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Paper Authors

G. PREM KUMAR REDDY
Mahaveer institute of Science and Technology, Hyderabad.
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HIGH-FREQUENCY-FED UNITY POWER-FACTOR AC-DC POWER CONVERTER WITH ONE SWITCHING PER CYCLE

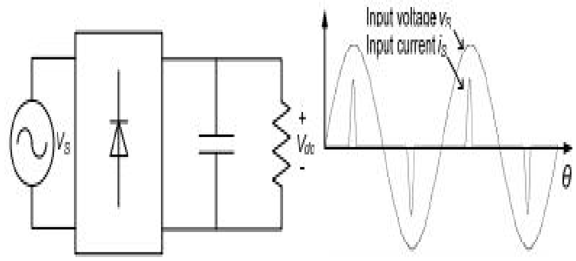
G. PREM KUMAR REDDY
Associate Professor, Mahaveer institute of Science and Technology, Hyderabad

Abstract—This paper presents a power converter and its control circuit for high-frequency-fed AC to DC conversion. Based on the resonant technique, the input current is shaped to be sinusoidal and is forced to follow the high-frequency sinusoidal input voltage so as toachieve unity power factor. 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 converter. 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 loss of the converter is small. A control scheme is also proposed for the converter. A proof-of-concept prototype operating at 400 kHz is constructed and its performance is experimentally measured. Results show that the proposed converter operates as theoretically anticipated.

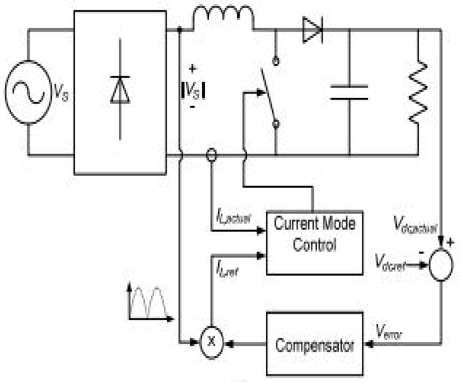
Index Terms— AC to DC conversion, Highfrequency rectifier, Power factor correction, resonant technique, Wireless powertransfer

I. INTRODUCTION

emerging technologies such as wireless power transfer (WPT) often adopt a high operating frequency in the range from a few hundred of kHz to over 10 MHz Recently, much research effort has been devoted to improving the performance of WPT systems in terms of transfer distance and system's energy efficiency There is a lack of research targeting the optimal design of the power converter at the receiver side. Traditionally, the simplest approach is to use a diode rectifier circuit with an output storage capacitor However, this capacitor is charged to a value close to the peak of the AC input voltage magnitude occurs near the peak of the AC input voltage. Discontinuous current implies that wireless power does not flow continuously from the primary side of the WPT system to the output of the system. Such diode rectifiers draw highly distorted current from the ac power source and result in a poor input power factor (PF). The energy efficiency and powertransfer 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 a rich high-order harmonic content which may cause the emission of electromagnetic interference (EMI) that affects the operation of neighbor electronic equipment.



A power electronic converter such as a boost converter can be used to shape the input AC current drawn by the rectifier to be sinusoidal and in phase with the AC voltage bridge rectifier to form a power factor correction (PFC) circuit. The output DC voltage is sensed and fed to an error amplifier. The difference between the actual and reference voltage is derived and applied to a compensator circuit such as a proportional-integral (PI) compensator. The output of the compensator is multiplied with the signal proportional to the AC voltage waveform vS to produce the reference current signal iL,ref. Afterwards, a current-mode controller is used togenerate the on and off signal to the switch shaping the current waveform of the inductor. Therefore, the average waveshape of the AC current is forced to follow the waveform of the AC voltage. depicts the input AC current waveform of the converter. It can be observed that the switching frequency of the PFC converter must be several times higher than the frequency of the AC system. Using a 400 kHz AC transmission system as an example, applying this currentshaping technology implies that the power switch has to operate in the tens of MHz. As a result, the switching loss becomes significant and the efficiency of the converter sharply reduces. Furthermore, MHz switching converter is also exposed to a number of problems arising from the passive and active components. For instance, the loss associated with the charging and discharging of the parasitic capacitance of power MOSFETs becomes significant The high-frequency behavior of the devices is very different from that of the lowfrequency behavior In terms of using passivecomponents in design, it is important to enhance their temperature stability and to minimize the unwanted stray and parasitic elementsFor the design of printed circuit board, it is crucial to eliminate undesired coupling between neighboring components and the rest of the circuit Without addressing these issues, the converter cannot be operated at a high frequency and achieved a high efficiency interconnection technologies are proposed to substantially reduce the structural parasitics and to improve the thermal management. However, the thermal performance and EMI are still big challenges which are difficult to solve individually as they are closely related to the circuit layout and packaging The paper is organized as follows. In Section II, the concept of using inductor-capacitor (LC) series resonant circuit to perform PF correction will be introduced. The operating principle of the proposed high-frequency-fed ac-dc power converter will be explicitly described using the corresponding timing diagrams and equivalent circuit diagrams. Then, the voltage conversion ratio and efficiency of the converter will be analytically investigated and presented in Section III. Afterwards, the construction of a proof-of-concept prototype and its experimental measurement results will be discussed. Section IV gives the conclusions of the paper.



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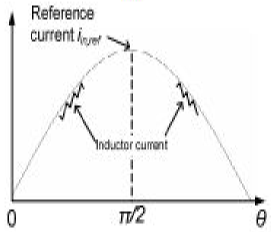
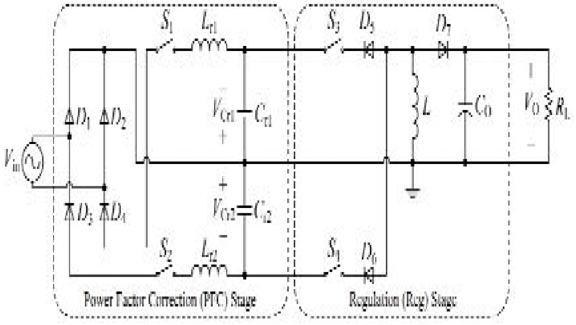


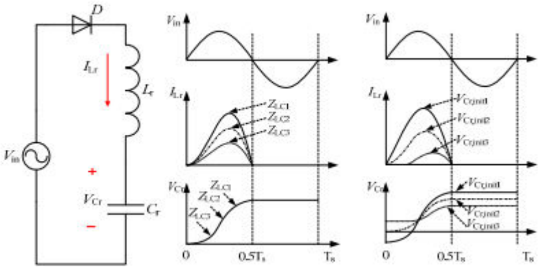
TOPOLOGY AND OPERATING PRINCIPLE



In this section, a high-frequency-fed ac-dc power converter is presented as given in Figure 3 and its operating and control principles are explained The advantageous features of this converter include near-unity input power factor and only one switching action per cycle for all the power switches.

A. LC Series Resonant Circuit

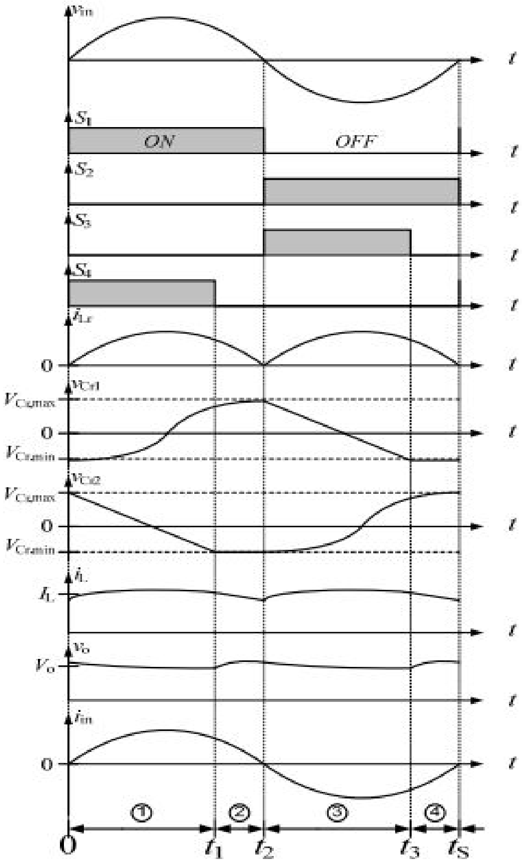
The power factor conditioning property is performed using the LC series resonant circuit at the input stage. The operation of the positive half cycle is used to describe how the LC resonant circuit can perform PF control in the high-frequency ac-dc power converterAssume that the source frequency is the same as the resonant frequency of the LC circuit ω= ωr=1/[2π(LrCr)1/2]and the initial current of the resonant inductor is zero. There are two parameters that will affect the amplitude and waveform of the inductor current. The first parameter is the equivalent impedance of the LC circuit which is designed by the resonant inductor and capacitor such that ZLC=(Lr/Cr)1/2, and the second parameter is the initial voltage of the resonant capacitor.



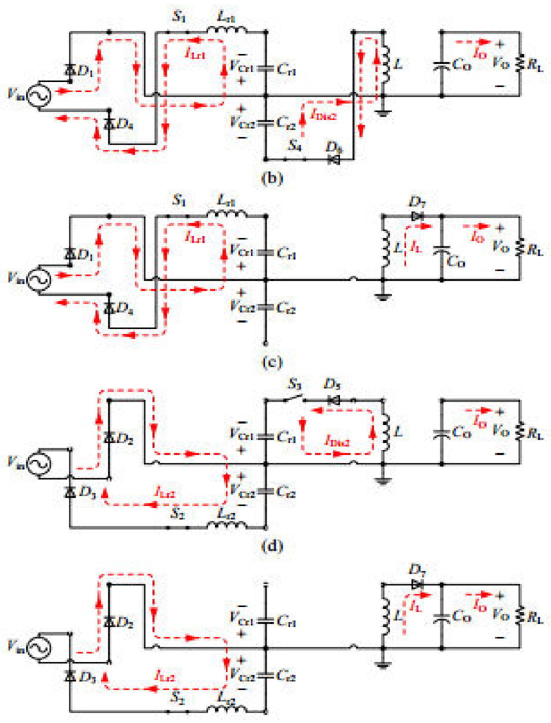
current and voltage waveforms of the LC resonant circuit with different equivalent impedances in the positive half cycle of the input voltage. The initial voltage of the resonant capacitor and the current of the resonant inductor are zero (VCr,init = 0 and ILr,init = 0). It can be observed that the source current is affected by the equivalent impedance of the LC circuit while the voltage waveform of the resonant capacitor remains the same. The total energy stored in the resonant capacitor over the positive half cycle is proportional to the size of the capacitance. voltage, the current of the resonant inductor, and the voltage of the resonant capacitor of the same circuit but with different initial conditions. It can be seen that the initial voltage value of the resonant capacitor can affect the magnitude of the resonant current of the inductor, of which the lower the initial resonant capacitor voltage, the higher the resonant inductor current becomes, and the lower the initial resonant capacitor voltage, the higher the capacitor voltage becomes at the end of the half cycle

Proposed Topology

The proposed two-stage circuit topology is shown in Figure3. The first stage (PFC stage) consists of two switches, four diodes, two resonant inductors, and two resonant capacitors. The second stage (regulation stage) consists of two switches, three diodes, one inductor, and one capacitor. In the PFC stage, the capacitor Cr1and Cr2are alternately charged by the input AC voltage source through the alternate switching actions of power switches S1and S2. Cr1is charged in the positive half cycle and Cr2is charged in the negative half cycle. In the regulation stage, the capacitors Cr1and Cr2, which have been charged by the first-stage converter, is commutated alternately as energy sources for the second-stage converter. Note that the second stage can be implemented by several types of power converters. In this paper, the buck-boost converter was selected for illustrating the proposed idea. The proposed topology can achieve high power factor by using the property of the series resonant circuit as discussed in Section II-A.C. Timing Diagram and Operating Modes The timing diagrams of the proposed high-frequency-fed acdc power converter that there are four operating modes select the resonant tanks Lr1-Cr1and Lr2-Cr2for the positive and negative half-cycles, respectively. In the regulation stage, S4and S3are the switches for controlling the buck-boost converter for the positive and negative half-cycles, respectively. Here, it is assumed that Cr1= Cr2and Lr1= Lr2.



Mode 1 (0 < t< t1):Prior to turning the switches S1and S4on, the capacitor Cr1and Cr2are assumed to be charged to VCr,minand VCr,max, respectively. The positive half-cycle begins at t=0. In the PFC stage, switch S1is turned on and switch S2is turned off. Diodes D1and D4are in the conducting state but diodes D2and D3are not conducting (see in Lr1and Cr1are connected in series forming a series resonant circuit. The first half of the resonance takes place and the inductor current starts from an initial value (zero), follows the first half of a sinusoidal waveform and then decreases to zero as D1and D4block the reverse current flow. Meanwhile, the voltage of capacitor Cr1is charged from its initial value VCr,minto a certain level at t= t1. In the regulation stage, switch S4is turned on and diode D6is in its conducting state. Switch S3is turned off and diodes D5and D7are reverse biased. The inductor Lis sufficiently large such that the current iLcan be assumed to be a constant magnitude. CapacitorCr2and inductor Lform a closed circuit. Cr2is discharged in one direction due to the polarity of diode D6until the voltage of capacitor Cr2is equal to the minimum voltage of capacitor Cr2 (VCr,min). The minimum voltage of capacitor Cr2is either a positive voltage (VCr,min> 0), zero voltage (VCr,min= 0) or negative voltage (VCr,min< 0) depending on the output power. Energy is transferred from the PFC stage to the regulation stage and is stored in the inductor L. In this time period, the output capacitor COdelivers energy to the output load resistor RL.



Mode 2 (t1 < t ≤ t2):In the PFC stage, the functions of the switches (S1 and S2) and diodes (D1, D2, D3and D4) are the same as that in Mode 1. Thus, the capacitor Cr1is kept charging by the power source to the level VCr,maxat t= t2, at which the positive cycle ends. Now, ILr1becomes zero and the switch S1is commutated off naturally. The diodes D1and D4become non conducting. In the regulation stage, S3and D5remain in the off state. S4is turned off at t= t1and D6is reverse biased when the voltage of Cr2is equal to VCr,min. Now, capacitor Cr2is not connected to the PFC or the regulation stage. The current of inductor Lcannot be changed instantaneously, resulting in the forward-biased conduction of diode D7. Therefore, the energy stored in inductor Lis delivered to the output capacitor COand the load resistorRL. Mode 3 (t2 < t ≤ t3):In the negative half-cycle of inv , the negative part of the waveforms are similar to that of the positive half-cycle. In the PFC stage, switch S2is turned on and switch S1is turned off. Diodes D2and D3are in the conducting state while diodes D2and D3are reverse biased (see in Figure 5(d)). Resonant tank Lr2-Cr2is connected in series with the input source Vin. The input current iinis shaped as a sinusoidal waveform. The voltage on capacitor Cr2is charged from the initial value VCr,minto VCr,max. Energy is transferred from the input source Vinto capacitor Cr2. In the regulation stage, switch S4and diode D6remain in the off state. Switch S3is turned on. Diode D5is in the conducting state while D7is reverse biased. The energy stored in resonant capacitor Cr1is transferred to inductor L. Cr1is discharged to Luntil the voltage of capacitor Cr1is equal to VCr,min. Similarly to

Mode 1, the load resistor RLis supplied by the output capacitor CO. Mode 4 (t3 < t ≤ tS):In the PFC stage, the switching state of the switches (S1 and S2) and diodes (D1, D2, D3and D4) are the same as that in Mode 3. In the regulation stage, switch S3is turned off at t= t3when the voltage of Cr1is equal to VCr,min. Energy stored in inductor Lis transferred to output capacitor COand load resistor RLthrough diode D7. Its equivalent circuit diagram is shown in Figure 5(e). Switch S2is commutated off naturally when input source Vinbecomes positive at t= tS. Afterwards, switches S1and S4 are turned on and the positive part of the operation is repeated.

CONCLUSION

A 400 kHz high-frequency-fed AC-DC PFC converter with one switching action per cycle is demonstrated. With a single converter topology, the converter is able to perform the function of a buck and boost conversion depending on the characteristic impedance of the resonant tank. The voltage conversion ratio of the converter can be further controlled by the initial voltage of the resonant capacitors. Experimental results prove that the converter is able to achieve a high power factor (PF > 0.9) and a low input current distortion (THD < 20%). A control scheme is also proposed for the converter. It can be realized by simple operational amplifiers and digital logic gates, and thereby can be easily fabricated as an integrated circuit (IC) for mass production. The distinctive features of this converter are favorable for future highfrequency AC power transfer system operating in the range from a few hundred kHz to the MHz range.

G. Prem Kumar Reddy completed his M. Tech (PID) from Jawaharlal Nehru Technological University, Ananthapur, Andhra Pradesh. B.Tech from Affiliated college of JNTUH, Hyderabad. His research interests include Power Semiconductor Drives, Power Quality, and Power Electronics. He has 12 years of teaching experience. He is presently working as Associate Professor in Mahaveer institute of Science and Technology, Hyderabad