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High step-up interleaved boost converter with low switch voltage stress

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ABSTRACT

A novel high step-up converter is proposed to achieve high voltage conversion ratio and high efficiency for renewable energy system applications in this paper. This converter with an interleaved structure combines a flyback converter and a conventional interleaved boost converter for reducing input current ripples and output voltage ripples. The primary winding of the flyback transformer is connected to the output terminal directly. The energy of transformer leakage inductance is recycled, and efficiency is greatly improved. In addition, the voltage stress of switches and diodes are reduced by adding switched capacitors, so that the lower voltage rating diodes and lower $R_{DS(ON)}$ switches can be selected to further reduce both switching and conducting losses. The operating principle and steady-state analyses are described to demonstrate the performance of the proposed converter. Finally, the prototype circuit with 200 V output voltage, 200 W output power is implemented to verify the effectiveness of the proposed converter. It shows that the highest efficiency is approximately 97.1%.

1. Introduction

Renewable energy sources such as wind energy, fuel cells, photovoltaic, geothermal energy receive a lot of attention around the world [1–3]. However, most renewable energy sources such as photovoltaic and fuel cells require a high step-up converter due to the low output voltage. Theoretically, boost, buck-boost and flyback converter are the excellent candidate for renewable energy system due to their simplest topologies and a high step-up voltage gain with extremely high duty ratio. As a matter of fact, the voltage gain is limited by the effect of rectifier diode, power switch, leakage inductance, and equivalent of series resistance (ESR) of inductor and capacitor [23]. Besides, large current ripples and diode reverse recovery problem is induced by the extreme duty ratio related to increasing of conduction losses [4,5].

Many quadratic converters and cascade structure have been investigated to raise the step-up voltage gain and prevent converters from operating at extreme duty cycle [6–9]. However, two stages structure induces not only the complex topology and the efficiency degradation, but also poor stability [6,7], and also the reverse recovery loss of the output diode is severe [8,9]. The isolated-type converter can easily offer a high step-up voltage gain with a transformer [10–12]. However, the leakage inductance of the transformer not only causes voltage and current spikes and induces high voltage stress of switches but also increases loss and noise, resulting in a low efficiency. A resistor-capacitor-diode (RCD) clamp circuit and an active-clamp circuit can reduce the voltage stress and switching losses, but at the cost of topology complexity and some losses related to the clamp circuit [13,14].

A number of non-isolated converters based on coupled inductor have been investigated for their simple structure and lower conduction loss [15–19]. However, they use snubbers such as voltage-clamp [16], active-clamp [17,18], passive regenerative [19] to limit the voltage spike across switches caused by the existence of leakage inductance of coupled inductor. However, all of these approaches lead to complex structure with increased number of switches and capacitors. The non-isolated high step-up converters, which based on boost integrated flyback and SEPIC converter, are proposed [20–23]. A high step-up voltage conversion ratio is achieved by changing coupled inductor's turn ratio. In addition, the energy of leakage inductance is used to the output terminal directly, so that the main switch's voltage spike and the output diode's turn-off current are limited [21,22]. However, due to the turn ratio of coupled inductor increased, the voltage stress of output diode is increased as well as the severe diode reverse recovery problem [20,21]. These converters are not suitable for high-power and high-current applications because their input current ripple is large with one-switch operating in spite of avoiding extreme duty

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ratio. The conventional interleaved boost converter is an excellent candidate for high-power applications and power factor correction due to its simple structure and small input and output ripples [26]. However, the step-up gain is low, and the voltage stress of switches and diodes are approximately equal to output voltage [24]. In order to overcome these problems, the switched capacitors and transformers or coupled inductors are integrated into the interleaved boost converter. Thus, high step-up gain, high efficiency, low voltage stress converters are achieved even for high-power applications [25–27].

This paper presents a novel step-up interleaved boost converter with low switch voltage stress. The proposed converter combines interleaved boost converter, a flyback converter and switched capacitors. This interleaved structure is used to reduce input current ripples and output voltage ripples. The flyback converter is designed to extend step-up gain and prevent from extreme duty ratio. Besides, the switched capacitors are added to reduce the voltage stress of switches and diodes. Thus, the lower voltage rating diodes and switches with low $R_{DS(ON)}$ can be selected to reduce switching and conduction losses. In addition, due to the primary winding of the transformer is connected to the output terminal, the energy of leakage inductance can be recycled, and the voltage spikes across the main switches can also be alleviated to improve the efficiency.

This paper is organized as follows: the topology derivation and operation principle of the proposed converter are presented in Section 2. The steady-state analysis is described in detail In Section 3. The experimental results of a 200-W prototype are presented to verify the converter performance in Section 4. Finally, Section 5 concludes the paper.

2. Topology derivation and operation principle

2.1. Topology derivation of the proposed converter

The boost converter with interleaved structure is a good candidate for renewable energy system due to its simple structure and small input and output ripples [26]. However, the voltage conversion ratio of the conventional interleaved boost converter [25] is low. Hence, the forward/Ćuk converter integrated to a conventional interleaved boost converter has been proposed [3,26]. The converters [3,26] can not only achieve a high step-up gain but also reduce the voltage stress of switches and diodes compare to the converter [25]. However, the forward/Ćuk integrated circuits are relatively complex and expensive. In generally, the flyback converter can provide a much higher step-up gain and its circuit structure is more simple compare to the forward-type/Ćuk-type converter. Therefore, similar to the converter [26], the flyback converter is another choice to integrate to the converter [25].

Fig. 1 is the circuit diagram and key waveforms of the two-phase interleaved converter. From Fig. 1(a), it can be seen that the converter is composed of two-phase interleaved circuits. The boost converter in the first phase composes of inductor L_1, switch S_1, S_2, switched capacitor C_1, C_2, and diode D_1. The second phase combines a boost converter and a flyback converter including inductor L_2, capacitor C_1, C_O, load R, switch S_2 and the primary side wingding N_P of isolated flyback converter. The turn ratio N is N_S/N_P. The primary winding of the transformer is connected to the output terminal directly. Thus, not only a high step-up gain is achieved by adjusting the transformer turn ratio but also the leakage energy stored in the leakage inductance L_{lk} is recycled. In addition, to reduce the voltage stress of switches and diodes, the switched capacitors C_1 and C_2 are used for the two phase circuits.

However, the interleaved converter in Fig. 1 has some drawbacks that cannot be neglected. From the key waveforms in Fig. 1(b),

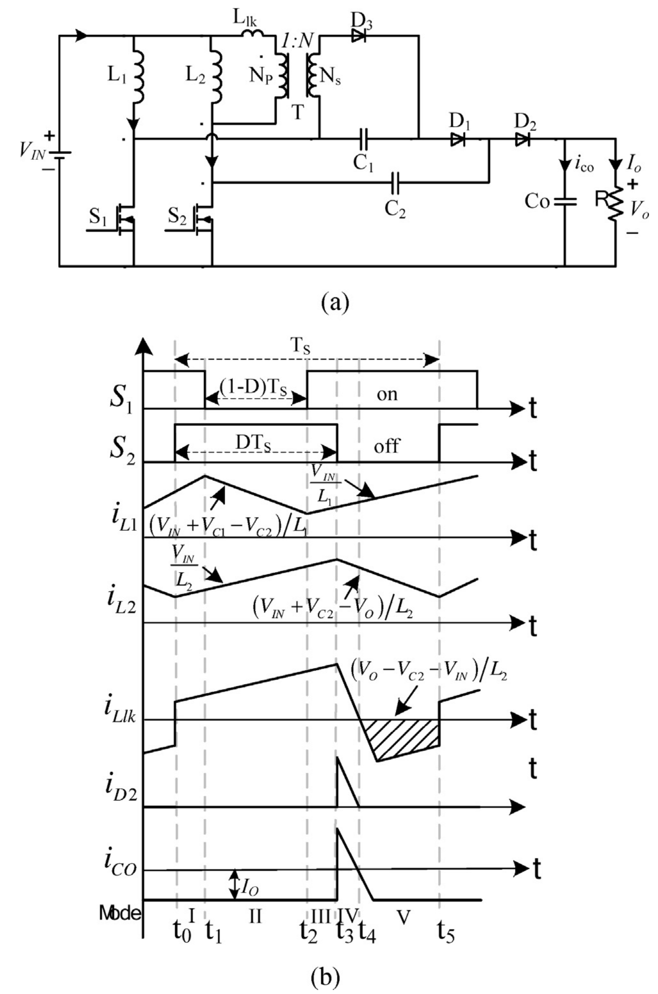

Fig. 1. Two-phase interleaved converter. (a) Circuit diagram. (b) Key waveforms.

it can be seen that when the switch S_2 turns on, the large currents of inductor L_2 and magnetizing inductance of the transformer across to the switch S_2. Therefore, there are very high current stress and conduction loss on switch S_2, and the efficiency drops. Besides, a huge amount of energy dissipates on the primary winding of the transformer when switch S_2 turns off. After the energy of the leakage inductance L_{lk} is released to zero on a short time interval, there will be no energy transferred to the output capacitor and load from the dc source V_{IN}. At time t_4, the current of the inductor L_2 start to flow into the primary winding of the transformer rather than the output, as the dash area shown in Fig. 1. Though the energy stored in the L_2 can be transferred to capacitor C_1 through the flyback transformer, large energy dissipated on the transformer and other components. Thus, the efficiency of the converter is decreased. Furthermore, the input current ripples are very large due to the second phase cannot transfer the energy of dc source V_{IN} to the output after time t_4.

In order to overcome these aforementioned questions, the proposed circuit topology depicted in Fig. 2 requires only one additional switch S_3 and one diode D_4. The switch S_3 is added to provide another path for the current of magnetizing inductance of the transformer to the output of converter and reduce the current stress and conduction loss of switch S_2, and the input current ripples. The diode D_4 is added to prevent the energy stored in inductor L_2 from transferring to the primary side winding of the transformer, but let the energy transfer to the output terminal when the switch S_2 turns off. Meanwhile, the leakage inductance energy of transformer can