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(54) **METHOD AND CIRCUITRY FOR IMPROVING THE MAGNITUDE AND SHAPE OF THE OUTPUT CURRENT OF SWITCHING POWER CONVERTERS**

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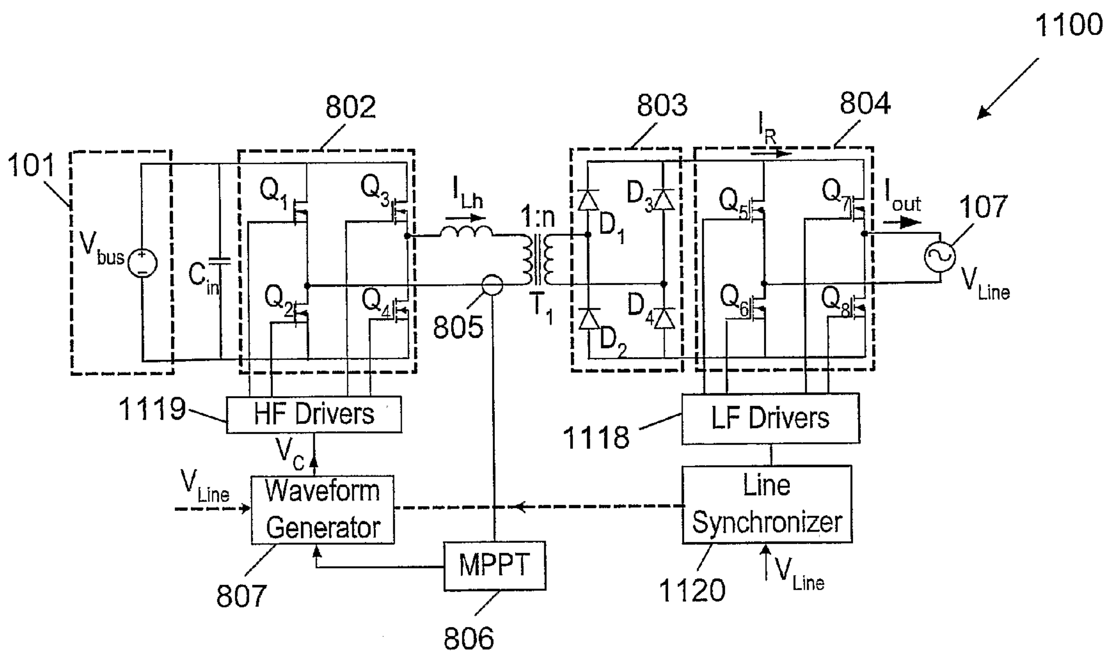
(57) **ABSTRACT**

Apparatus of a grid-connected switching inverter for injecting it current into a power line comprises: (a) an electrical energy source for providing the substantially DC voltage to the apparatus; (b) a switching inverter connected to the electrical energy source for converting the substantially DC voltage of the electrical energy source to a high frequency alternating voltage; (c) a waveform generator for controlling the magnitude and shape of the alternating high frequency voltage outputted from the switching inverter by means of a control signal fed into the switching inverter; (d) an inductor connected to an output of the switching inverter for generating an alternating current from the alternating high frequency voltage, wherein the magnitude of the alternating current depends on a frequency of the alternating high frequency voltage: (e) a rectifier connected in series with the inductor for rectifying the alternating current and for outputting a rectified unipolar alternating current, wherein the rectified average value of the alternating current is proportional to the absolute magnitude of the power line voltage; and (t) a polarity commutator connected to an output of the rectifier for converting the rectified unipolar alternating current into a bipolar alternating current, and for injecting the bipolar alternating current into a power line, wherein the bipolar alternating current is substantially in phase with and of shape of the power line voltage of the power line.



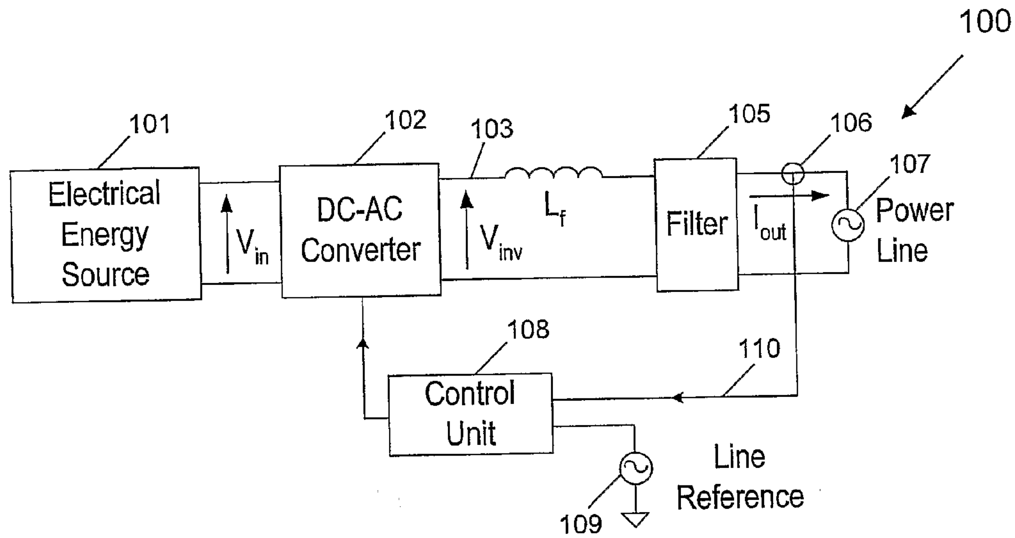


Fig. 1 (Prior Art)

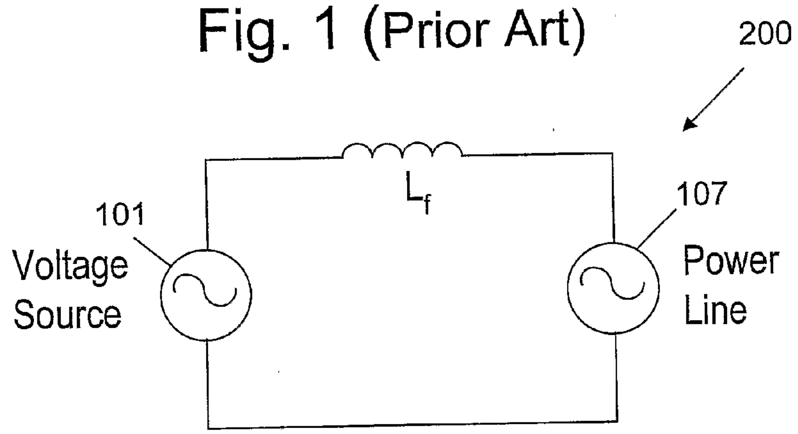


Fig. 2 (Prior Art)

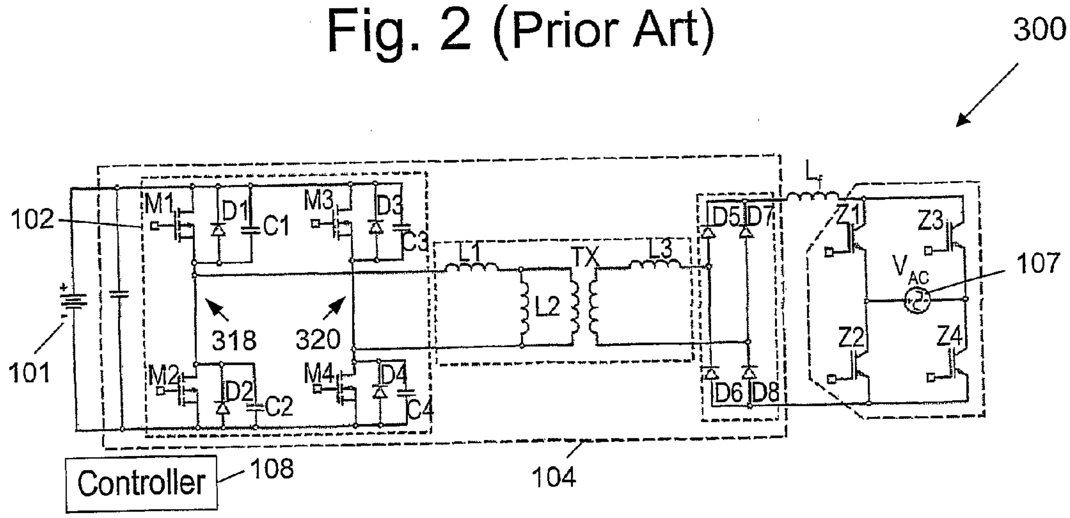


Fig. 3 (Prior Art)

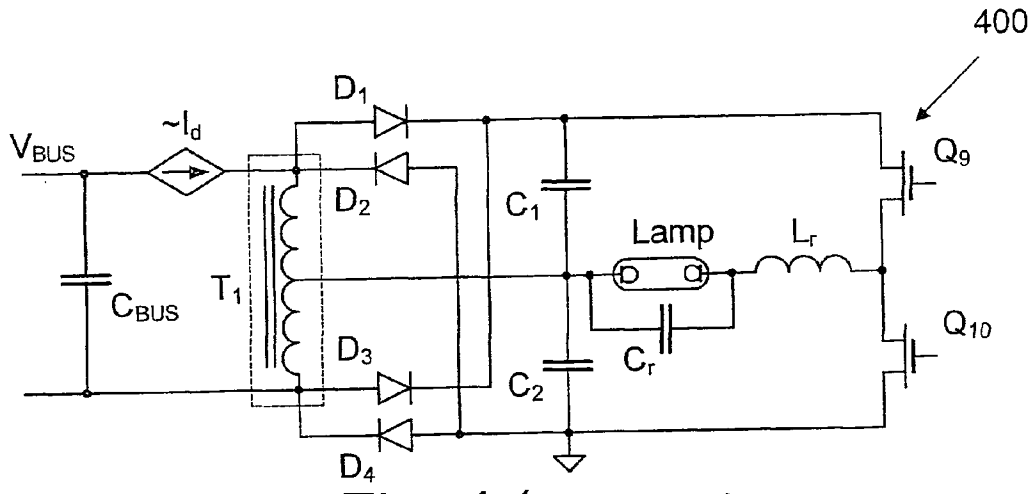


Fig. 4 (Prior Art)

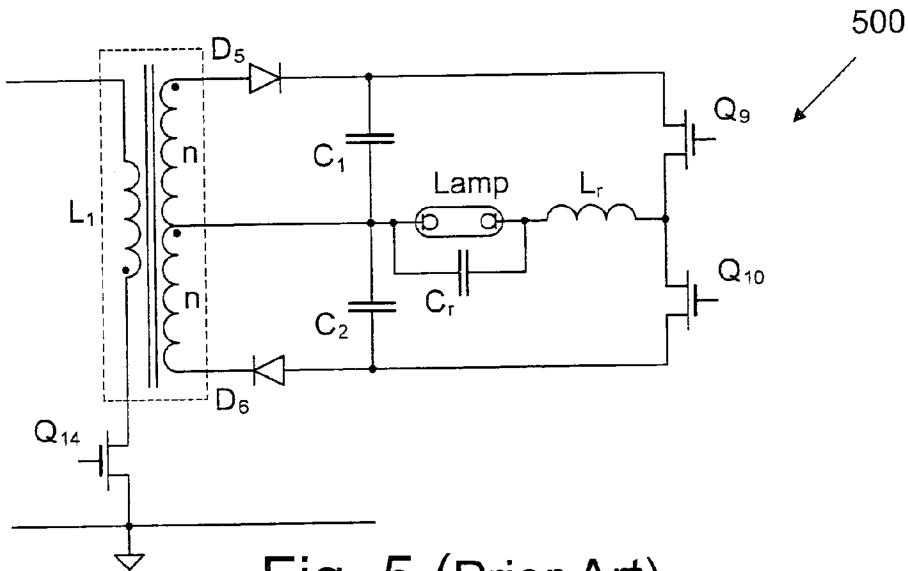


Fig. 5 (Prior Art)

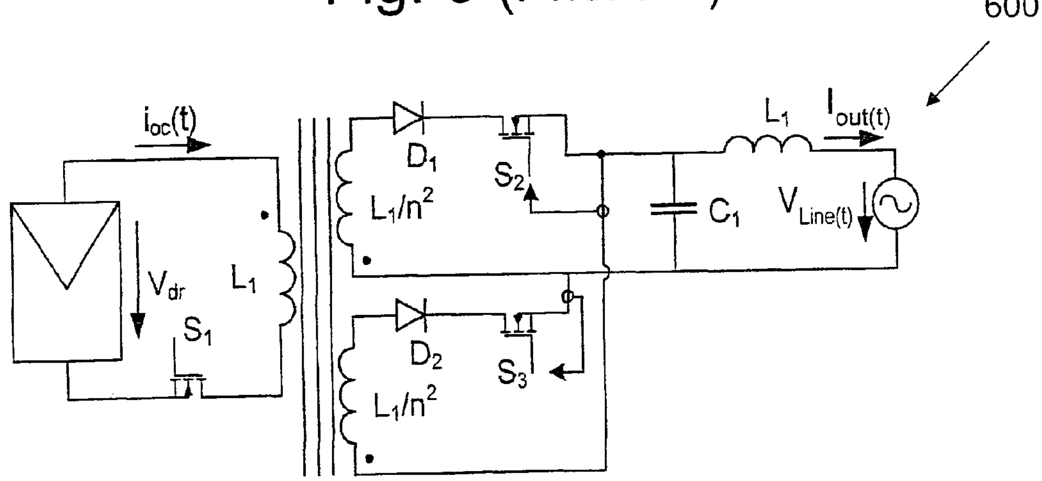


Fig. 6 (Prior Art)

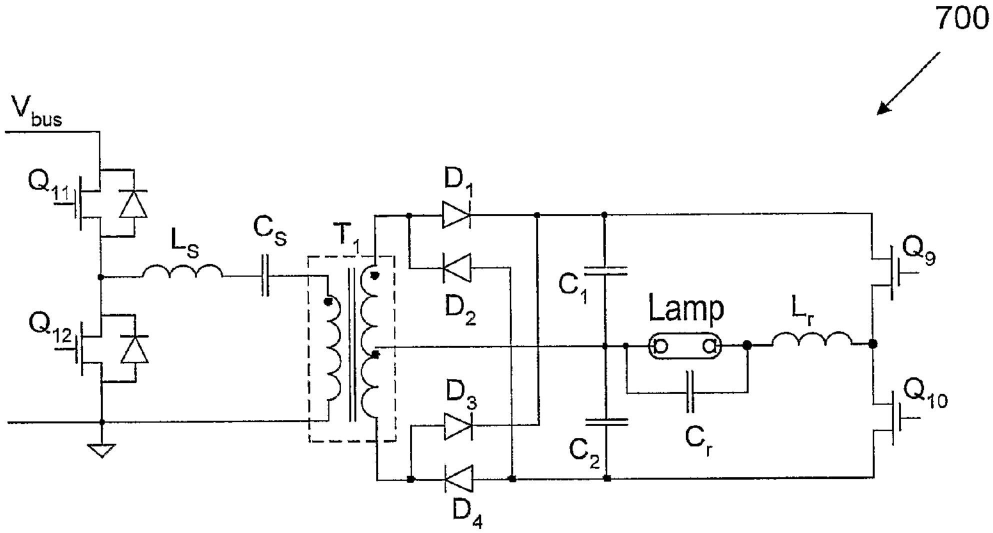


Fig. 7 (Prior Art)

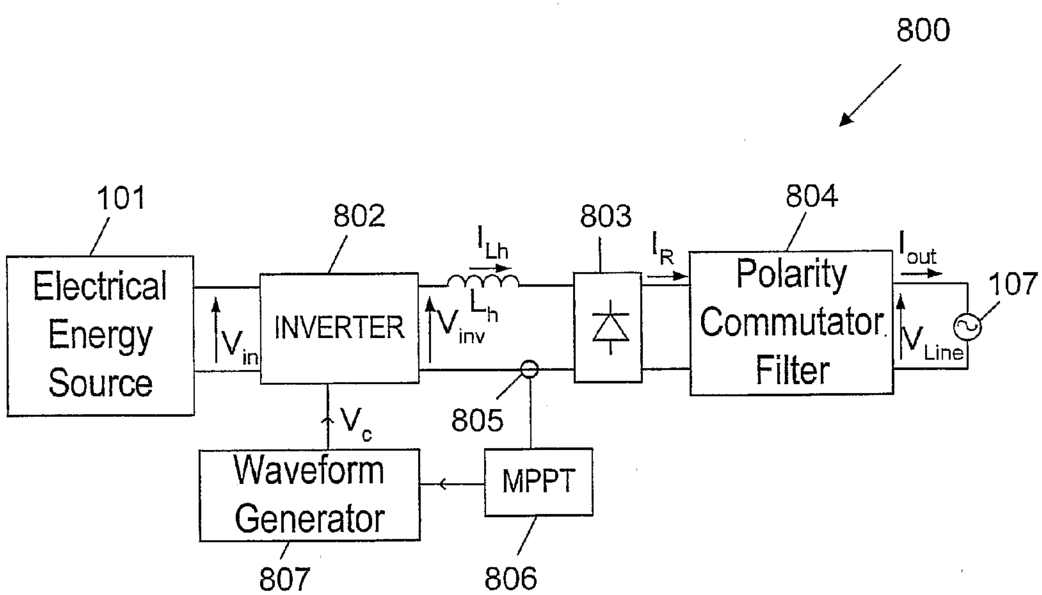


Fig. 8

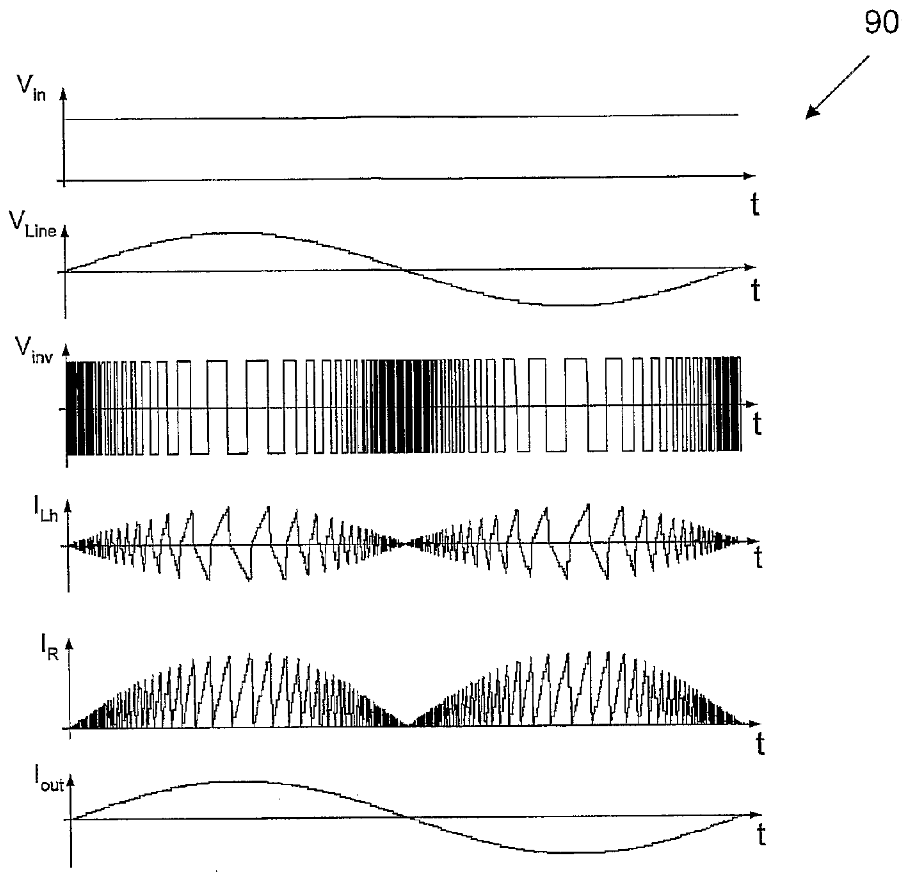

900
V_{in}
t
V_{Line}
t
V_{inv}
t
I_{Lh}
t
I_R
t
I_{out}
t

Fig. 9

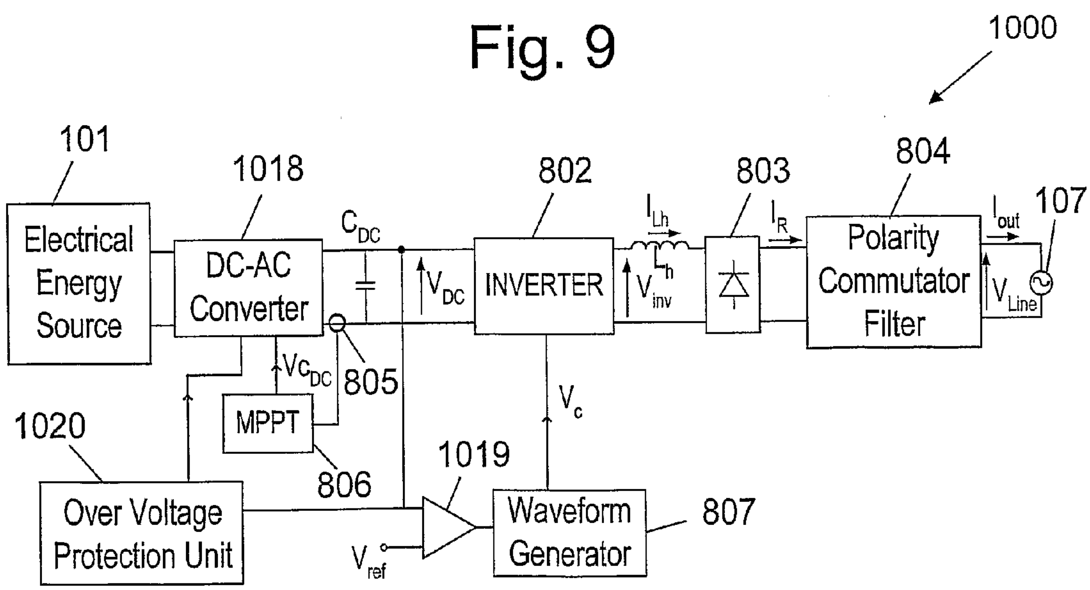

1000
101
Electrical Energy Source
1018
DC-AC Converter
C_{DC}
V_{DC}
802
INVERTER
I_{Lh}
L_h
V_{inv}
803
I_R
804
Polarity Commutator Filter
I_{out}
107
V_{Line}
Vc_{DC}
805
MPPT
806
1020
Over Voltage Protection Unit
V_c
1019
V_{ref}
Waveform Generator
807

Fig. 10

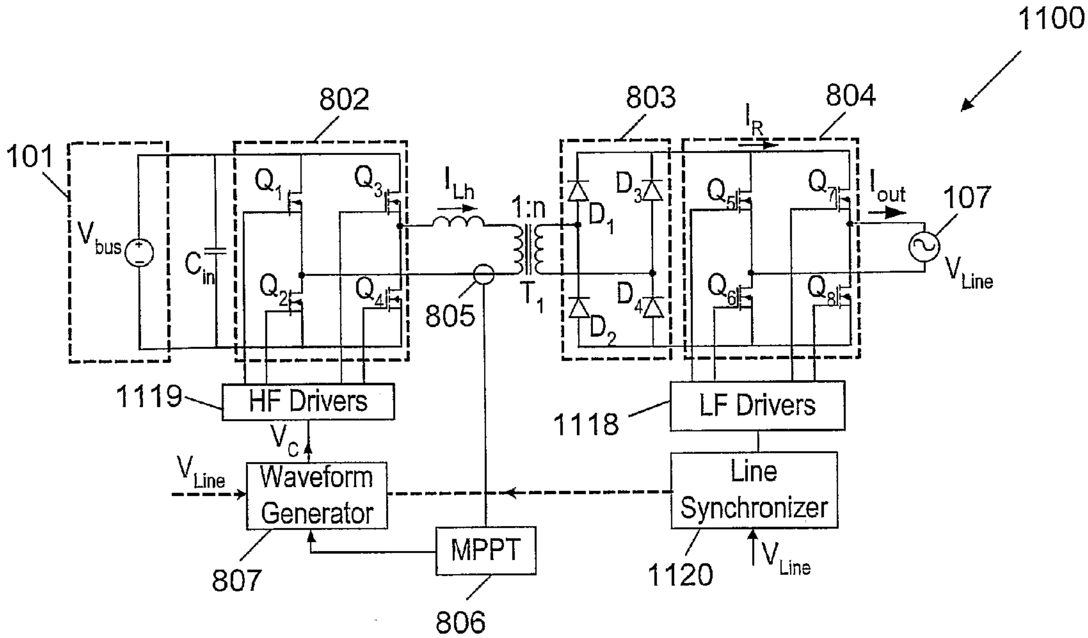

1100
101
802
803
804
I_R
V_{bus}
C_{in}
Q_1
Q_2
Q_3
Q_4
I_{Lh}
1:n
T_1
805
D_1
D_2
D_3
D_4
Q_5
Q_6
Q_7
Q_8
I_{out}
107
V_{Line}
1119
HF Drivers
V_C
V_{Line}
Waveform Generator
807
MPPT
806
1118
LF Drivers
Line Synchronizer
1120
V_{Line}

Fig. 11

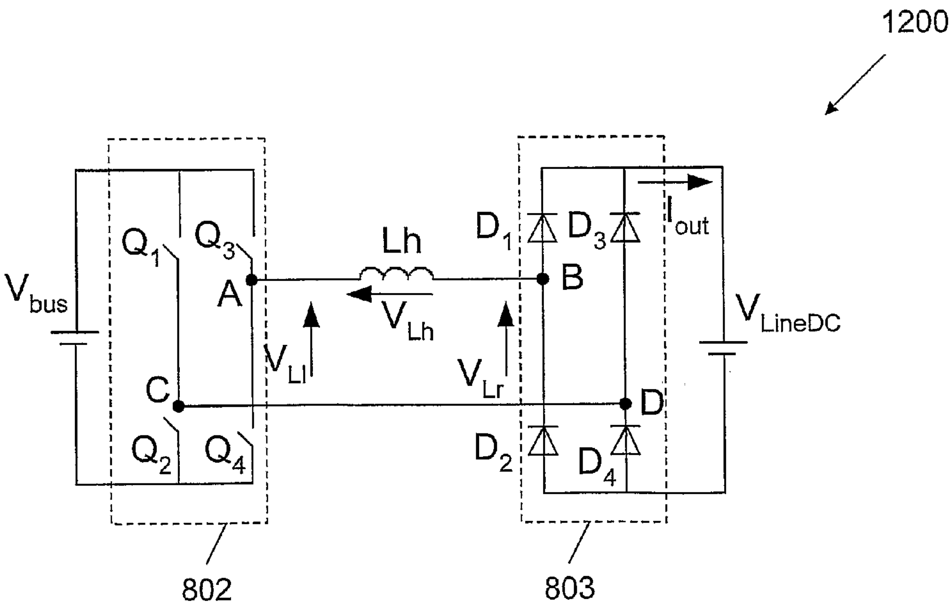

1200
V_{bus}
Q_1
Q_3
A
C
Q_2
Q_4
Lh
V_{Lh}
V_{Ll}
V_{Lr}
D_1
D_3
B
D
D_2
D_4
I_{out}
V_{LineDC}
802
803

Fig. 12

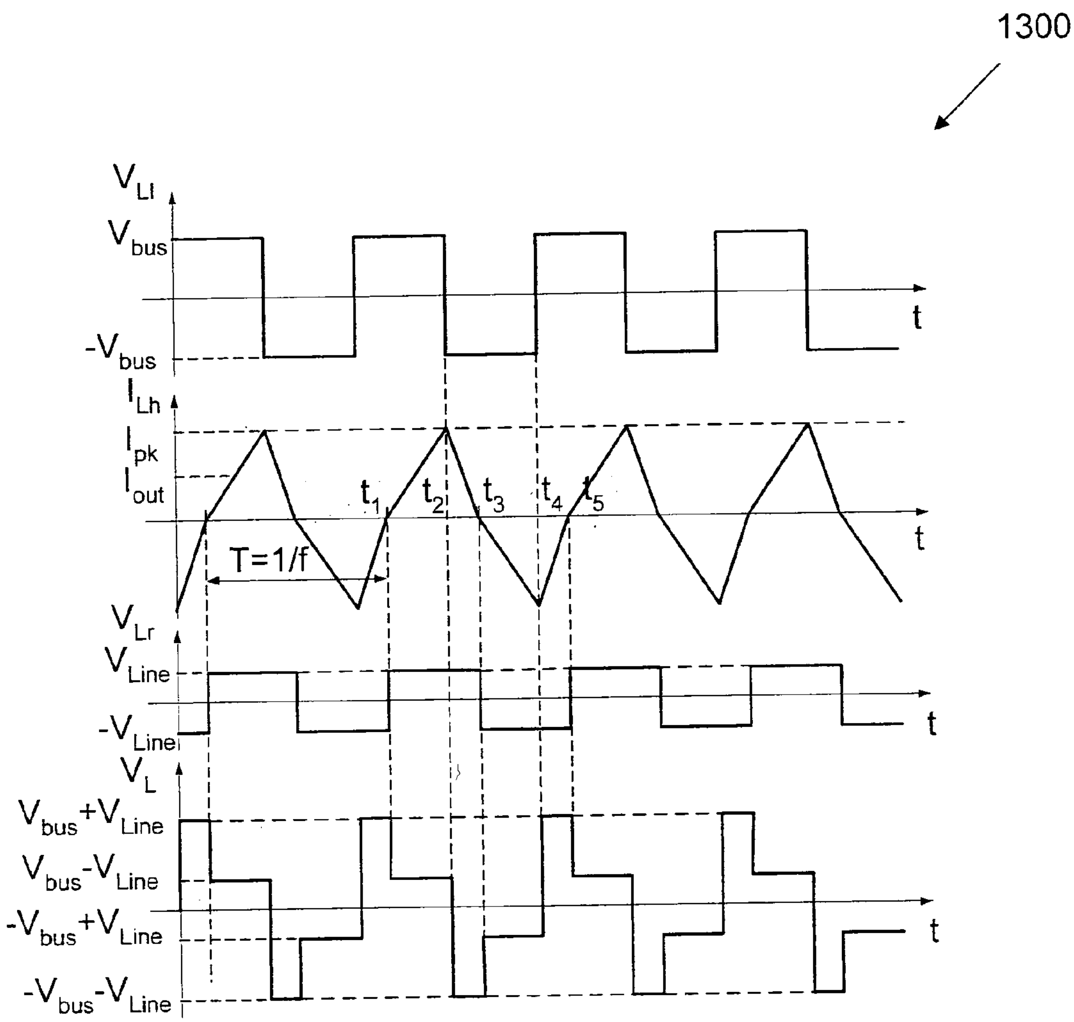

1300
V_{Ll}
V_{bus}
$-V_{bus}$
t
I_{Lh}
I_{pk}
I_{out}
t_1
t_2
t_3
t_4
t_5
t
T=1/f
V_{Lr}
V_{Line}
$-V_{Line}$
t
V_L
$V_{bus}+V_{Line}$
$V_{bus}-V_{Line}$
$-V_{bus}+V_{Line}$
$-V_{bus}-V_{Line}$
t

Fig. 13

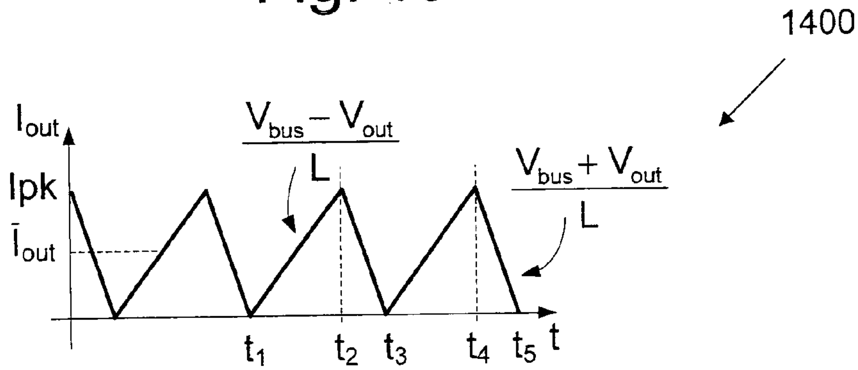

1400
I_{out}
Ipk
$\bar{I}_{out}$
$\frac{V_{bus}-V_{out}}{L}$
$\frac{V_{bus}+V_{out}}{L}$
t_1
t_2
t_3
t_4
t_5
t

Fig. 14

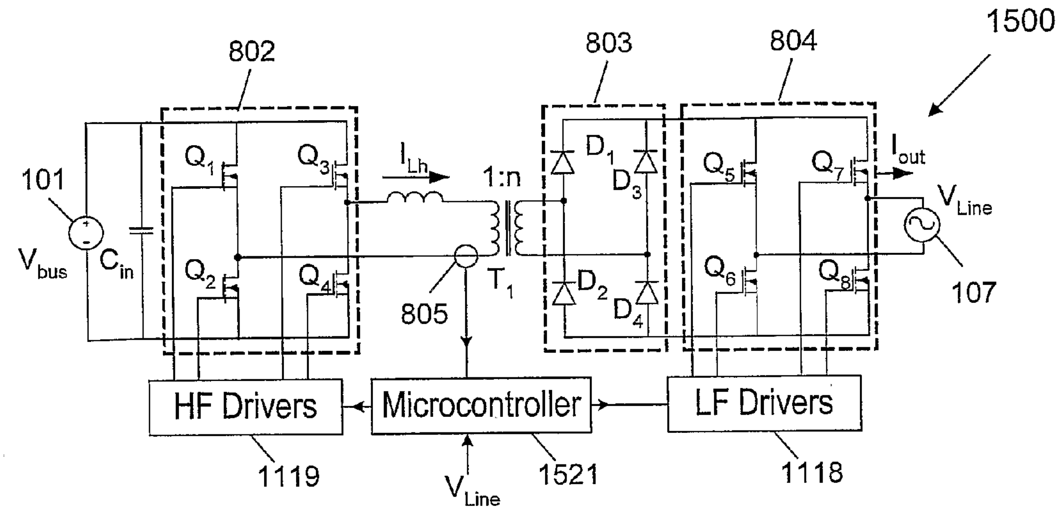

1500
802
803
804
101
Vbus
Cin
Q1
Q2
Q3
Q4
ILh
1:n
T1
805
D1
D2
D3
D4
Q5
Q6
Q7
Q8
Iout
VLine
107
HF Drivers
Microcontroller
LF Drivers
1119
1521
1118
VLine

Fig. 15

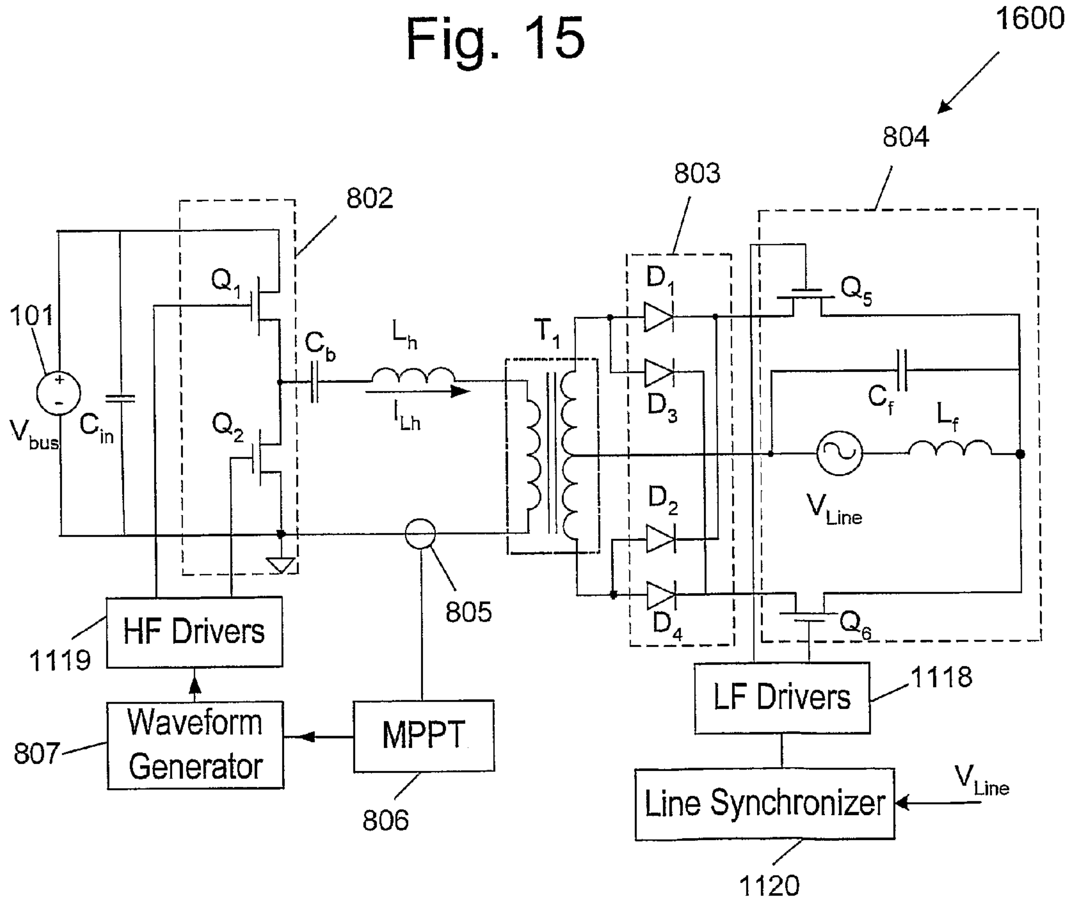

1600
804
803
802
101
Vbus
Cin
Q1
Q2
Cb
Lh
ILh
T1
D1
D3
D2
D4
Q5
Q6
Cf
Lf
VLine
805
HF Drivers
1119
Waveform Generator
807
MPPT
806
LF Drivers
1118
Line Synchronizer
VLine
1120

Fig. 16

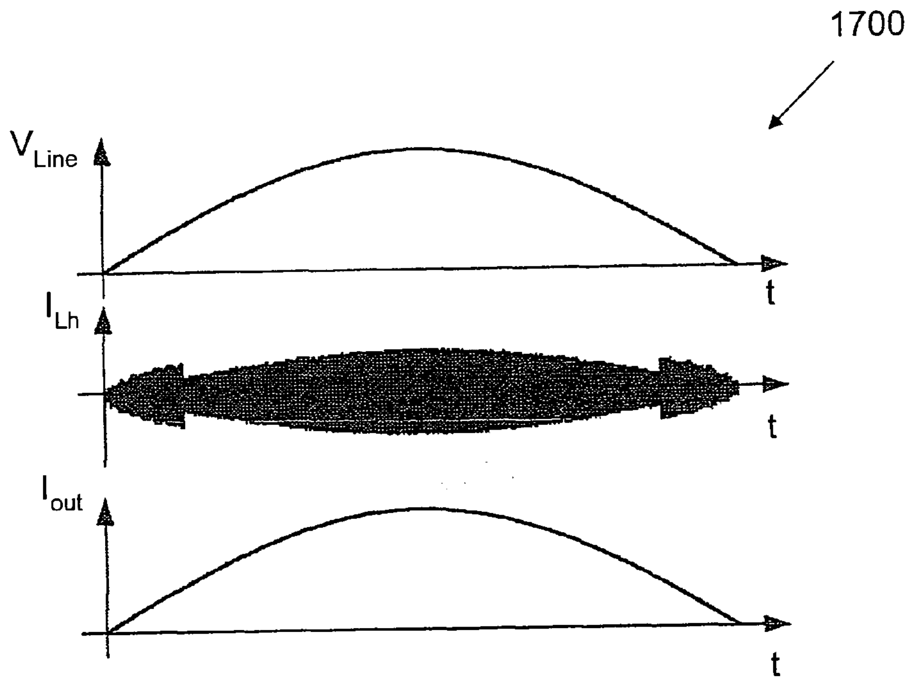


Fig. 17

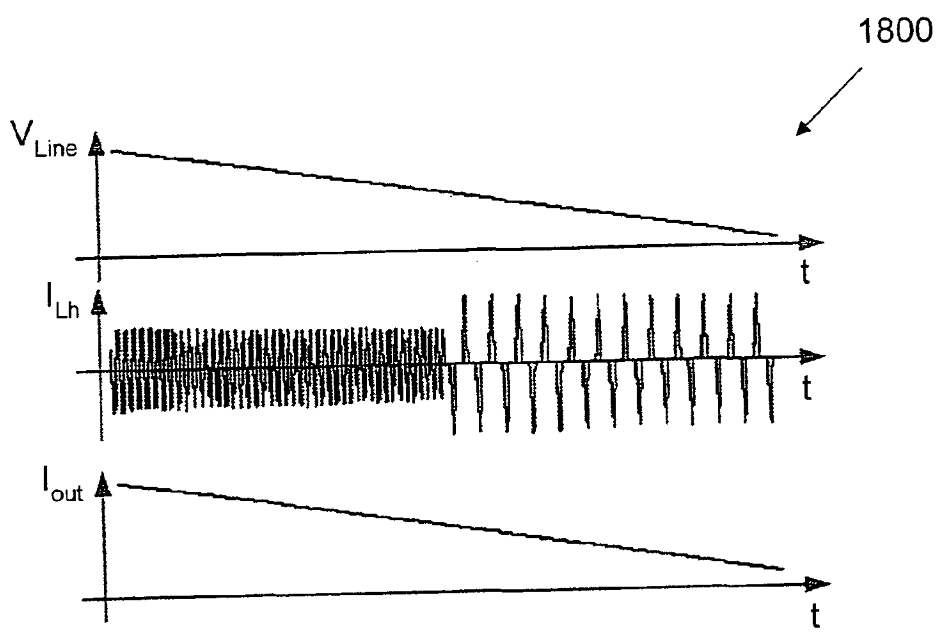


Fig. 18

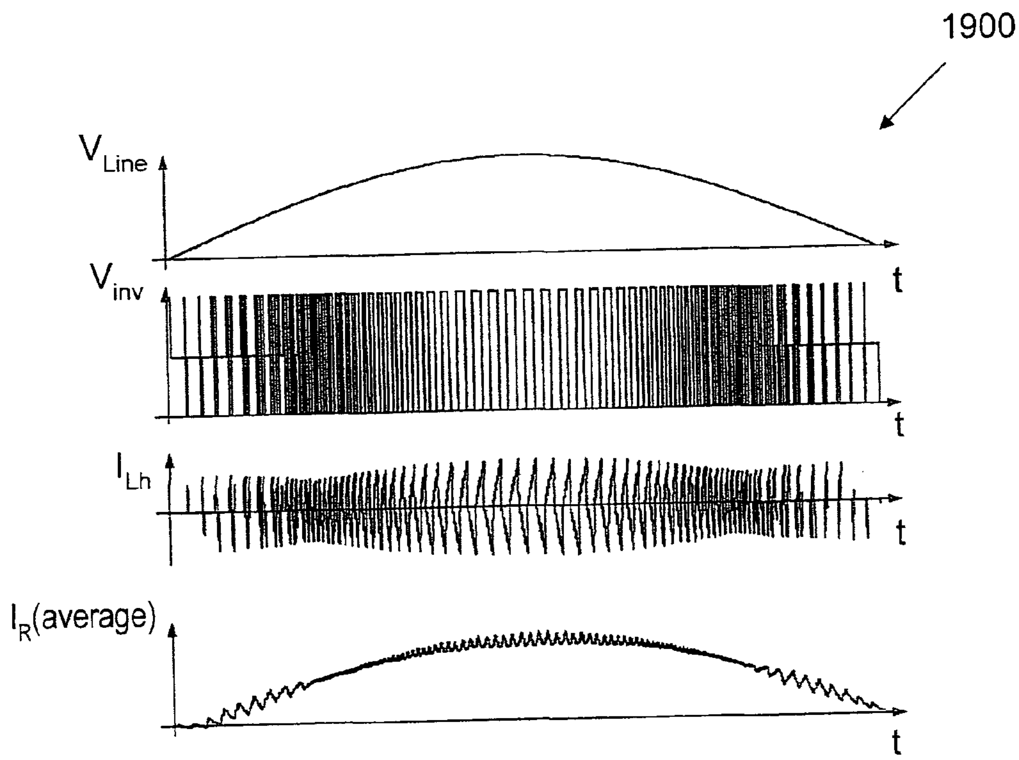

1900
V_Line
t
V_inv
t
I_Lh
t
I_R(average)
t

Fig. 19

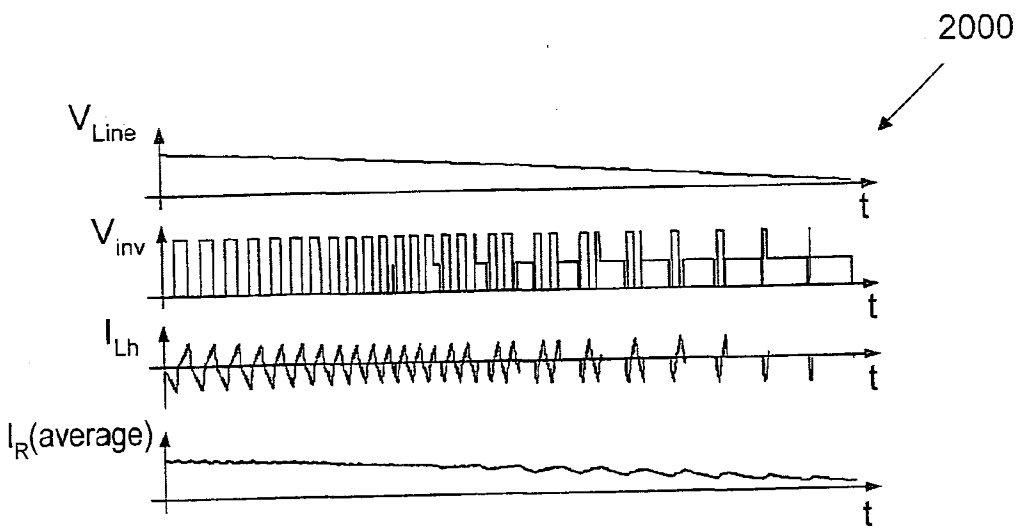

2000
V_Line
t
V_inv
t
I_Lh
t
I_R(average)
t

Fig. 20

METHOD AND CIRCUITRY FOR IMPROVING THE MAGNITUDE AND SHAPE OF THE OUTPUT CURRENT OF SWITCHING POWER CONVERTERS

FIELD OF THE INVENTION

[0001] The present invention relates to switching power converters. More particularly, the invention relates to a method and circuitry for improving the magnitude and shape of the output current of switching power converters.

BACKGROUND OF THE INVENTION

[0002] Currently, there are several types of power converters which are widely used for the DC-to-DC (Direct Current), DC-to-AC (Alternating current), AC-to-DC and AC-to-AC power conversion. In some applications, the purpose of the converter is to provide a regulated output voltage. In other applications, the purpose of the power conversion scheme is to regulate the output current independent of the load voltage. For example, in the case of a battery charger, the converter needs to feed the battery with a current rather than with a fixed output voltage. Another example is a grid-connected inverter for feeding energy into the power line. In this case, the required shape of the current is a sinusoidal waveform synchronized to the grid frequency having a magnitude that depends on the power capabilities of the source, which can be an array of photovoltaic cells, fuel cells, wind turbines and the like. Thus, a large family of applications requires that the switch mode converter behaves like a current source rather than a voltage source.

[0003] According to the prior art, two approaches have been suggested in the prior art to achieve the current source behavior. The first one is by adding a current feedback loop to a voltage source. The second approach is based on circuits that behave naturally as current sources. The advantage of the natural current source approach is that it does not rely on extra control loops that add to the cost of the units and reduce the reliability. The latter is due to the fact that current control loops of a voltage source converter are sensitive to deterioration of electrical components, spurious signals, noise and the like. Once the current loop is lost, the system may not only malfunction but could be severely damaged when the voltage sourcing converter is connected to a load which behaves like a voltage source. On the other hand, if the converter behaves naturally as a current source, there is no danger of runaway even without a dedicated current loop, since the converter keeps the current at a safe level by itself.

[0004] Currently, there is a growing use of converters that are required to behave like a current source in connection with the drive for alternative energy sources. Alternative energy sources such as solar cells and wind generators, can be used in an autonomous mode and grid-connected mode. In the first case, the generated energy is used to feed local loads. This mode of operation is rather limited in that it does not contribute to the general electrical energy needs. In the second case, in grid-connected mode, the energy is fed to power line when energy is available (during the day in case of solar cells or windy periods in the case of wind generators). Hence, the power grid serves, in a sense, as energy storage. When the alternative energy is available, it absorbs energy, and at that time, lowers the need for electrical energy generation by the grid power stations. When the alternative energy source is unavailable, the power line can still feed all loads connected to it.

[0005] The case of a grid-connected solar cells array is an example of a case in which electrical energy needs to be fed into a voltage source. The power line system behaves as a rigid voltage source with a low internal resistance. Hence, when connecting an external source to the grid, one has to make sure that energy flows from the source to the power line and not backward from grid to source. The latter not only constitutes a malfunction, but may cause severe damage to the feeding source. Another issue that needs to be carefully taken care of is the requirement of feeding the power line with a current of low harmonics content. That is, the shape of the injected current needs to be close to sinusoidal and in phase with the line voltage. This requirement is mandatory since the injection of high harmonic current is harmful; it increases power losses and could generate voltage interferences that might disturb other customers of the power line. Further, the recommended and mandatory standards, such as "EN61000-3-2", set a limit to the high order harmonics that are allowed to be injected into the power line.

[0006] Most prior art solutions to the problem of current injection to the grid are based on generating a voltage source with a sinusoidal average output voltage and a filter inductor to reduce the ripple current. Typically, the sinusoidal voltage source is generated by a switch mode converter running at high switching frequency. The fundamental block diagram **100** of this prior art approach is depicted in FIG. **1**. According to FIG. **1**, an Electrical Energy Source **101** is feeding a switch mode DC-AC Converter **102** generating at its output **103** a switched voltage V_{inv} with an average sinusoidal shape. Although the output is a sinusoidal signal, Converter **102** operates as a DC-DC converter with a time dependent output voltage. This voltage is fed into a filter inductor Lf to reduce the ripple current, and then to Power Line **107** via an optional Filter **105** to further reduce the high frequency ripple current. A Sensor **106** measures the current I_{out} that is injected into Power Line **107**, and generates a signal on line **110** that is proportional to the injected current I_{out}. This signal is compared to a line voltage reference signal **109** by a Control Unit **108** that adjusts the output of DC-AC Converter **102**, such that the injected current will follow a sinusoidal shape synchronized to the line voltage. The need for the feedback arrangement via Control Unit **108** is clear to a person in the art, considering the voltage sourcing nature of this injection circuitry **200**, shown generically in FIG. **2**. According to FIG. **2**, the prior art method is described in its fundamental nature as an AC Voltage Source **101** feeding Power Line **107** via a Filter Inductor **104**, which is inserted for the purpose of reducing the high frequency ripple current. However, since the impedance of this inductor to the line frequency (50 Hz or 60 Hz depending on country) is very small, any voltage deviations between a Voltage Source **101** and a Power Line **106** will cause large uncontrolled current. To harness this undesired behavior, a current feedback loop must be included in the system. Even so, the reliability of such a system is low, since a loss of the current feedback, due to noise or failure of components will be catastrophic. Furthermore, the inclusion of a feedback loop may cause dynamic instability and will add to the cost of the system.

[0007] FIG. **3** is an example of the voltage source implementation **300**, according to the prior art, as described in US 2005/0180175. Similarly to FIG. **1**, the circuitry of FIG. **3**

comprises Voltage/Electrical Source **101**, DC-DC converter **102**, Filter Inductor L_f, Power Line **107**, and Control Unit **108**.

[0008] Another prior art approach for current injection is described in connection with electronic ballasts for HID (High Intensity Discharge) lamps. Discharge lamps need to be fed by a current source to maintain stable operation. For example, such an approach is described in U.S. Pat. No. 7,084,584, as illustrated in FIG. **4**. In this case, a current source Id rather than a Voltage Source **102** (FIG. **2**) is fed to the load (Lamp), after some polarity processing. Notwithstanding the fact that current injection approach of U.S. Pat. No. 7,084,584 is superior to that of the voltage source scheme, the teaching of U.S. Pat. No. 7,084,584 does not include the generation of a sinusoidal current as is required in the case of a grid (Power Line) injection. Also, the teaching of U.S. Pat. No. 7,084,584 does not cover the issue of maximum power point tracking (MPPT) as is required in the case of alternative energy sources. The MPPT is required for extracting the maximum possible energy from the source. For example, as known to workers in the field, maximum energy is obtained from a solar cell panel when loaded by a load that exhibits a specific resistance value. Hence, for the optimal operation in terms of highest efficiency, the system that connects an alternative energy source to the grid must not only behave as a current source, but needs to track the maximum power point.

[0009] According to the prior art, a number of approaches have been proposed to realize the inherent current source behavior. One approach is based on a buck-boost or flyback converter. In this case the magnetic element is charged by the primary energy source and discharges into the load or power line (in the case of a grid-connected system). Such approach is disclosed in U.S. Pat. No. 7,084,584, as illustrated on FIG. **5**. By turning the switch Q_{14} ON an OFF, the coupled inductor L_1 is charged via its primary wing and discharged by the secondary wing; Q_9 and Q_{10} are then used as polarity reversal switches to generate a bipolar square wave current at the load (HID Lamp). This concept was presented by Kyritsis et al. (A. C. Kyritsis, N. P. Papanikolaou, E. C. Tatakis, and J. C. Kobougias, "Design and control of a current source flyback inverter for decentralized grid connected photovoltaic systems," *European Conference on Power Electronics and Applications,* 2005, pp. 1-10, 11-14, September 2005) to realize a grid-connected system illustrated in FIG. **6**. Although the arrangement of the polarity reversal switches (S_2, S_3) is somewhat different from the illustrated in FIG. **5**, the two circuits presented on these figures are identical in concept and implementation, except for the arrangement of switches and diodes. The shortcomings of the circuit presented on FIG. **5**, as a source for a grid-connected system, are: poor utilization of the magnetic element; high voltage stresses on the primary switch; voltage spikes associated with the parasitic inductance of the coupled inductor; the pulsating current at the output; and low energy levels that can be processed by a flyback stage at reasonable losses. Another way to realize a current sourcing circuit is by using the AC inductor, as is demonstrated in U.S. Pat. No. 7,084,584 and shown in FIG. **7**. In this case, an inductor L_8 is subject to a high frequency AC voltage and consequently exhibits a high impedance. This high impedance serves as a current limiter realizing thereby the current sourcing nature of the system. One of the additional major advantages of this system is that the transistors operate under zero voltage switching due to the phase lag of the inductor's current and the reversal of current every half cycle. However, the system of FIG. **7** does not generate a sinusoidal current, synchronized to the power line voltage, as is required for the grid (power line) connected source.

[0010] Therefore, there is a continuous need for providing current sourcing soft-switched inverters based on "AC inductors" that can be used reliably to inject to the grid a sinusoidal current, synchronized to the power line voltage. It is further desirable that such converters will be capable of operating without a current loop, or if a current loop is used, not to go astray or be damaged, when the current feedback is lost.

[0011] It is an object of the present invention to provide a method and circuitry for injecting a current into an output voltage source, such as a power line, while presenting to the input electrical energy source, such as a solar cell panel, the desired characteristics, such as the optimum loading for achieving the maximum power.

[0012] It is another object of the present invention to provide a method and circuitry for connecting an alternative energy source to the power line by a current source circuitry to reduce the cost and increase the reliability of the system.

[0013] It is still another object of the present invention to provide economical and efficient method and circuitry for improving the performance and reliability of switch mode based systems that behave as sinusoidal current sources.

[0014] It is still another object of the present invention to provide a method and circuitry for tracking the maximum power point of a source and behaving as a current source with respect to its load.

[0015] It is still another object of the present invention to provide a method and circuitry for transferring energy from an electrical energy source to power line by using an AC inductor as a current limiter and adjuster.

[0016] It is a further object of the present invention to provide a method and circuitry of a switch-mode inverter suitable for grid connection applications, which has improved reliability and improved programmability features compared to prior art grid-connected inverters.

[0017] It is still a further object of the present invention to provide a method and circuitry, in which a current feedback loop is not required for the basic operation of injection of a current into a power line.

[0018] It is still a further object of the present invention to provide a method and circuitry, in which the injection of a current into a power line is not influenced by distortions of the current within said power line.

[0019] It is still a further object of the present invention to provide a method and circuitry, in which the soft switching is provided for maintaining the output current signal substantially undistorted.

[0020] It is still a further object of the present invention to provide a method and circuitry, which is relatively inexpensive.

[0021] Other objects and advantages of the invention will become apparent as the description proceeds.

SUMMARY OF THE INVENTION

[0022] Hereinafter, when the term "inherent current source" is mentioned, it should be understood that it refers to a source that can inject the desired current independently from the voltage of the load.

[0023] The present invention is directed to a method and circuitry (apparatus) that behaves as an inherent current source, for injecting a sinusoidal current into a power line. According to an embodiment of the present invention, a current feedback loop is not required for the basic injection operation. In addition, if a current feedback loop is not used, undesired currents will not be injected to the grid, and the circuitry will not be damaged by the grid when the current feedback loop is lost.

[0024] The apparatus of a grid-connected switching inverter for injecting a current into a power line comprises: (a) an electrical energy source for providing the substantially DC voltage to said apparatus; (b) a switching inverter connected to said electrical energy source for converting said substantially DC voltage of said electrical energy source to a high frequency alternating voltage; (c) a waveform generator for controlling the magnitude shape and frequency of said alternating high frequency voltage outputted from said switching inverter by means of a control signal fed into said switching inverter; (d) an inductor connected to an output of said switching inverter for generating an alternating current of variable magnitude and frequency from said alternating high frequency voltage, wherein the magnitude of said alternating current depends on a frequency of said alternating high frequency voltage; (e) a rectifier connected in series with said inductor for rectifying said alternating current and for outputting a rectified unipolar alternating current, wherein the rectified average value of said alternating current is proportional to the absolute magnitude of the power line voltage; and (f) a polarity commutator connected to an output of said rectifier for converting said rectified unipolar alternating current into a bipolar alternating current, and for injecting said bipolar alternating current into a power line, wherein said bipolar alternating current is substantially in phase with and of shape of said power line voltage of said power line.

[0025] According to an embodiment of the present invention, the apparatus further comprises a MPPT unit for tracking the maximum power point of the electrical energy source.

[0026] According to another embodiment of the present invention, the electrical energy source is one or more of the following: (a) a solar cell; (b) a fuel cell; (c) a wind turbine; (d) a battery or accumulator; and (e) a generator.

[0027] According to a particular embodiment of the present invention, the switching inverter is a H-bridge or half bridge switching inverter.

[0028] According to another particular embodiment of the present invention, the polarity commutator is a H-bridge or half bridge polarity commutator.

[0029] According to still another particular embodiment of the present invention, the switching inverter comprises two or more switches that are driven by means of high frequency control signals outputted from high frequency drivers.

[0030] According to a further particular embodiment of the present invention, the polarity commutator comprises two or more switches that are driven by means of low frequency signals outputted from low frequency drivers.

[0031] According to an embodiment of the present invention, the magnitude of the alternating current of the inductor depends on the duty cycle of the control signal fed to the inverter.

[0032] According to another embodiment of the present invention, the magnitude of the alternating current of the inductor is controlled by means of sequences of ON and OFF periods of the high frequency control signal fed to the inverter.

[0033] According to still another embodiment of the present invention, the magnitude of the alternating current of the inductor is controlled by means of the duty cycle of the control signal fed to the inverter.

[0034] According to still another embodiment of the present invention, the apparatus further comprises a pulse width modulation unit for keeping a signal switching the switches at a predefined maximal frequency.

[0035] According to still another embodiment of the present invention, the apparatus further comprises a line synchronizer for sensing the line voltage and generating corresponding synchronization commands.

[0036] According to still another embodiment of the present invention, the synchronization commands are fed into the low frequency drivers.

[0037] According to still another embodiment of the present invention, the synchronization commands are fed into the waveform generator.

[0038] According to a particular embodiment of the present invention, the apparatus further comprises an overvoltage protection unit for guarding said apparatus from dangerous DC voltage levels under no load conditions.

[0039] According to a further embodiment of the present invention, the apparatus further comprises a microcontroller for controlling the operation of said apparatus.

[0040] According to still a further embodiment of the present invention, the apparatus further comprises a transformer for galvanically isolating the electrical energy source from the power line.

[0041] According to still a further embodiment of the present invention, the apparatus further implements soft switching of the switches of the inverter for reducing the power and stresses of said switches.

[0042] According to still a further embodiment of the present invention, the apparatus further comprises a DC-DC converter, placed between the electrical energy source, and switching inverter for adjusting the voltage level of said electrical energy source to that required for said switching inverter.

[0043] According to still a further embodiment of the present invention, the alternating current is generated in the inductor due to imposing a bipolar high frequency voltage across said inductor.

[0044] According to still a further embodiment of the present invention, the alternating current in the inductor is controlled by varying the frequency of the bipolar high frequency voltage.

[0045] According to still a further embodiment of the present invention, the alternating current in the inductor is controlled by toggling the bipolar voltage signal ON and OFF.

[0046] According to still a further embodiment of the present invention, the alternating current in the inductor is controlled by varying the ON time within each switching period of the bipolar voltage.

[0047] The method for injecting a current into a power line comprises: (a) providing an inductor, a terminal of which is, connected in series to a first input of a rectifier; (b) generating an alternating current of variable magnitude and frequency in said inductor by applying a high frequency voltage between the other terminal of said inductor and a second input of said rectifier; (c) rectifying said alternating current by means of said rectifier, thereby obtaining the magnitude of the rectified average value of the alternating current that is proportional to the absolute magnitude of the power line voltage; (d) commutating the polarity of the rectified alternating current to be synchronized with the phase of the power line current; and (e) injecting the synchronized rectified alternating current into said power line.

[0048] The method for injecting a current into a power line comprises: (a) providing the substantially DC voltage by means of an electrical energy source; (b) converting said substantially DC voltage of said electrical energy source to a high frequency alternating voltage by means of a switching inverter connected to said electrical energy source; (c) controlling the magnitude shape and frequency of said alternating high frequency voltage outputted from said switching inverter by means of a control signal fed into said switching inverter from a waveform generator; (d) generating an alternating current of variable magnitude and frequency from said alternating high frequency voltage by means of an inductor connected to an output of said switching inverter, wherein the magnitude of said alternating current depends on a frequency of said alternating high frequency voltage; (e) rectifying said alternating current and outputting a rectified unipolar alternating current by means of a rectifier connected in series with said inductor, wherein the rectified average value of said alternating current is proportional to the absolute magnitude of the power line voltage; and (f) converting said rectified unipolar alternating current into a bipolar alternating current and injecting said bipolar alternating current into a power line by means of a polarity commutator connected to an output of said rectifier, wherein said bipolar alternating current is substantially in phase with and of shape of said power line voltage of said power line.

BRIEF DESCRIPTION OF THE DRAWINGS

[0049] In the drawings:

[0050] FIG. **1** is a schematic illustration of a voltage source grid-connected inverter, according to the prior art;

[0051] FIG. **2** is a schematic illustration of the connection of a voltage source inverter to a power line, according to the prior art;

[0052] FIG. **3** is a schematic illustration of the power stage of a voltage source inverter connection to the power line, according to the prior art;

[0053] FIG. **4** is a schematic illustration of the connection of a current source HID (High Intensity Discharge) lamp ballast, according to the prior art;

[0054] FIG. **5** is a schematic illustration of the connection of a current source HID lamp ballast implemented by a flyback converter, according to the prior art;

[0055] FIG. **6** is a schematic illustration of a flyback-based grid-connected inverter, according to the prior art;

[0056] FIG. **7** is a schematic illustration of a current source HID lamp ballast implemented by a half-bridge inverter and an AC inductor, according to the prior art;

[0057] FIG. **8** is a schematic block diagram of a circuitry of a grid-connected inverter, according to an embodiment of the present invention;

[0058] FIG. **9** is a schematic illustration of waveforms of signals of FIG. **8**, according to an embodiment of the present invention;

[0059] FIG. **10** is a schematic block diagram of a circuitry of a grid-connected inverter, according to another embodiment of the present invention;

[0060] FIG. **11** is a schematic illustration of a buck converter stage of a circuitry of a grid-connected inverter, according to an embodiment of the present invention;

[0061] FIG. **12** is a schematic illustration of a circuitry of grid-connected inverter, according to still another embodiment of the present invention;

[0062] FIG. **13** is a schematic illustration of waveforms of signals of FIG. **12**, according to an embodiment of the present invention;

[0063] FIG. **14** is a schematic illustration of the output current waveform of FIG. **12**, according to an embodiment of the present invention;

[0064] FIG. **15** is a schematic illustration of a circuitry of a microcontroller-based grid-connected inverter, according to an embodiment of the present invention;

[0065] FIG. **16** is a schematic illustration of a circuitry of a half-bridge based grid-connected inverter, according to an embodiment of the present invention;

[0066] FIGS. **17** and **18** are schematic illustrations of waveforms of a current I_{Lh} of inductor L_h and of an output current I_{out}, according to another embodiment of the present invention; and

[0067] FIGS. **19** and **20** are schematic illustrations of waveforms of a current I_{Lh} of inductor L_h and of a current I_R, according to still another embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0068] The present invention is directed to a method and circuitry (apparatus) that behaves as an inherent current source, for injecting a sinusoidal current into a power line.

[0069] FIG. **8** is a schematic block diagram **800** of a of a circuitry (apparatus) of a grid-connected inverter for injecting a current into a Power Line **107**, according to an embodiment of the present invention. The circuitry of the grid (Power Line **107**) connected inverter comprises: an Electrical Energy Source **101** for providing the substantially DC voltage to said circuitry; an Inverter **802** for converting said substantially DC voltage of said Electrical Energy Source **801** to a high frequency alternating voltage V_{inv}; a Waveform Generator **807** for controlling said high frequency alternating voltage V_{inv} by means of a control signal V_c fed into said Inverter **802**; an inductor L_h connected in series to an output of said Inverter **802** for generating an alternating current I_{Lh} due to the high frequency alternating voltage V_{inv}; a Rectifier **803** connected to said inductor L_h for rectifying said high frequency alternating current I_{Lh}; a Polarity Commutator **804** connected to said Rectifier **803** for converting said rectified unipolar alternating current into a bipolar alternating current I_{out} and for injecting said bipolar alternating current I_{out} into a power line (grid); and, optionally, a MPPT unit for tracking the maximum power point of said circuitry **800** to operate it with maximal (optimal) efficiency.

[0070] It should be noted that the alternating voltage V_{inv} imposed on inductor L_h, causes it to operate as an AC inductor. Such voltage generates an alternating current I_{Lh} with a temporal magnitude that depends on the switching frequency and the wave form of V_{inv}. These are controlled by signal V_c that is generated by the Waveform Generator **807**. By changing this control voltage as a function of time, the current I_{Lh} can be increased or decreased. For example, if the frequency of V_c is decreased, the switching frequency of the inverter will decrease and the V_{inv} frequency will be lower. This will increase the current I_{Lh} due to the fact that the impedance of an inductor becomes lower at lower frequencies. V_c can thus change the output voltage V_{inv} such that the envelope of I_{Lh}

will be sinusoidal. After passing a Rectifier **803**, the average current is unipolar having the form of a rectified sinusoidal wave. It should be noted that the rectified average value of the alternating current is proportional to the absolute magnitude of the power line voltage. The unipolar current is then converted into a bipolar AC current I_{out} by a Polarity Commutator **804** that might include a filter to attenuate the high frequency ripple current.

[0071] According to an embodiment of the present invention, MPPT unit **806** measures by means of a sensor **805** the magnitude of I_{Lh}, which in turn reflects the current injected to the grid (Power Line **107**), and adjusting signal V_c (the Duty cycle of signal V_c) outputted from Waveform Generator **807** such that I_{Lh} has the maximum possible value. For a given V_{line}, a maximum I_{out} (when I_{Lh} also has the maximal value) is, by definition, the maximum power point.

[0072] It should be noted that Electrical Energy Source **101** can be any electrical source, such as one or more solar, fuel cells, wind turbines, batteries, accumulators, (diesel) generators, etc.

[0073] FIG. **9** is a schematic illustration **900** of waveforms of signals of FIG. **8**, according to an embodiment of the present invention. V_{Line} is an output voltage and a voltage of Power Line **107** (it is shown as a time reference); Vin represents an input DC voltage Vin of Electrical Energy Source **101**; the voltage V_{inv} at an output of Inverter **802** is shown as a sequence of pulses with variable frequency and possibly variable pulse width; I_{Lh} is a current through AC inductor L_h, reflecting the variable voltage V_{inv} on said AC inductor L_h; I_R is a current at the output of Rectifier **803**, showing its unipolar nature; and I_{out} is an output current of circuitry **800**, injected to Power Line (grid) **107** after performing polarity commutation and filtering by means of Polarity Commutator Filter **804**.

[0074] FIG. **10** is a schematic block diagram **1000** of a circuitry of a grid-connected inverter, according to another embodiment of the present invention. According to this embodiment, a front end DC-DC converter **1018** is placed between Electrical Energy Source **101** and Inverter **802**. The purpose of said DC-DC converter **1018** is to adjust the voltage level of Electrical Energy Source **101** to that required for Inverter **802**. For example, if low voltage solar cell array is used (e.g., for safety reason, economics, redundancy and the like), and the optimum input voltage to the inverter is higher than said low voltage (from an operational point of view, efficiency and the like), the DC-DC converter **1018** adjusts the voltage levels. According to an embodiment of the present invention, for ensuring the maximum power point tracking of circuitry **1000**, MPPT unit **806** can be placed around DC-DC converter **1018**, as illustrated on FIG. **10**. MPPT unit **806** will extract the maximum power from Electrical Energy Source **101**, feeding it to an output capacitor C_{DC} for storage. To guard from dangerous V_{DC} levels under no load conditions, circuitry **1000** can also comprise an Overvoltage Protection Unit **1020**. In the normal operation, Inverter **1012** increases the AC inductor current I_{Lh} (that is proportional to the line injected current I_o) until V_{DC} is stabilized around the desired value. This is accomplished in present invention by measuring V_{DC} and comparing the measured value to the desired voltage V_{ref}. This comparison is carried out by an Error Amplifier/Compensator **1019** that feeds Waveform Generator **807**.

[0075] FIG. **11** is a schematic illustration **1100** of a buck converter stage of a circuitry of a grid-connected inverter, according to an embodiment of the present invention. According to this embodiment, Inverter **802** is implemented by a high frequency H-bridge configuration having switches Q_1-Q_4, which are driven by HF (High Frequency) Drivers **1119**. Polarity Commutator **804** (FIG. **10**) is implemented by a low frequency H-bridge realized by switches Q_5-Q_8 driven by a LF (Low Frequency) Drivers **1118**. The line synchronization command is generated by a Line Synchronizer **1120** that sense the line voltage and generates the synchronization commands that is fed to LF Drivers **1118** and, optionally, to Waveform Generator **807**. Due to said synchronization commands, the rectified alternating current I_R is synchronized with the phase of the power line current I_{out}. Waveform Generator **807** can receive the V_{Line} signal, which is proportional to the signal of Power Line **107**. The operation of Waveform Generator **807** can be based on the waveform of V_{Line} or on a sinusoidal oscillator locked to the power line frequency by a phase lock loop (PLL) or similar circuits.

[0076] The generation of the required current to be injected to AC Power Line **107** requires the generation of control signals V_c by the waveform generator, such that the average waveform of the current I_R (I_{Lh} after rectification) and, in turn, the average waveform of the output current Io, will be sinusoidal. According to an embodiment of the present invention, this requirement is met by controlling the inverter according to the mathematical relationship between the output of the inverter **802**, the inductor current I_{Lh} and the outputted current to the grid. This relationship is shown in reference to FIGS. **12** and **13** below.

[0077] In FIG. **12**, an output Inverter (Polarity Commutator) **804**, which is implemented by means of switches Q_5 to Q_8, is switched at the line frequency (e.g., 50 Hz) so that the voltage reflected to the output of Rectifier **803** (implemented by means of diodes D_1 to D_4) is always positive. For simplicity of the mathematical derivation given below (in reference to FIG. **13**), it is assumed that the line voltage V_{Line} is constant over a switching cycle this assumption is correct because the switching frequency is much higher than the line frequency. For example, if the HF Drivers **1119** (FIG. **12**) switching frequency is 50 kHz, then the period of each switching cycle is 20 microseconds. During such a short time, the line voltage does not change appreciably, since the power line frequency is 50 Hz or 60 Hz. That is, the duration of one switching cycle is about one thousandth of the line period. During this relative short duration that represents much less than one degree of the line phase angle, the line voltage does not change much and hence can be considered constant for that and neighboring periods of the switching frequency. Therefore, for a given voltage point of the line voltage, the power stage of FIG. **11** can be simplified to the circuit of FIG. **11**. It includes the energy source V_{bus}, inverter **802**, inductor L_h, diodes **803** and the reflected line voltage V_{LineDC} [change in FIG. **12** V_{Line} to V_{LineDC}] assumed to be constant for the analysis instance. Polarity Commutator **804** is not shown in FIG. **12**, because it is locked during the period of interest to one position. That is, either both Q_5 and Q_8 are conducting or both Q_7 and Q_6 are conducting—it depends on the momentary polarity of the line voltage.

[0078] It is assumed that circuit **1200** of FIG. **12** operates with 50% Duty Cycle, and hence, a symmetrical bipolar square wave signal V_{L1} is generated at the output of inverter **802**. In this case, the voltages applied to both terminals (points A and B) of AC inductor L_h are bipolar and the inductor's current I_{Lh} flows in both directions with zero average component since the voltages of **802** and **803** do not include a DC components. This is because the switches are run at 50% Duty cycle, and hence generate bipolar waveforms. However, due to non-symmetry of the inverter's output voltage, a DC error component may appear at terminal A of inductor L_h. This DC error component can be removed by a series capacitor, or by applying peak current control. Due to the output diode bridge (diodes D_1 to D_4), the polarity of the voltage V_{Lr} that is seen at terminal B of inductor L_h is reversed every zero-crossing of the inductor's current.

[0079] During time interval t_1-t_2 (FIG. **13**) voltage V_{L1} at the input side (at terminal A) of inductor L_h is positive (V_{bus}), the inductor's current is positive and diodes D_1 and D_3 are at their conducting state. Consequently, the voltage seen by the inductor is positive and equal to $V_{bus}-V_{line}$; and the inductor's current is positive and is increasing. At t_2, the polarity of the input voltage switches. The current through the inductor keeps flowing in the same direction, so diodes D_1, D_3 keep conducting. The voltage applied to the inductor will now be negative and equal to $(-V_{bus}-V_{line})$ and the inductor's current will start decreasing. At t_3, the inductor's current crosses zero and its polarity reverses. As a result, diodes D_2 and D_4 are turned on; voltage V_{Lr} seen by terminal B of inductor L_h is V_{out}; and the net voltage applied to the inductor is $-V_{bus}+V_{line}$. That is, the magnitude of the voltage applied to the inductor during time interval t_3-t_4 is equal to that of time interval t_1-t_2, but opposite in polarity. Similarly, the inductor's voltage during time interval t_4-t_5 is equal in magnitude but opposite in polarity to that of time interval t_2-t_3. Consequently, the current through the inductor reverses its polarity every input voltage switching cycle.

[0080] FIG. **13** is a schematic illustration **1300** of waveforms of signals of FIG. **12**, according to an embodiment of the present invention. The illustrated signals are:

[0081] voltage V_{L1} between terminal A of inductor L_h and terminal C of switch Q_4;

[0082] current I_{Lh} passing through inductor L_h;

[0083] voltage V_{Lr} between terminal B of inductor L_h and terminal D of switch Diode D_3; and

[0084] voltage V_{Lh} across inductor L_h.

[0085] During the time interval t_1-t_2, the peak inductor current I_{pk} is:

$$I_{pk} = \frac{V_{bus} - V_{Line}}{L}(t_2 - t_1) \tag{1}$$

where L is the inductance of inductor L_h. Similarly, during the time interval t_2-t_3, I_{pk} is expressed as:

$$I_{pk} = \frac{V_{bus} + V_{Line}}{L}(t_3 - t_2) \tag{2}$$

[0086] From (1) and (2), taking into account that (t_3-t_1) is half a switching cycle, yields:

$$(t_2 - t_1) + (t_3 - t_2) = I_{pk} L \frac{2V_{bus}}{V_{bus}^2 - V_{Line}^2} = \frac{1}{2F} \tag{3}$$

where F is the switching frequency. Rearranging (3) back for I_{pk}, leads to:

$$I_{pk} = \frac{V_{bus}^2 - V_{Line}^2}{4LFV_{bus}} \tag{4}$$

[0087] FIG. **14** is a schematic illustration **1400** of the output current waveform of FIG. **12**, according to an embodiment of the present invention. The output current I_{out} is the rectified inductor's current. Since output current I_{out} is of a triangular shape, its average value is a half of its peak value:

$$\bar{I}_{out} = \frac{1}{2} I_{pk} = \frac{V_{bus}^2 - V_{Line}^2}{8LFV_{bus}} \tag{5}$$

where $\bar{I}_{out}$ is the output current averaged over the switching cycle.

[0088] It should be noted that the equation (5) is obtained considering some time instant t. Thus, output current $\bar{I}_{out}$ of inverter **802** (FIG. **12**) over the line cycle is defined as following:

$$\bar{I}_{out}(t) = \frac{V_{bus}^2 - V_{Line}^2(t)}{8LF(t)V_{bus}} \tag{6}$$

[0089] According to an embodiment of the present invention, grid-connected inverter **802** delivers the current which is in phase with and of shape of the line voltage V_{Line}. The line voltage is considered as:

$$V_{Line}(t) = V_{out}(t) = V_{rms}\sqrt{2}\,\sin 2\pi f_{line} t \tag{7}$$

where V_{rms} is the RMS (Root Mean Square) line voltage, and f_{line} is the line frequency.

[0090] Consequently, the inverters output current is given by:

$$\bar{I}_{out}(t) = \frac{P_{out}}{V_{rms}}\sqrt{2}\,\sin 2\pi f_{line} t = \frac{P_{out} V_{out}(t)}{V_{rms}^2} \tag{8}$$

where P_{out} is an average power delivered to the line. Substituting (8) into (6) yields:

$$F(t) = \frac{V_{rms}^2}{8LP_{out}} \frac{V_{bus}^2 - V_{Line}^2(t)}{V_{bus} V_{Line}(t)} \tag{7}$$

[0091] As a result, if the switching frequency F(t) is set (programmed) according to (7), output current $\bar{I}_{out}$ will follow the line voltage. In addition, it follows from (7) that when the line voltage is low, the frequency can go too high. Therefore, according to another embodiment of the present invention, this problem is overcome by providing a PWM (Pulse Width Modulation) unit. That is, the control signal is kept at some predefined maximum frequency F_{lim} awhile; the pulse width (t_{on}) of the control signal is varies to generate the desired current level. It can be shown that the average output current will follow the line voltage, if t_{on} is programmed according to (8):

$$t_{on}(t) = \sqrt{\frac{P_{out}V_{Line}(t)L}{V_{rms}^2 V_{bus}}\frac{V_{bus}+V_{Line}(t)}{V_{bus}-V_{Line}(t)}\cdot\frac{1}{F_{lim}}} \quad (8)$$

[0092] The signal $V_{Line}(t)$ can be obtained by sampling the output voltage, from a local oscillator locked to the power line frequency or from a table stored in a digital memory. As a result, the magnitude and shape of the output current of circuitry **1100** is improved.

[0093] According to still another embodiment of the present invention, the drive frequency F(t) and $t_{on}(t)$ are generated by a circuit that compares current I_{Lh} of inductor L_h and the waveform of V_{Line}. The deviations are translated into the excitation of voltage V_c (FIG. **11**).

[0094] FIG. **15** is a schematic illustration **1500** of a circuitry of a microcontroller-based grid-connected inverter, according to an embodiment of the present invention. According to this embodiment, the electrical energy source is galvanically isolated from the line by a transformer T_1. A digital microcontroller **1521** carries out a specific algorithm for operating the circuitry, said operating includes line synchronization, MPPT, waveform generation, switch driving and etc. Said digital microcontroller **1521** can be used to control the two stage system: Inverter **802** and Polarity Commutator **804** by means of HF (High Frequency) **1119** and LF (Low Frequency) Drivers **1118**, respectively.

[0095] FIG. **16** is a schematic illustration **1600** of a circuitry of a half-bridge based grid-connected inverter, according to an embodiment of the present invention. According to this embodiment, Inverter **802** and Polarity Commutator **804** are realized by half bridge topologies. In this case, inverter **802** is represented by a high frequency half bridge configuration containing switches Q**1** and Q**2**, and Polarity Commutator **804** is represented by a low frequency half bridge configuration containing switches Q**4** and Q**5**. Capacitor Cb is used as a blocking capacitor to pass only AC current. At the output, the LP (Low Pass) Filter represented by capacitor C_f and inductor L_f is used to reduce the current ripple injection to Power Line **107**.

[0096] As would be clear to a person trained in the art, the grid connected inverter according to an embodiment of the present invention, adds an advantage of soft switching of all power components. Zero Voltage Switching (ZVS) of inverter **802** is achieved by the fact that the inductor L_h current is switching direction every half cycle of the switching cycle. Consequently, during the dead time following the turn OFF of one transistor in each of the half bridges of the inverter (switches Q_1, Q_2 and switches Q_3, Q_4), the current of L_h causes self commutating of the voltage of the mid point of the half bride, and the complementary switch will be turned ON under ZVS. The soft switching has the advantage of lowering the switching losses (of reducing the power and stresses of switches), and hence improving efficiency. Another advantage of the soft switching is the lowering of the spurious signals that may cause electromagnetic interferences. Polarity Commutator **804** is switching under zero voltage and current conditions—at the zero crossing of the line voltage. Furthermore, the rectifying diodes assembly **803**, exhibits lower reverse recovery losses due to the fact that the current is controlled by the inductor L_h.

[0097] FIGS. **17** and **18** are schematic illustrations **1700** and **1800**, respectively, of waveforms of a current I_{Lh} of inductor L_h (FIG. **8**) and of an output current I_{out} (FIG. **8**), according to another embodiment of the present invention. FIG. **18** is a zoom of FIG. **17**. In this embodiment the frequency is not increased beyond a predetermined value when low feed currents are required (at the beginning and at the end of a half mains cycle). Rather, the Duty cycle (that is, the relative duration that the switches are on) is varied according to the required current. By limiting the Duty cycle of the inverter's switches to below 50%, the current increase in L_h (I_{Lh}) is controlled such that the average feed current to the power line follows the desired shape. The advantage of this optional method is in the fact that the switching frequency is not allowed to increase to very high values that might cause increased switching losses. This operation is depicted in the plot of I_{Lh} of FIG. **18**. Rather than increasing the frequency farther at low line voltages (and hence line currents), the switching frequency is kept at a constant value but the Duty cycle of the inverter's switches is controlled such that the average of the inductor current (I_{Lh}, shown as triangles) will be equal to the required average line current (shown in FIG. **15** as I_{out}).

[0098] FIGS. **19** and **20** are schematic illustrations **1900** and **2000**, respectively, of waveforms of a current I_{Lh} of inductor L_h (FIG. **8**) and of a current I_R(average) (FIG. **11**), according to still another embodiment of the present invention. FIG. **20** is a zoom of FIG. **19**. Similarly to FIGS. **17** and **18**, in this particular mode of operation, lower switching losses are also achieved. The switching frequency at low injected current is not increased beyond a predetermined value to avoid high switching losses. The frequency limit will be based on the type of switches used and other engineering considerations. According to an embodiment of the present invention, the frequency for low injection currents is kept at a constant low value, while the Duty cycle of switches (Q_1 to Q_4) of Inverter **802** (FIG. **8**) is maintained at 50%. The control of the shape of the injected current is obtained in this case by dithering. That is, driving the sequence Q_1, Q_4 and Q_2, Q_3 transistors for few switching cycles, and then turning all transistors OFF for a period of time such that the average current fed to the line is at the required value. This 'ON' and 'OFF' sequence is similar to a PWM (Pulse Width Modulation) operation in which the 'ON' period constitute a number of switching cycles.

[0099] While some embodiments of the invention have been described by way of illustration, it will be apparent that the invention can be put into practice with many modifications, variations and adaptations, and with the use of numerous equivalents or alternative solutions that are within the scope of persons skilled in the art, without departing from the spirit of the invention or exceeding the scope of the claims.

1. An apparatus of a grid-connected switching inverter for injecting a current into a power line, comprising:

a. an electrical energy source for providing the substantially DC voltage to said apparatus;

b. a switching inverter connected to said electrical energy source for converting said substantially DC voltage of said electrical energy source to a high frequency alternating voltage;

c. a waveform generator for controlling the magnitude, shape and frequency of said alternating high frequency voltage outputted from said switching inverter by means of a control signal fed into said switching inverter;

d. an inductor connected to an output of said switching inverter for generating an alternating current of variable magnitude and frequency from said alternating high frequency voltage, wherein the magnitude of said alternating current depends on a frequency of said alternating high frequency voltage;

e. a rectifier connected in series with said inductor for rectifying said alternating current and for outputting a rectified unipolar alternating current, wherein the rectified average value of said alternating current is proportional to the absolute magnitude of the power line voltage; and

f. a polarity commutator connected to an output of said rectifier for converting said rectified unipolar alternating current into a bipolar alternating current, and for injecting said bipolar alternating current into a power line, wherein said bipolar alternating current is substantially in phase with and of shape of said power line voltage of said power line.

2. Apparatus according to claim **1**, further comprising an MPPT unit for tracking the maximum power point of the electrical energy source.

3. Apparatus according to claim **1**, wherein the electrical energy source is one or more of the following:

a. a solar cell;

b. a fuel cell;

c. a wind turbine;

d. a battery or accumulator; and

e. a generator.

4. Apparatus according to claim **1**, wherein the switching inverter is an H-bridge or half bridge switching inverter.

5. Apparatus according to claim **1**, wherein the polarity commutator is a H-bridge or half bridge polarity commutator.

6. Apparatus according to claim **1**, wherein the polarity commutator comprises two or more switches that are driven by means of low frequency signals outputted from low frequency drivers.

7. Apparatus according to claim **1**, wherein the magnitude of the alternating current of the inductor depends on the duty cycle of the control signal fed to the inverter.

8. Apparatus according to claim **7**, further comprising a modulation unit for limiting the alternating current of the inductor to a predefined maximal frequency.

9. Apparatus according to claim **1**, further comprising a line synchronizer for sensing the line voltage and generating corresponding synchronization commands.

10. Apparatus according to claim **1**, further comprising an overvoltage protection unit for guarding said apparatus from dangerous DC voltage levels under no load conditions.

11. Apparatus according to claim **1**, further comprising a microcontroller for controlling the operation of said apparatus.

12. Apparatus according to claim **1**, further comprising a transformer for galvanically isolating the electrical energy source from the power line.

13. Apparatus according to claim **1**, further implementing soft switching of the switches of the inverter for reducing the power and stresses of said switches.

14. Apparatus according to claim **1**, further comprising a DC-DC converter, placed between the electrical energy source, and switching inverter for adjusting the voltage level of said electrical energy source to that required for said switching inverter.

15. Apparatus according to claim **1**, wherein the alternating current is generated in the inductor due to imposing a bipolar high frequency voltage across said inductor.

16. Apparatus according to claim **13**, wherein the alternating current in the inductor is controlled by varying the frequency of the bipolar high frequency voltage or by toggling the bipolar voltage signal ON and OFF.

17. Apparatus according to claim **13**, wherein the alternating current in the inductor is controlled by varying the ON time within each switching period of the bipolar voltage.

18. A method for injecting a current into a power line, comprising:

a. providing an inductor, a terminal of which is, connected in series to a first input of a rectifier;

b. generating an alternating current of variable magnitude and frequency in said inductor by applying a high frequency voltage between the other terminal of said inductor and a second input of said rectifier;

c. rectifying said alternating current by means of said rectifier, thereby obtaining the magnitude of the rectified average value of the alternating current that is proportional to the absolute magnitude of the power line voltage;

d. commutating the polarity of the rectified alternating current to be synchronized with the phase of the power line current; and

e. injecting the synchronized rectified alternating current into said power line.

19. A method for injecting a current into a power line, comprising:

a. providing the substantially DC voltage by means of an electrical energy source;

b. converting said substantially DC voltage of said electrical energy source to a high frequency alternating voltage by means of a switching inverter connected to said electrical energy source;

c. controlling the magnitude, shape and frequency of said alternating high frequency voltage outputted from said switching inverter by means of a control signal fed into said switching inverter from a waveform generator;

d. generating an alternating current of variable magnitude and frequency from said alternating high frequency voltage by means of an inductor connected to an output of said switching inverter, wherein the magnitude of said alternating current depends on a frequency of said alternating high frequency voltage;

e. rectifying said alternating current and outputting a rectified unipolar alternating current by means of a rectifier connected in series with said inductor, wherein the rectified average value of said alternating current is proportional to the absolute magnitude of the power line voltage; and

f. converting said rectified unipolar alternating current into a bipolar alternating current and injecting said bipolar alternating current into a power line by means of a polarity commutator connected to an output of said rectifier, wherein said bipolar alternating current is substantially in phase with and of shape of said power line voltage of said power line.

20. Method according to claim **19**, further comprising tracking the maximum power point of the electrical energy source by means of a MPPT unit.

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