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(71) **Applicant**: **THE UNIVERSITY OF HONG KONG** [CN/CN]; Pokfulam Road, Hong Kong (CN).

(72) **Inventors**: **LEE, Chi Kwan**; Flat RC, 59th Floor, Tower 8, Le Prime LOHAS Park, Tseung Kwan O, New Territories, Hong Kong (CN). **KIRATIPONGVOOT, Sitthisak**; Flat 1002, 10th Floor, Shin Nga House, Fu Shin Estate, 12 On Po Road, Tai Po, New Territories, Hong Kong (CN).

(74) **Agent**: **CHINA PATENT AGENT (H.K.) LTD.**; 22/F., Great Eagle Center, 23 Harbour Road, Wanchai, Hong Kong (CN).

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(54) **Title**: ELECTRONIC APPARATUS AND CONTROL METHOD FOR HIGH FREQUENCY AC TO DC CONVERSION

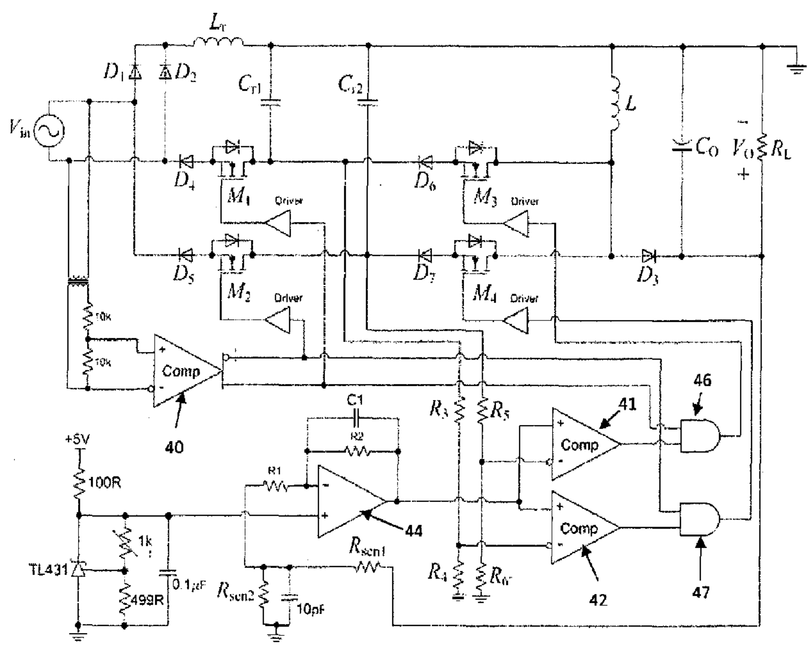


Figure 8

(57) **Abstract**: A high-frequency AC-DC power converter takes an input AC signal and converts it to an output DC signal. The converter has at least two front-end rectifier diodes arranged as a full wave rectifier of the input AC signal. A first inductor positioned at the output of the full wave rectifier. An output capacitor is connected across a load for the converter. There are at least one additional inductor and one additional capacitor. A switching circuit selectively forms different LC resonant circuits with the inductors and capacitors during a cycle of the input AC signal to form a AC-DC power converter.

WO 2015/109727 A1

Electronic Apparatus and Control Method for High Frequency AC to DC Conversion

Field of the Invention

[0001] The present invention relates generally to high frequency AC to DC conversion for the purpose of wireless power transfer.

Background of the Invention

[0002] Wireless power transfer (WPT) based on the magnetic resonance and near-field coupling of two loop resonators was reported by Nicola Tesla a century ago. It transmits electric energy and information from a transmitter to the receiver without physical contact. Since the 1960s, and particularly over the last few decades, WPT has been an active research area in regard to transcutaneous energy systems for medical implants. For modern short-range applications, inductive power transfer (IPT) systems and wireless charging systems for portable electronic equipment have attracted much attention since 1990's and 2000's respectively. Wireless charging technology for portable electronic devices has reached commercialization stage through the launch of the "Qi" Standard by the Wireless Power Consortium, now comprising over 135 companies worldwide. The recent research activities on this topic have focused on mid-range applications comprising 2-coil, 4-coil, relay resonators and domino-resonator systems.

[0003] At present, a lot of research is focused on improving the performance of WPT systems, such as to increase the transfer distance, to improve the efficiency and to widen the operating frequency. There is a lack of research examining and addressing the problems arising from the receiver side, which also has a significant influence on the performance and efficiency of the system. In most of the applications, the AC power output from the receiver is first converted to a DC voltage. The simplest approach is to use a diode rectifier 10 with a capacitor 12 connected at the DC output side as shown in Figure 1(a). However, this capacitor is charged to a value close to the peak of the AC input voltage (see Figure 1(b)). As a result, the input current is very large near the peak of the AC input voltage and it does not flow continuously. These diode rectifiers draw highly distorted current from the AC source and result in a poor power factor (PF). The energy efficiency and power transfer capability of a poor PF system are relatively low because of the high conduction loss in the power converters and transmission wires. Additionally, the distorted current has rich harmonic content which may create extra electromagnetic interference (EMI) in neighboring electronic equipment.

[0004] An electronic power converter, such as a boost converter, can be used to shape the line current drawn by the rectifier so it is sinusoidal and in phase with the line voltage. Figure 2(a) shows a classical boost converter connected after a diode bridge rectifier to form a power factor correction (PFC) circuit. The output dc voltage $V_{dc\ actual}$ is sensed and fed to an error amplifier 20. The difference V_{error} between the actual and reference voltage $V_{dc\ ref}$ is derived and applied to a compensator circuit 22, such as a proportional-integral (PI) compensator. The output of the compensator is multiplied in circuit 24 with the signal proportional to the line voltage waveform v_S to produce the reference current signal $i_{L,ref}$. Afterward, a current-mode controller 26 is used to generate the on and off signal to the switch 28 shaping the current waveform of the inductor 11. Therefore, the average waveshape of the line current is forced to follow the waveform of the line voltage.

[0005] Figure 2(b) depicts the current waveform of the converter. It can be observed that the switching frequency of the PFC converter must be many times higher than the frequency of the AC system. The typical operating frequency of a modern PFC converter is in the range of 20 to 40 kHz which is over 100 times higher than the frequency of the AC system. Using a 400 kHz WPT system as an example, applying this current-shaping technology implies that the switch 28 has to operate at 40 MHz. In fact, when the switching frequency approaches tens of megahertz, the switching loss becomes significance and the efficiency of the converter is sharply reduced. The converter also has a number of other problems and limitations, including parasitic inductance and capacitance of the interconnections, stray inductances of the magnetic components, and parasitic and junction capacitances of the semiconductor diodes and switches. The EMI, thermal, insulation and isolation problems of the converter are not easy to solve individually. Hence, the conventional current-shaping PFC technology is not suitable for high frequency ac system since the fundamental frequency is already in the range of hundreds of kilohertz to a few megahertz.

Summary of the Invention

[0006] This invention provides an electronic apparatus and control method for high frequency AC to DC conversion. Based on the resonant technique, the line current is shaped to be sinusoidal and is forced to follow the line voltage. Hence, the input side AC power factor of the converter is close to unity. With the proper selection of the characteristic impedance of the resonant tank, the converter is able to perform the function of a buck, boost or buck-boost converters. The initial condition of the resonant tank is used to control the output voltage gain of the converter. Since all the switches are operated at the fundamental frequency of the input AC source, the switching losses of the converter are small. A control scheme is also proposed for the converter. It can be realized by simple operational amplifiers and digital logic gates that can be easily fabricated into a single integrated circuit (IC) for mass production. The distinctive features of this invention are favorable for the high frequency AC to DC conversion including inductive/capacitive wireless/contactless power transfer system.

[0007] The present invention provides a solution for high frequency AC to DC conversion with power factor correction. The distinctive features of this new invention are summarized as follow:

- With the use of a resonance technique, the AC line current is shaped to be sinusoidal and the AC power factor of the converter is near unity.
- The output voltage gain of the converter can be controlled above or below the AC line voltage.
- All the semiconductor devices are operated at a constant frequency which is equal to the frequency of the AC source.
- The control scheme can be realized by simple analog and digital circuits which is favorable for integrated circuit (IC) fabrication.

Brief Description of the Drawings

[0008] The foregoing and other features of the present invention will be more readily apparent from the following detailed description and drawings of an illustrative embodiment of the invention in which:

[0009] Fig. 1(a) is a schematic of a prior art simple diode rectifier with an output storage capacitor and Fig. 1(b) shows the input voltage and current waveforms for the circuit of Fig. 1(a);

[0010] Fig. 2(a) is a schematic of a prior art power factor correction circuit and Fig. 2(b) shows the input voltage and current waveforms for the circuit of Fig. 2(a);

[0011] Fig. 3 shows a half wave rectifier with an inductive-capacitive load;

[0012] Fig. 4(a) shows the input voltage of the circuit of Fig. 3, Fig. 4(b) shows the current in the inductor of Fig. 3 and Fig. 4(c) shows the voltage on the capacitor of Fig. 3.

[0013] Fig. 5(a) shows a switched capacitor bank with a binary-weighted structure and Fig. 5(b) shows the ac to dc converter of the present invention with switched LC circuits:

[0014] Fig. 6(a) shows the waveforms for the circuit of Fig. 5(b), and Figs 6(b)-6(e) show the four states of the circuit of Fig. 5(b) during an input ac voltage cycle;

[0015] Fig. 7(a) shows the circuit of Fig. 5(b) with a switch control, Fig. 7(b) shows a detail of the phase detector in Fig. 7(a) and Fig. 7(c) shows a detail of the pulse width modulation (PWM) generator in Fig. 7(a)

[0016] Fig. 8 is a schematic diagram of an integrated circuit form of the circuit of Fig. 7(a);

[0017] Fig. 9 are simulated waveforms for the circuit of Fig. 8; and

[0018] Fig. 10 is a graph of the output voltage gain versus normalized control voltage for the circuit of Fig. 8.

Description of an Illustrative Embodiment of the Invention

[0019] According to the present invention, a new concept is proposed to realize high frequency AC to DC conversion with input AC side power factor correction (PFC) and output DC voltage regulation. Considering a half wave rectifier with an inductive-capacitive (LC) load as shown in Figure 3. The voltage source V_{in} is ac and its angular frequency is ω . A LC load is selected such that its angular resonance frequency $\omega_r = 1/\left(2\pi\sqrt{L_r C_r}\right)$ is equal to the angular frequency of the source. For the positive half-cycle of the source in this circuit, the diode is forward biased. The current produced by the LC resonance will be forced into a sinusoidal form. The power flow is controlled by the characteristic impedance $Z_r = \sqrt{L_r / C_r}$ and the initial condition of the capacitor $V_{Cr,0}$. Figures 4(a) – 4(c) depict the input voltage and corresponding current and voltage waveforms, respectively, of the rectifier under different initial values of the capacitor. For the negative half-cycle of the source, the diode is reverse biased, making the current zero. The energy stored in the capacitor C_r must be dissipated in a resistive load. Hence the rectifier is effective at the next positive half-cycle.

[0020] Figure 5(a) depicts a switched capacitor bank for changing the capacitance. The value of an individual capacitor can be arranged in a binary-weighted structure. The angular resonant frequency ω_r of the LC load can be dynamically changed by controlling the switches.

[0021] Figure 5(b) shows the proposed high frequency AC to DC converter with a sinusoidal input voltage source v_{in}. For simplicity, the diodes and switches are considered ideal. The inductor L and output capacitor C_o are assumed sufficiently large, which result in a constant current and output voltage V_o under steady-state. During the positive half-cycle of the source, the switches S_1 and S_4 conduct together. Conversely, the switches S_2 and S_3 conduct together in the negative half-cycle. The diodes D_1 and D_2 cannot be on at the same time. The capacitor C_{r1} and C_{r2} serve as the function of storing and transferring energy from the input to the output. The operating states and corresponding waveforms of the converter are shown in Figures 6(a) – 6(e).

A. Operating Principle

[0022] ***State 1*** ($0 < t \le t_1$), Fig. 6(b): Prior to turning the switches S_1 and S_4 on, the capacitor C_{r1} and C_{r2} are assumed to be charged to $V_{Cr,min}$ and $V_{Cr,max}$, respectively. The positive half-cycle begins at t=0. The switches S_1 and S_4 are turned on. Fig. 6(b) The input voltage v_{in}, inductor L_r and capacitor C_{r1} are connected in series to form a series resonance circuit. The increasing of v_{in} causes D_1 to conduct. The input current i_{in} is forced into a sinusoidal form. The L_r and C_{r1} together determine the angular resonance frequency ω_r of the converter which is equal to the angular frequency of the voltage source. The inductor L is sufficiently large such that the current I_L can be assumed to be a constant magnitude. Thus, the capacitor C_{r2} discharges into the inductor L and the capacitor voltage linearly drops to zero. Hence, C_{r2} is charged to $V_{Cr,min}$ by the inductor L. In this time period, the output capacitor C_o delivers energy to the output load resistor R_L.

[0023] ***State 2*** ($t_1 < t \leq t_2$, Fig. 6(c)): At $t = t_1$, the capacitor C_{r2} has been charged to $V_{Cr,min}$. The switch S_4 is turned off. Fig. 6(c) The current of the inductor L flows to the output capacitor C_o and load resistor R_L through the diode D_3. At $t = t_2$, inductor current i_{Lr} returns to zero, the capacitor V_{Cr1} is charged from $V_{Cr,min}$ to $V_{Cr,max}$. The switch current S_1 is commutated off naturally and the gate/base drive from the switch should be removed at this point. The negative cycle begins.

[0024] ***State 3*** ($t_2 < t \leq t_3$, Fig. 6(d)): In the negative half-cycle of v_{in}, the switches S_2 and S_3 are turned on. The negative part of waveform is similar to the positive half-cycle. The inductor L_r and capacitor C_{r2} are connected in series to form a series resonance circuit shaping the input current into a sinusoidal form. Energy is transferred from the input source v_{in} to capacitor C_{r2}. In the meantime, the energy stored in C_{r1} is transferring to the inductor L. Similarly, the load is supplied by the output capacitor C_o.

[0025] ***State 4*** ($t_3 < t \leq t_4$, Fig. 6(e)): At $t = t_3$, switch S_3 is turned off when the voltage of C_{r1} is equal to $V_{Cr,min}$. Energy stored in L feeds to the output capacitor C_o and load resistor R_L. When the source voltage again becomes positive at $t = t_4$, switch S_2 is turned off and switches S_1 and S_4 are turned on again. The positive part of the waveform is repeated.

B. Control of the Converter

[0026] The method that can provide control for the converter is described in Figures 7(a)- 7(c), which depict a simplified control block diagram that generates control signals for the converter in order to regulate the output dc voltage V_o. The ac source voltage v_{in} is sensed as a feedback signal applied to phase detector circuit 30. The phase detector circuit is a comparator which derives the phase information of the ac source as shown in Figure 7(b). The outputs of the phase detector circuit are connected to the gate/base driver circuit 32 to control the on/off time of the switches S_1 and S_2 so they follow the ac source frequency. The signals Crt_S_1 and Crt_S_2 are the control signals of switches S_1 and S_2, respectively. The outputs of the phase detector 30 are also applied to the Pulse-Width Modulation (PWM) generator 34 to derive the control signals Crt_S_3 and Crt_S_4 for switches S_3 *and* S_4. The instantaneous output voltage V_o of the converter is sensed and subtracted in circuit 36 from the reference voltage $V_{\mathrm{o\_ref}}$ to determine the error. The error signal is applied to a compensator 38 to generate the reference voltage $V_{\mathrm{Cr\_ref}}$ for the resonant capacitors C_{r1} and C_{r2}. Figure 7(c) shows that the instantaneous voltages of the resonant capacitors C_{r1} and C_{r2} are sensed and compared to the reference voltage $V_{\mathrm{Cr\_ref}}$ in the PWM generator 34 which sets the pulse width of the switches S_3 and S_4.

[0027] In Fig. 7(a) the diodes D_1, D_2, switches S_1, S_2, and reactance L_r, C_{r1} and C_{r2} act as a ac-dc power factor correction circuit of the input ac voltage V_{in} to generate a current i_{Lr} as shown in Figs. 6(a) – (e). The switches S_3 and S_4, diode D_3, output inductor L and output capacitor C_o form a dc-dc power converter to regulate the output voltage V_o.

[0028] An example of the realization of proposed high frequency AC to DC converter using metal-oxide-semiconductor field-effect transistor (MOSFET) is shown in Figure 8. The control circuit is implemented by discrete components including analog comparators 40-42, operational amplifier 44 and logic gates 46, 47. The converter is designed to convert a 500 kHz AC voltage source into a DC source. The input voltage and the expected output power of the converter are 50 Vpeak and 100 W, respectively. The output load resistance of the converter is 100 Ω. To verify the advantage of the present invention, a simulation study was conducted. Table 1 summarizes the specification of the converter.

Converter Specifications	
Input AC voltage	50Vpeak
Input AC frequency	500kHz
Output DC voltage	100V
Output DC power	100W
Resonant Tank Inductor L_r	10.132μH
Capacitor C_{r1} , C_{r2}	10nF
Main Inductor L	3.236mH
Output Capacitor C_o	1.092μF

Table 1 Converter Specifications.

[0029] Figure 9 shows the simulated voltage and current waveforms of the converter by simulation. The simulation waveforms are in good agreement with the theoretical analysis given in A. Operating Principle. The voltage conversion ratio against the normalized threshold voltage V_{Cr_ref}/V_O is plotted in Figure 10. It can be observed that the output voltage of the converter is dependent on the characteristic impedance Z_r (input impedance) of the converter and the output load resistance R_L. With the proper selection of the characteristic impedance of the resonant tank, the converter is able to perform the function of a buck and boost conversion.

[0030] While the present invention has been particularly shown and described with reference to a preferred embodiment thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention. The invention is not limited by this description, but only by the appended claims.

Claims

What is claimed is:

1. A high-frequency ac-dc power converter with an input ac signal and an output dc signal, comprising:

at least two front-end rectifier diodes arranged as a full wave rectifier of the input ac signal,

a first inductor with an input connected to the output of the full wave rectifier and an output connected to one end of a load for the converter,

an output capacitor connected across the load for the converter,

at least one additional inductor and one additional capacitor,

a switching circuit for selectively forming different (LC) resonant circuits with the inductors and capacitors during predetermined parts of a cycle of the input ac signal to form a ac-dc power converter.

2. A high-frequency ac-dc power converter according to claim 1 wherein the LC resonant circuits are tuned to the frequency of the input voltage.

3. A high-frequency ac-dc power converter according to claim 1 wherein the capacitors of the LC resonant circuits are constructed by a switched capacitor bank and the resonant frequency is changed by controlling the switches of the capacitor bank.

4. A switched capacitor bank according to claim 3 wherein the value of the capacitors is arranged in a binary-weighted structure.

5. A high-frequency ac-dc power converter according to claim 1 wherein a switch S1 is turned on for the positive half cycle of the input ac signal and a switch S2 is turned on for the negative half-cycle thereof.

6. A high-frequency ac-dc power converter according to claim 1 wherein the dc-dc power converter is implemented as a fly-back converter.

7. A high-frequency ac-dc power converter according to claim 1 wherein the connection of the LC resonant circuits and the dc-dc power converter is achieved by the control of a switch S4 for the positive half cycle of the input ac signal and a switch S3 for the negative half cycle thereof.

8. A high-frequency ac-dc power converter according to claim 1 wherein the control of the power converter can be achieved with the use of a phase detector that detects the phase of the input ac signal, a PWM generator that drives the switching based on the phase of the input ac signal, and an output feedback loop with a compensator whose input is the difference between the output voltage and a reference, said compensator affecting the PWM generator operation.

9. A high-frequency ac-dc power converter according to claim 1 further including a third diode and wherein the at least one additional inductor is connected in series with the third diode across the load for the converter.

10. A high-frequency ac-dc power converter according to claim 9
wherein the at least one additional capacitor is first and second capacitors with ends connected together and to the output of the first inductor, the other end of the first capacitor being connected through a switch S_1 of the switching circuit to a negative terminal for the input ac signal and the other end of the second capacitor being connected through a switch S_2 of the switching circuit to a positive terminal for the input ac signal,
wherein a switch S_3 of the switching circuit is connected from the additional inductor where it connects to the third diode to the first capacitor where it connects to the switch S_1 and a switch S_4 of the switching circuit is connected from the additional inductor where it connects to the third diode to the second capacitor where it connects to the switch S_2, and
wherein the switching circuit operates to close switches S_1 and S_4 and opens switches S_2 and S_3 during most of the positive cycle of the input ac signal, further opens switch S_4 during the remaining portion of the positive cycle, closes switches S_2 and S_3 and opens switches S_1 and S_4 during most of the negative cycle of the input ac signal and further opens switch S_3 during the remainder of the negative cycle of the input ac signal.

11. A high-frequency ac-dc power converter according to claim 10 wherein the opening and closing of switches is achieved with the use of a phase detector that detects the phase of the input ac signal, a PWM generator that drives the switching based on the phase of the input ac signal, and an output feedback loop with a compensator whose input is the difference between the output voltage and a reference, said compensator affecting the PWM generator operation.

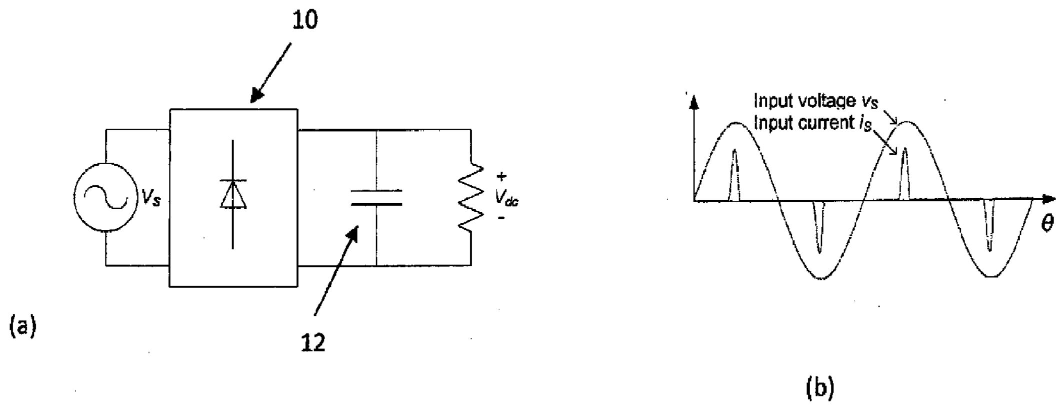


Figure 1

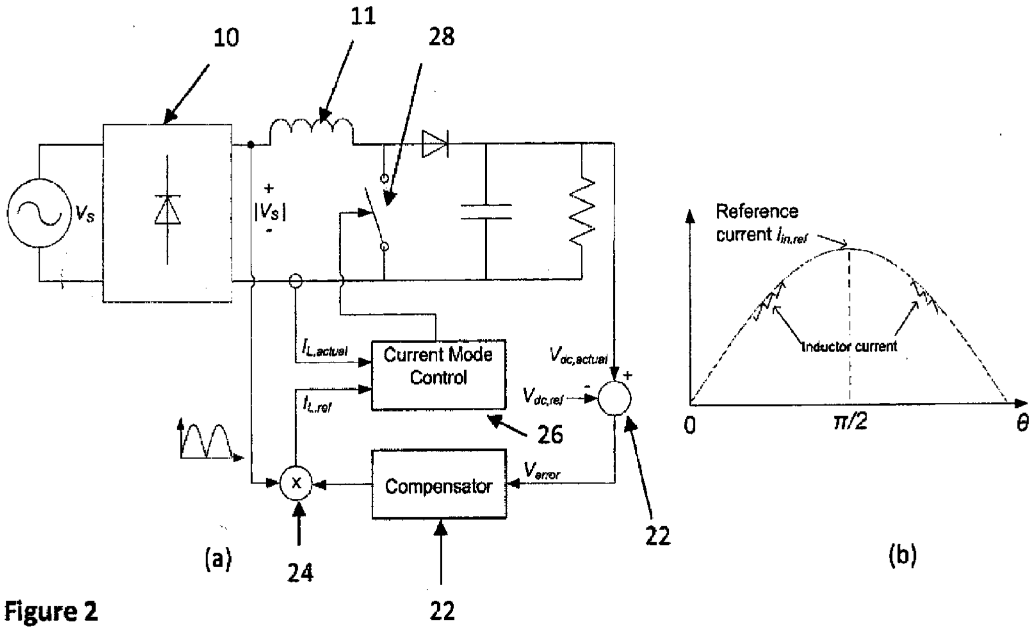


Figure 2

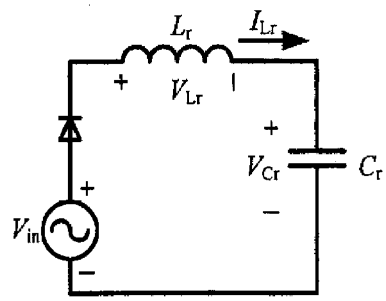


Figure 3

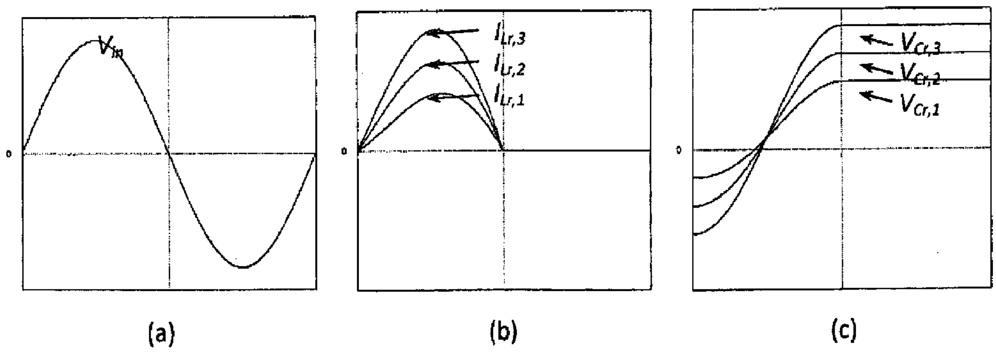


Figure 4

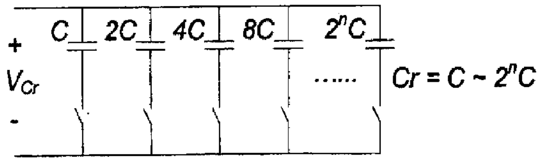


Figure 5(a)

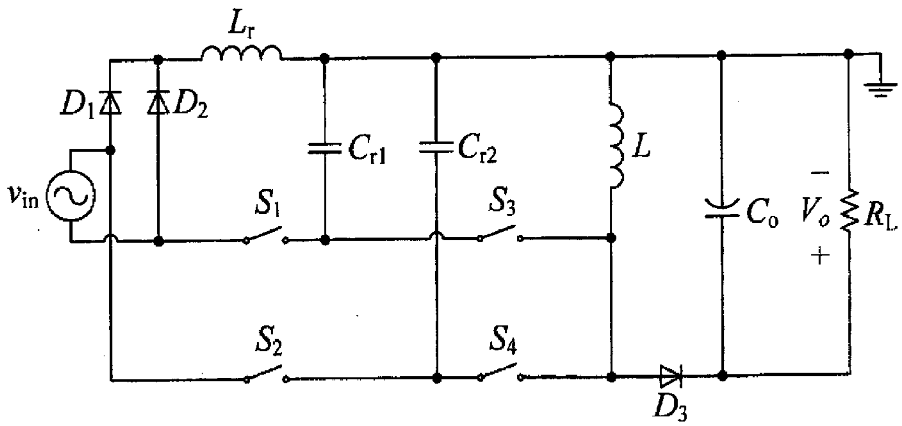


Figure 5(b)

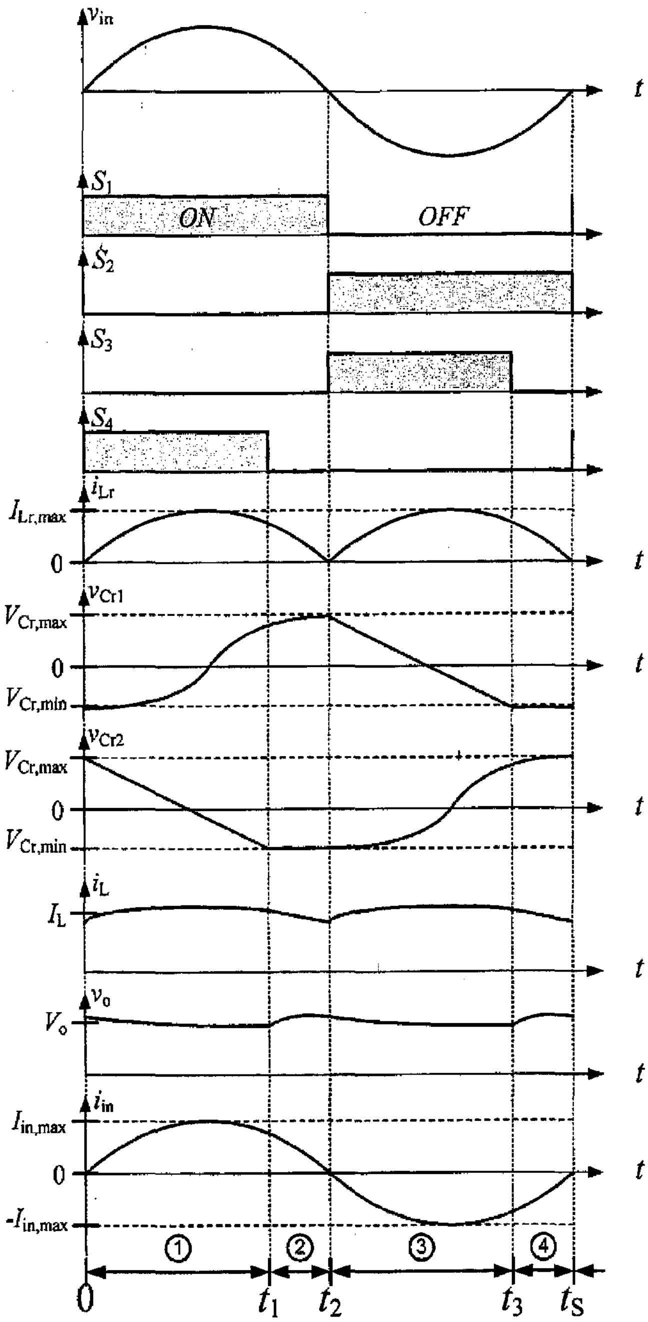
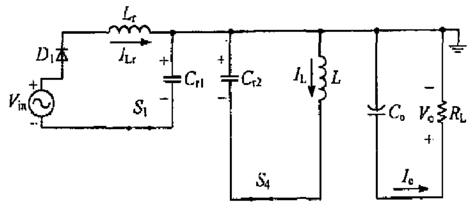
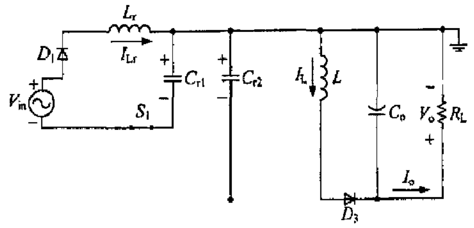


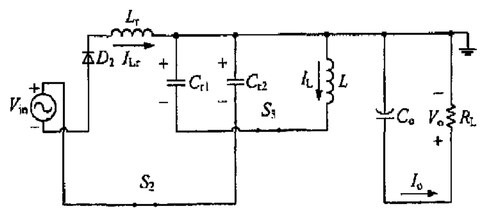
Figure 6(a)



(b) State 1



(c) State 2



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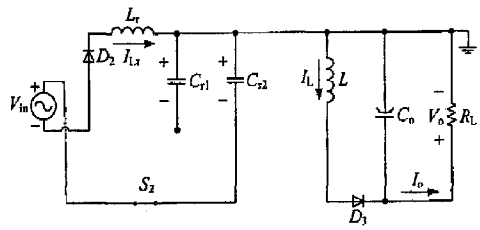


(e) State 4

Figures 6(b)-(e)

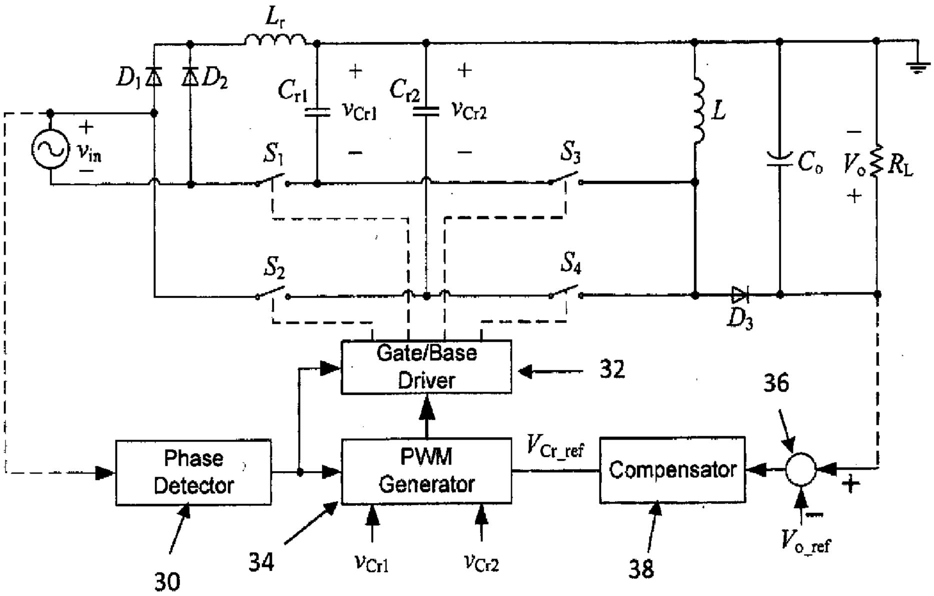
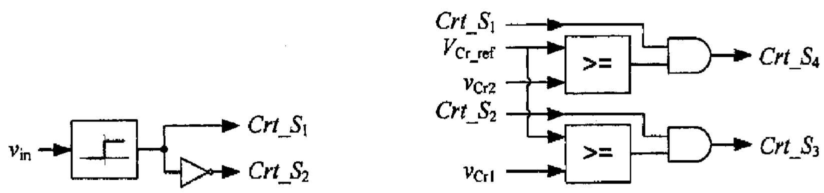


Figure 7(a)



(b) (c)

Figure 7(b)

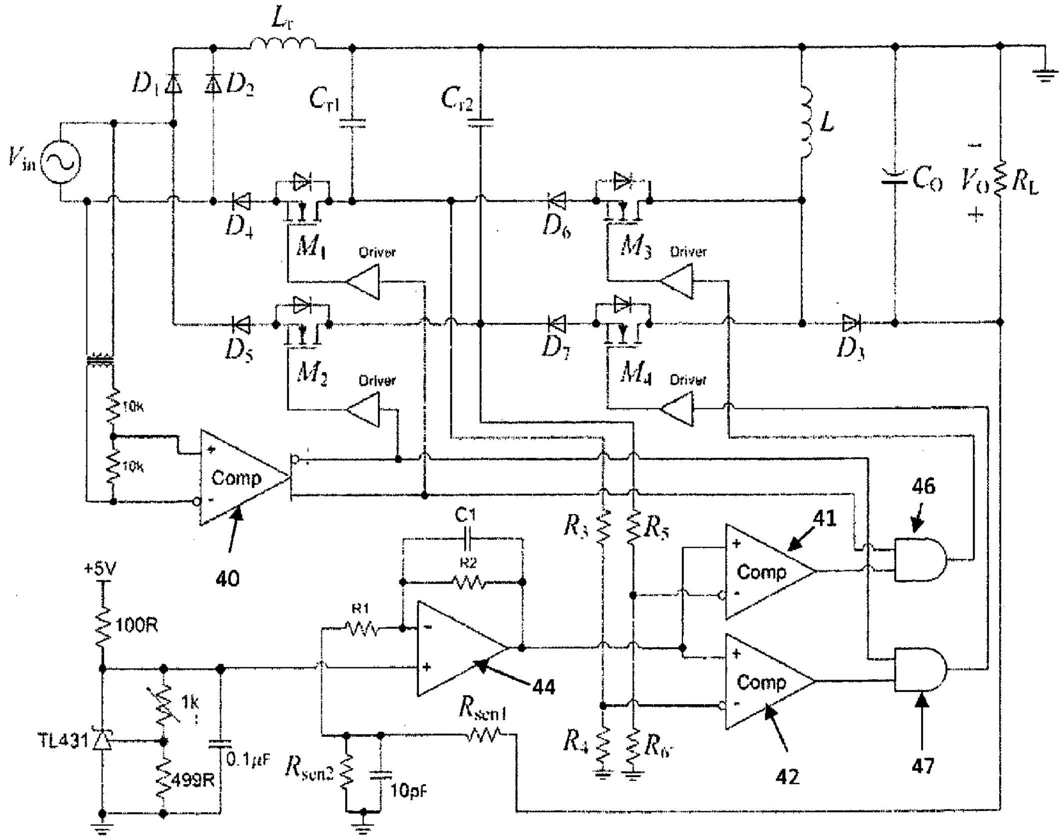

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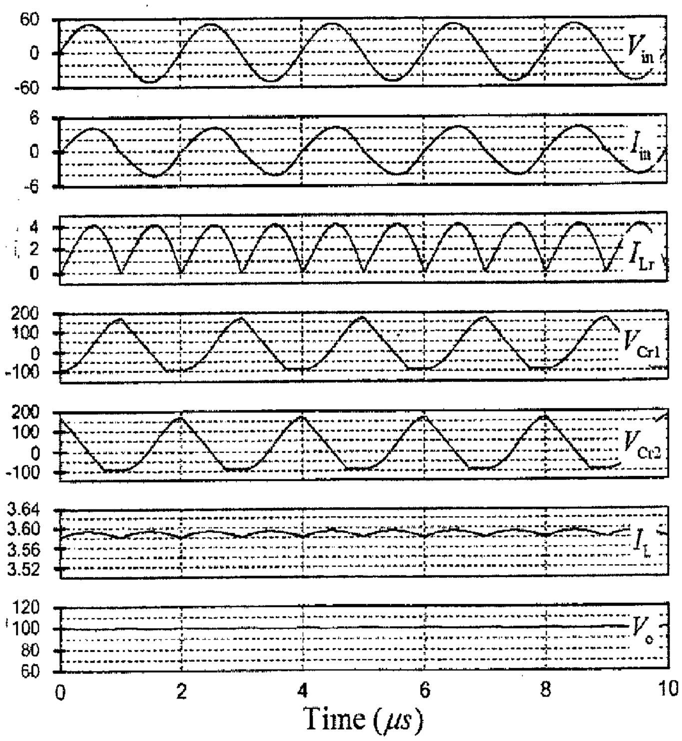
Figure 8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200
100
0
-100
V_{Cr2}
3.64
3.60
3.56
3.52
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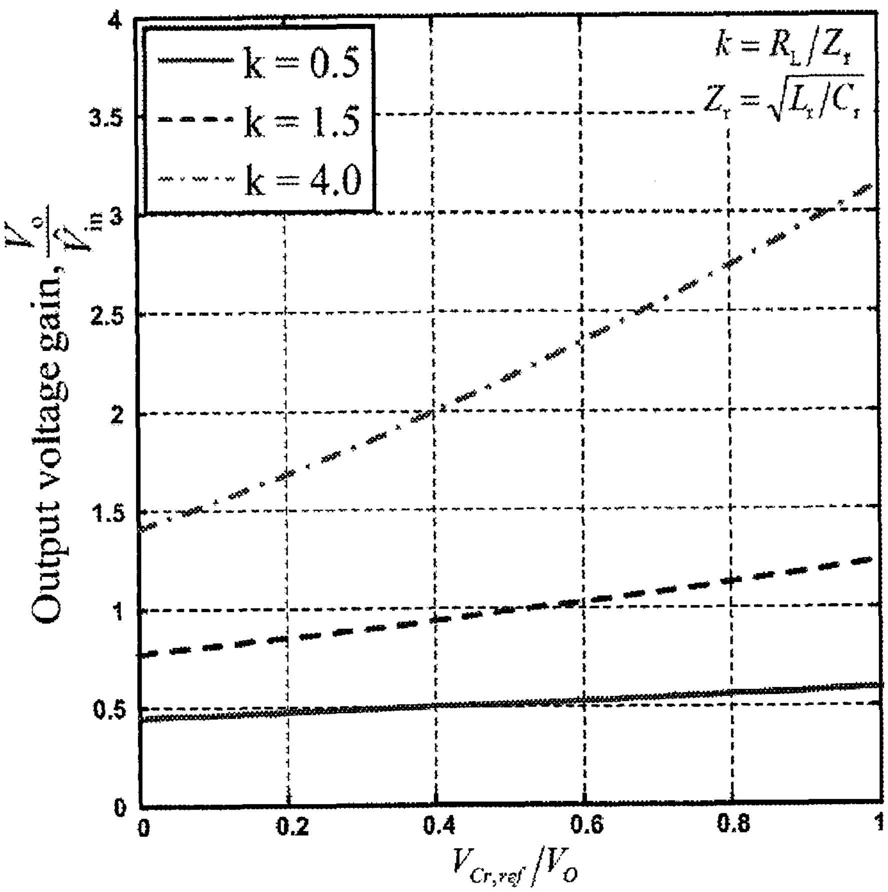
120
100
80
60
V_o
0
2
4
6
8
10
Time (μs)

Figure 9



k = 0.5
k = 1.5
k = 4.0
$k = R_L / Z_r$
$Z_r = \sqrt{L_r / C_r}$
Output voltage gain, $\frac{V_o}{\hat{V}_{in}}$
$V_{Cr,ref} / V_O$
0
0.5
1
1.5
2
2.5
3
3.5
4
0
0.2
0.4
0.6
0.8
1

Figure 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2014/079446

A. CLASSIFICATION OF SUBJECT MATTER

H02M 7/12 (2006.01) i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H02M;G05F

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

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

CNPAT,CNKI,EPODOC,WPI,GOOGLE:power, converter, inductor, capacitor, switch, diode, resonant, ac, dc, harmonic, sin, wave, shape, distort, factor, unity

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TW 561675 B (INDUSTRIAL TECHNOLOGY RESEARCH INSTITUTE) 11 November 2003 (2003-11-11) description, page 7, line 21 to page 11, line 18 and figures 5-7	1-9
X	JP H0787749 A (TOSHIBA LIGHTING & TECHNOLOGY) 31 March 1995 (1995-03-31) description, paragraphs [0033]-[0060] and figures 1-16	1-9
A	CN 103066873 A (FUZHOU UNIVERSITY) 24 April 2013 (2013-04-24) the whole document	1-11
A	FR 2742277 A1 (SGS THOMSON MICROELECTRONICS SA SOCIETE ANONYME) 13 June 1997 (1997-06-13) the whole document	1-11
A	FR 2744857 A1 (HUGUENY ALAIN) 14 August 1997 (1997-08-14) the whole document	1-11

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
08 October 2014	**27 October 2014**

Name and mailing address of the ISA/CN	Authorized officer
STATE INTELLECTUAL PROPERTY OFFICE OF THE P.R.CHINA(ISA/CN) **6,Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088 China**	**GE,Jiawu**
Facsimile No. **(86-10)62019451**	Telephone No. **(86-10)62413332**

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2014/079446

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
TW	561675	B	11 November 2003	US	2003107354	A1	12 June 2003
				US	6690143	B2	10 February 2004
JP	H0787749	A	31 March 1995	JP	3431099	B2	28 July 2003
CN	103066873	A	24 April 2013		Non	e	
FR	2742277	A1	13 June 1997	FR	2742277	B1	16 January 1998
				US	5783933	A	21 July 1998
FR	2744857	A1	14 August 1997		Non	e	