iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 3 **Issue:** III **Month of publication:** March 2015

DOI:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Non-Isolated Boost Converter with Zero-Voltage-Switching (ZVS) Capability

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Abstract-Our proposed topology in this paper is a no isolated boost converter with zero-voltage-switching (ZVS) capabilities is proposed. The auxiliary circuit only consists of a coupled inductor and a diode, which operates with a zero-current-switching (ZCS) condition. The ZVS, the reverse recovery problem of MOSFET antiparallel body diodes can be resolved, and the voltage and current stresses on the switch components are also reduced. The detailed operating analysis of the proposed converter and the design method of the main circuit are presented. Our aim is to verify the effectiveness and feasibility of the proposed boost converter, a experimental prototype is built up, and the related experimental waveforms and the efficiency curve are presented.
Keywords: Zero-Voltage-Switching (ZVS), MOSFET, IGBT, KVL, KCL.

I. INTRODUCTION

The conventional non-isolated boost converter topology has been extensively used in various ac/dc and dc/dc applications. In fact, the front end of today's ac/dc power supplies with power-factor correction (PFC) is almost exclusively implemented with the boost topology. The boost topology is also used in numerous battery-powered applications to generate a high output voltage from a relatively low battery voltage. However in some applications, it may be advantageous to use a boost converter with a galvanic ally isolated input and output. For example, fault tolerant power systems that use a dual ac-input architecture can be implemented with isolated boost converters, [1], [2]. In fact, the isolated-boost-converter implementation offers a reduced number of components compared to the implementations with non-isolated boost converters in applications which require dual ac input [2]. Also, in applications where a power supply with both ac and dc inputs is required, the isolated boost converter can be applied to provide safety-required isolation between the inputs. So far, a number of boost topologies utilizing an isolation transformer have been proposed, [3]-[8]. Generally, these circuits exhibit increased voltage stresses on the switches and/or diodes due to the parasitic ringing of the leakage inductance of the transformer with the output capacitances of the switching devices. To control the parasitic ringing voltage, these converters rely on various snubber, which have detrimental effect on their efficiency and also limit their switching frequency. In this paper, a two-switch implementation and a three switch implementation of an isolated boost converter that exhibits voltage waveforms without parasitic voltage ringing across all semiconductor devices on the primary and secondary sides of the transformer are introduced. Ringing free operation in the presence of the transformer's leakage inductance is achieved by clamping the voltages of the primary switches and rectifiers to the voltage of the primary side energy-storage capacitor and clamping the voltage across the secondary-side rectifiers to the output filter capacitor. The circuit diagram of the proposed two-switch isolated boost converter is shown in Fig. 1. The primary side consists of boost inductor LB, switches S1 and S2, primary-side energy-storage capacitor CB, rectifiers D1 through D4, and the primary winding of transformer TR. The output side of the circuit consists of the secondary winding of transformer TR connected to the full-bridge rectifier implemented with rectifiers DR1 through DR4, and capacitive filter CF connected across load RL. To facilitate the explanation of the circuit operation, Fig. 2 shows a simplified circuit diagram of the circuit in Fig. 1. In the simplified circuit, energy-storage capacitor CB and filter capacitor CF are modeled by voltage sources VB and VO, respectively, by assuming that the values of capacitors CB and CF are large enough so that the voltage ripple across the capacitors are small compared to their dc voltages. In addition, isolation transformer TR is modeled by leakage inductance LLK, magnetizing inductance LM, and an ideal transformer with turns ratio n=NP/NS, where NP is the number of turns of the primary winding and NS is the number of turns of the secondary winding. Finally, in this analysis it is also assumed that all semiconductor components represent zero impedances in the on state and infinite impedances in the off state. To further facilitate the analysis of operation, Fig. 3 shows the topological stages of the circuit in Fig. 1 during a switching cycle, whereas Fig. 4 shows its

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key waveforms assuming that the inductance of boost inductor LB is large enough to keep input current iIN continuously flowing. The reference directions of currents and voltages plotted in Fig. 4 are shown in Fig. 2. As can be seen from the timing diagram of the control signals for switches S1 and S2 shown in Fig. 4, switches S1 and S2 of the proposed circuit are simultaneously turned on and off.

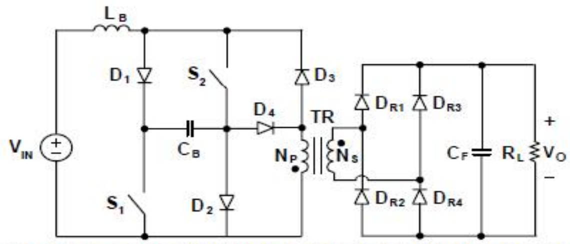

Fig. 1. Proposed two-switch implementation of isolated boost converter.

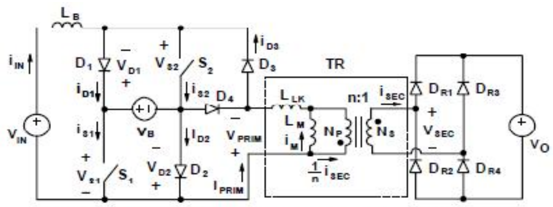

Fig. 2. Simplified circuit diagram of proposed converter with reference directions of voltage and currents.

II. PROPOSED FUNCTIONALITY

Boost converters, as a kind of common converters, are utilized in various areas. As for automotive applications, the boost converters can be used in the fuel cell vehicles to match the voltage levels of the fuel cell and the motor inverter [1]. Also, they can be adopted for power factor correction (PFC) applications [2]–[4]. In [10] and [16], boost converters are used for photovoltaic (PV) generation systems. In order to meet the requirements of small size, light weight, and high reliability for dc–dc converters, high switching frequency is employed, which will result in high switching losses and low efficiency. Soft-switching technologies are considered as the best method to reduce switching losses, and to improve efficiency and reliabilities. The soft-switching techniques can be divided into two kinds such as zero-voltage switching (ZVS) and zero-current switching (ZCS). The ZVS approaches are usually used in MOSFET-based topology. The ZVS turn-on is implemented by conducting the body diode before applying the turn-on signal, thus the reverse recovery problem of the body diode can be solved. When the MOSFET is turned off, the snubber capacitor can make the terminal voltage go up slowly, so ZVS turn-off is obtained. Furthermore, the ZCS approaches are desirable for insulated gate bipolar transistors (IGBTs) to solve the tail current problem. When IGBTs are turned off, the turn-off losses are large. In order to realize soft switching conditions, adopting additional quasi-resonant circuits is considered as a common approach. The auxiliary circuits generally consist of power semiconductor switches, inductors, and capacitors [5]–[12]. It usually results in high voltage and current stresses for power semiconductors [5]. Thus, power semiconductors with a high voltage level will be used, and the cost will be also raised. In [8], the auxiliary resonant circuit consists of an inductor, an IGBT, two capacitors, and two diodes. ZVS turn-on and turn-off for the main IGBT are achieved in this boost converter. The auxiliary IGBT can realize ZCS turn on and ZVS turn-off, but many additional components are needed, and it will result in the complex control method. In [10], the similar resonant topology to that in [8] is presented. The two same IGBT operated as the main switches can achieve ZCS turn-on and ZVS turn-off. However, from the experimental results, it can be seen that there are obvious overlaps of current and voltage waveforms, so the turn-off process is not very good. In [12], nine components are added to make the MOSFET realize the ZCS turn-on, and the operating principles are very complicated. In interleaved soft-switching converters [13]–[21], compared to conventional boost converters, much more components and more complex control methods are needed. In [15], two conventional boost converters are connected in parallel, and an additional inductor that connects two phases is adopted to generate ZVS conditions for two MOSFETs. In [17], the main switches can achieve the characteristics of ZVS and ZCS simultaneously with a wide range of load. In [18], there are three interleaved phases, and the inductor current of each phase is bidirectional, which supplies the inverse current to conduct the body diode.

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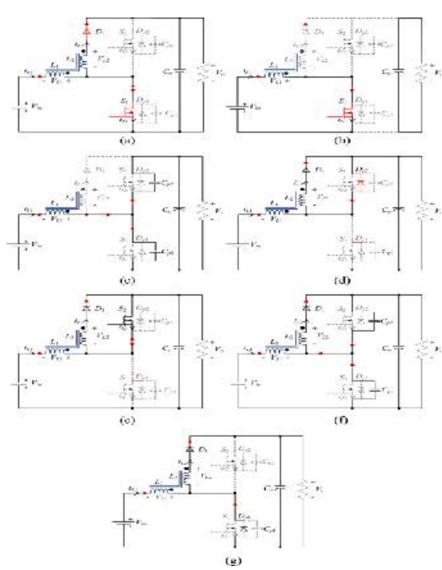
TABLE I
RELATED SPECIFICATIONS OF THE PROPOSED CONVERTER

Parameters	Values
V_{in}	40 V
V_o	80 V
P_{output_max}	500 W
η^*	0.9
$I_{load\,max}$	6.25 A
$I_{in\,max}$	13.9 A
f_{sw}	60 kHz
T	16.67 µs
L_1 (*turns*)	104 µH (18)
L_2 (*turns*)	8.3 µH (5)
k	0.78
C_{p1}, C_{p2}	33 nF
MOSFETs S_1, S_2	IPW60R041C6
Diode D_1	60EPU02PbF

The similar topology is presented in [19], where the inductors of two phases are coupled to reduce the size of the inductors. However, for interleaved structures, a lot of components are needed, and the control methods are complicated. In addition, using the coupled inductors is a method to achieve soft-switching technologies [22]–[25]. In [24] and [24], the auxiliary coupled inductor can supply additional power flowing channel, so the currents of MOSFETs are bidirectional, which is critical for ZVS turn-on. In order to overcome the problems of superabundant auxiliary components, complex control methods, as well as possible high voltage and current stresses, a simple new ZVS boost converter topology based on the coupled inductor is proposed, which just needs an auxiliary winding and a diode compared with the conventional synchronous boost converter. Two inductors are coupled with the same magnetic core to reduce the iron core loss, size, and cost of the converter. In addition, the auxiliary winding in the coupled inductor can help implement ZVS conditions as mentioned above. The control method is the same as that of conventional Pulse Width-Modulated (PWM) controllers. The main MOSFETs can operate under ZVS conditions in all load conditions, and the auxiliary diode operates with a ZCS condition. The experimental prototype is built up to verify all the theoretical analysis of the proposed soft switching boost converter.

III. WORKING OPERATION



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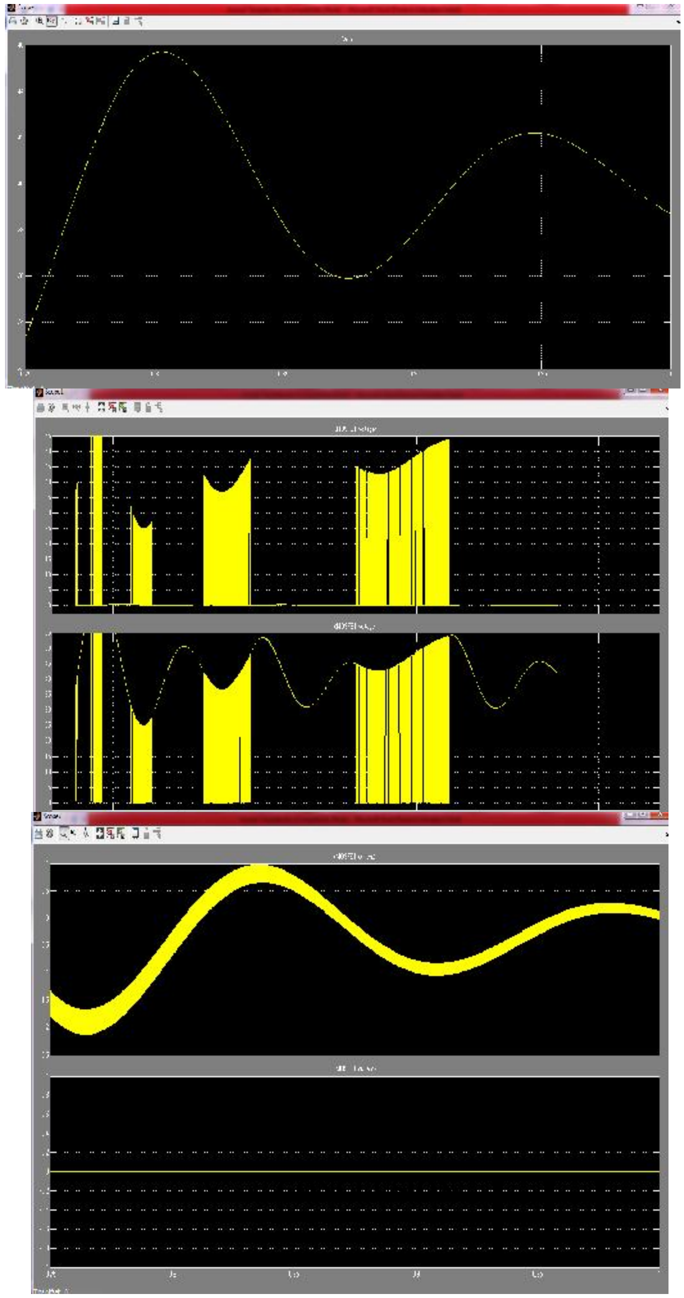
IV. SIMULATION SCREENSHOTS



In our project we proposed a new no isolated ZVS boost converter was proposed. The auxiliary circuit that only consists of a coupled inductor and a diode is very simple, and the additional cost is also very low. The detailed operation principles and the design method of the main circuit are presented. Based on the parameter design method, the 500Wexperimental prototype of the proposed converter was built, and the experimental results can verify that ZVS for two main MOSFETs and ZCS for the auxiliary diode at the maximum load are achieved. Moreover, it means that the soft-switching conditions can be obtained at other load conditions. The efficiency at the maximum load is very high. Since the auxiliary components are very few, and the control method is very simple, the authors believe that this topology can be used in various areas including PFC applications with extended voltage ranges.

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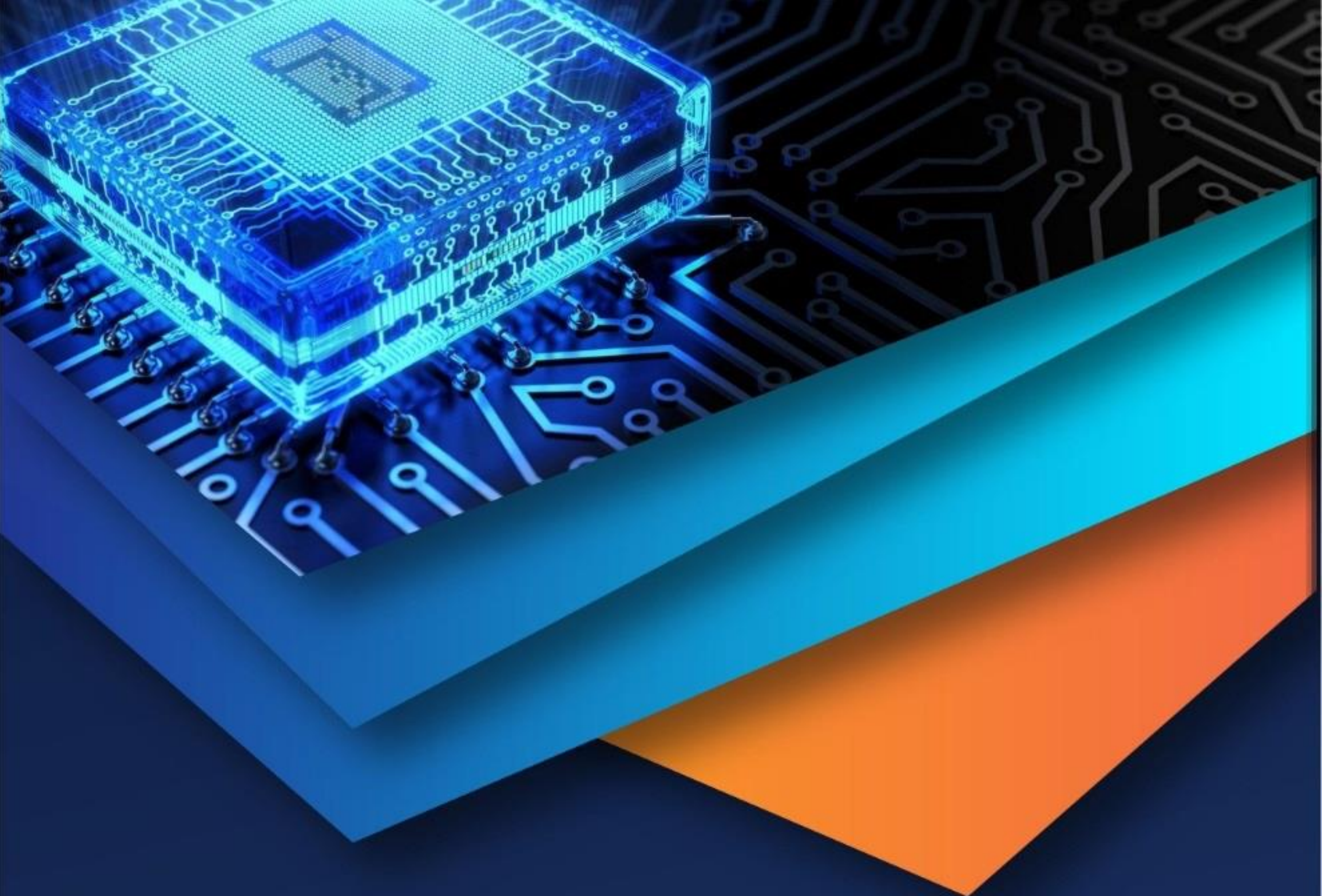

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