mode Control **120'**, which in turn drives the Gate Pattern Generator **110'**.

[0054] An example of the implementation of the input voltage control scheme based on a proportional-integral (PI) compensator is shown in FIG. **14**. In FIG. **14** the input voltage is sampled and applied to both a Root-Mean Square Converter **132** and a Phase-Locked Loop circuit **134**. Comparators **114** and **116** are used to generate the output e_{Vc} in the same way as shown in FIG. **11**, except that one of the inputs to comparator **116** is the output of Root-Mean Square Converter **132** instead of the input voltage Vs. The signal e_{Vc} is applied to the Proportional-Integral (PI) compensator **136**, whose output is applied to Magnitude Calculation circuit **138**. Note that circuit **138** does not generate a phase signal, only the magnitude signal M. Further, the signal M drives the Sinusoidal Wave Generator **140**. The output of Phase-Locked Loop circuit **134** is also applied to generator **140**, which has an output that drives the PWM generator **142**. Generator **142** controls the AC-Power Converter **100**.

[0055] The input voltage control scheme proposed in this invention does not exclude a control methodology that involves the use of output voltage feedback to assist the proposed input voltage control. An example of an implementation of the input voltage control scheme of FIG. **11**, as represented by the arrangement of FIG. **14**, assisted with the output voltage feedback for the "input voltage control" of the bi-directional power converter, is shown in FIG. **15**. In particular, instead of the output of the Phase-Locked Loop circuit **134** being applied directly to generator **140**, it is applied to a comparator **156**. The dc output voltage of the arrangement V_{dc} is compared to a reference in comparator **150**. The output e_{dc} drives a second PI controller **152**, whose output drives an Angle Calculation circuit **154**. The output of the Angle Calculation circuit **154** is the second input to comparator **156**. It is the output of comparator **156** that drives the Sinusoidal Wave Generator **140** along with the signal M from the Magnitude Calculation circuit **138**.

[0056] While certain exemplary techniques have been described and shown herein using various methods and systems, it should be understood by those skilled in the art that various other modifications may be made, and equivalents may be substituted, without departing from claimed subject matter. Additionally, many modifications may be made to adapt a particular situation to the teachings of the claimed subject matter without departing from the central concept described herein. Therefore, it is intended that the claimed subject matter not be limited to the particular examples disclosed, but that such claimed subject matter may also include all implementations falling within the scope of the appended claims, and equivalents thereof.

[0057] Any reference in this specification to "one embodiment," "an embodiment," "exemplary embodiment," etc., means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. The appearances of such phrases in various places in the specification are not necessarily all referring to the same embodiment. In addition, any elements or limitations of any invention or embodiment thereof disclosed herein can be combined with any and/or all other elements or limitations (individually or in any combination) or any other invention or embodiment thereof disclosed herein, and all such combinations are contemplated with the scope of the invention without limitation thereto.

[0058] It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

What is claimed is:

1. A bi-directional power converter fed by an input ac power source and providing an output to an electric load (which may have at least one energy storage element), said converter being able to handle active power, reactive power or both in a bi-directional manner, comprising:

an input voltage control and regulator; and

wherein the voltage and current vectors of the said power converter are not restricted to 90 degrees.

2. The power converter of claim **1** wherein the input ac power source is an unstable ac mains voltage generated by an a.c. power source with substantial intermittent renewable energy sources.

3. The power converter of claim **1** wherein said input voltage control and regulator controls the input current magnitude and its phase angle with respect to the input ac voltage in order to regulate the input ac voltage to a nominal value or within a range of nominal values.

4. The power converter of claim **1** wherein said input voltage control and regulator generates voltage magnitude and phase angle signals for the control of the power converter when voltage-mode control is adopted, and the generation of current magnitude and phase angle signals for the control of the power converter when current-mode control is adopted.

5. The power converter of claim **4** wherein the phase angle signal is generated with the use of a synchronization circuit.

6. The power converter of claim **1** wherein said input voltage control and regulator is implemented by one of various control approaches including proportional-integral-differential (PID) methods, lead-lag compensation methods and, state-space control, sliding mode control, non-linear boundary control methods.

7. The power converter of claim **1** further including an output voltage feedback loop.

8. The power converter of claim **1** wherein it processes active power or reactive power or both between the input ac power source and the output load; and

wherein the voltage vector and the current vector generated by the power converter can deviate from 90 degree so as to process active power.

9. The power converter of claim **1** wherein the electric load contains at least one energy storage element or power source, and said power converter transfers active and reactive power from the load back to the input ac power source in order to regulate the input ac voltage of the input power source.

10. The power converter of claim **1** wherein the converter is an AC-DC power converter or AC-DC-AC power converter or AC-AC power converter.

11. The power converter of claim **1** wherein the input voltage control and regulator uses droop control techniques in a control loop for the input voltage control.

12. The power converter of claim **1** wherein the input voltage control and regulator includes phase-shift control and pulse-width-modulated switching methods.

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