

A Review of Non-Isolated High Step-Up DC/DC Converters in Renewable Energy Applications

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Abstract—With the shortage of the energy and ever increasing of the oil price, research on the renewable and green energy sources, especially the solar arrays and the fuel cells, becomes more and more important. How to achieve high step-up and high efficiency DC/DC converters is the major consideration in the renewable grid-connected power applications due to the low voltage of PV arrays and fuel cells. The topology study with high step-up conversion is concentrated and most topologies recently proposed in these applications are covered and classified. The advantages and disadvantages of these converters are discussed and the major challenges of high step-up converters in renewable energy applications are summarized. This paper would like to make a clear picture on the general law and framework for the next generation non-isolated high step-up DC/DC converters.

I. INTRODUCTION

The massy usage of the fossil fuels, such as the oil, the coal and the gas, result in serious greenhouse effect and pollute the atmosphere, which has great effect on the world. Meanwhile, there is a big contradiction between the fossil fuels supply and the global energy demand, which leads to a high oil price in the international market recently. The energy shortage and the atmosphere pollution have been the major limitations for the human development. How to find renewable energy is becoming more and more exigent.

Photovoltaic (PV) sources are one of the significant players in the world's energy portfolio and will become the biggest contributions to the electricity generation among all renewable energy candidates by year 2040 because it is truly a clean, emission-free renewable electrical generation technology with high reliability.

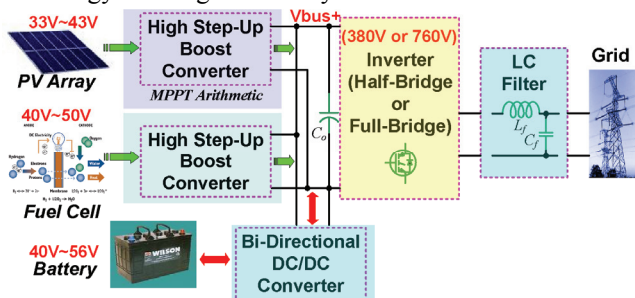


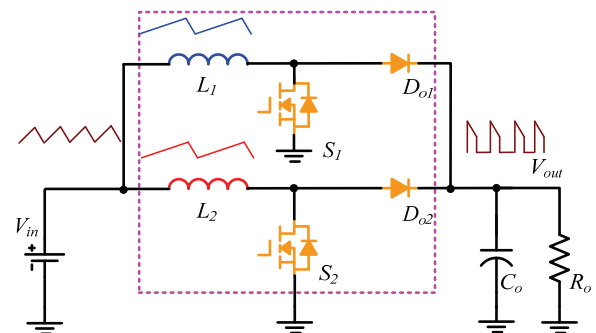
Fig. 1. Diagram of single-phase hybrid renewable energy grid-connected system.

Fig.1 is an example of single-phase hybrid renewable energy grid-connected system. The output voltage generated

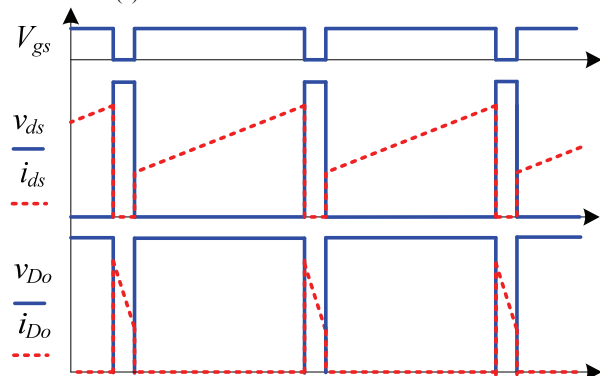
by the photovoltaic arrays, the fuel stacks, the super capacitors or the battery sources is relatively low, even lower than 48V [1-3]. It should be boosted to a high voltage, such as 380V for the full bridge inverter or 760V for the half bridge inverter in the 220V AC grid-connected power system. How to realize high step-up DC/DC converters with high performance is one of the main issues in the renewable energy applications [4-5].

The limitations of the conventional boost converters are analyzed and the conceptual solution for high step-up conversion is proposed in this paper. Then the state-of-the-art topologies are covered and classified based on the circuit performance. The challenges in high step-up renewable energy applications are summarized to generate the next generation non-isolated high step-up DC/DC converters.

II. LIMITATIONS OF CONVENTIONAL BOOST CONVERTERS



(a) Conventional interleaved boost converter



(b) Waveforms in high step-up applications

Fig. 2. Conventional interleaved boost converter and its key waveforms in high step-up applications.

The conventional interleaved boost converter is shown in Fig.2(a) and its key waveforms in high step-up applications is given in Fig.2(b). In theory, the voltage gain of the boost converter is extremely large when the duty cycle is close to 1.

However, there are some limitations for the conventional interleaved boost converter in high step-up DC/DC conversion.

1:) The current ripples of the switches and the output diodes are large.

2:) The switch voltage stress is equal to the output voltage, which is large in high output voltage applications.

3:) The switching losses and the output diode reverse-recovery losses are large due to the hard switching operation and high switch voltage stress.

The conceptual solution with the voltage gain extension in high step-up conversion is given in Fig.3. With the conceptual solution, the switch turn-off period is extended and the extreme duty cycle is avoided. The switch voltage stress is reduced and the low-voltage MOSFETs can be employed. The current ripple is decreased to reduce the conduction losses. And the dynamic response can be improved because the duty cycle has a large variation range.

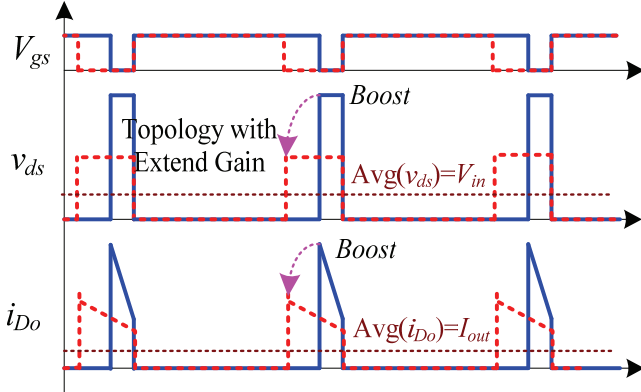


Fig.3. Performance improvements with voltage gain extension at high step-up applications.

Three-level boost converter can double the voltage gain and halve the voltage stress of the power device compared with the conventional two-level boost converter, which is more suitable in low-voltage-input high-voltage-output applications [6-7]. The conventional three-level boost converter is shown in Fig.4. Low voltage power device can be employed to reduce the conduction losses. The switching losses are reduced and the EMI noise is suppressed due to the low dv/dt stress. However, the power devices operate under hard switching condition and the output diode reverse-recovery problem is severe. And the voltage gain still cannot be suitable for very high step-up conversion, for example, in a 12V-380V DC/DC conversion.

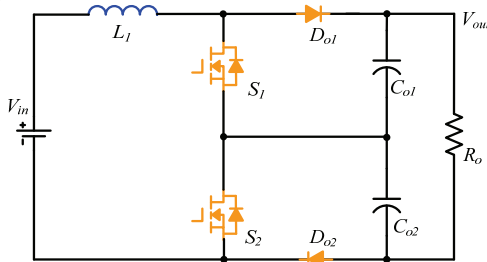


Fig.4. Conventional three-level boost converter.

The voltage gain can be extended and the current ripple can be reduced to satisfy the high step-up requirement by employing cascade structure [8]. Fig.5 is the schematic of a

cascade three-level boost converter. The voltage stress of the first stage is low and it can be operate with a high switching frequency to improve the power density. The second stage can work with a low switching frequency to reduce the switching losses. However, the cascade converter requires two sets of power devices, magnetic cores and control circuits, which is complex and increases the circuit cost. The system stability with cascade structure is a big issue and the control circuit should be designed carefully [9]. The output diode reverse-recovery problem of the second stage is severe because a high voltage level should be sustained in the high output voltage applications. So the efficiency is not high and the EMI noise problem is serious.

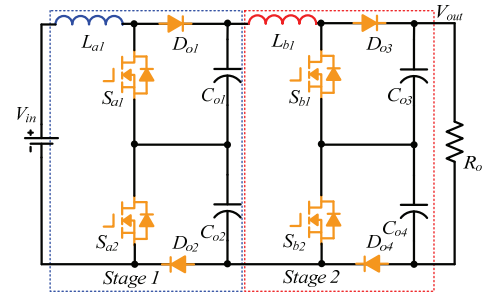


Fig.5. Cascade three-level boost converter.

III. HIGH STEP-UP BOOST CONVERTERS

In order to satisfy the stringent requirements in high step-up and high efficiency DC/DC conversion, more and more researches focus on how to achieve high step-up converters with high circuit performance. Among these achievements, they can be classified into the following catalogues: high step-up converter with coupled inductor, high step-up converter with switched capacitor, high step-up converter with inductor and switched capacitor, high step-up converter with coupled inductor and switched capacitor and so on.

(A): High step-up converter with coupled inductor

Coupled inductor can serve as a transformer to extend the voltage gain in non-isolated DC/DC converters. Fig.6 is the schematic of a high step-up converter with coupled inductor [10-12]. The coupled inductor has two windings. The primary winding serves as the similar function as the filter inductor. The second winding operates as a voltage source in series to the power branch. The voltage gain can be extended by a proper turns ratio design of the coupled inductor. The leakage energy of the coupled inductor can be absorbed and the turn-off voltage ringing on the MOSFET can be suppressed by the clamp diode D_c and the clamp capacitor C_c .

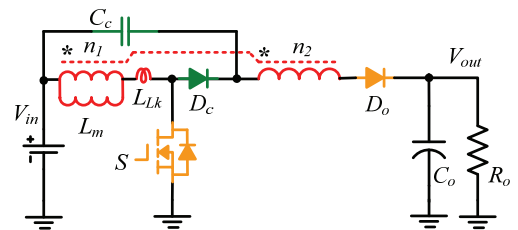


Fig.6. High step-up boost converter with coupled inductor.

High step-up flyback-boost converter can be derived by combining the conventional boost converter and the flyback

converter as shown in Fig.7 [13-14]. The inductor of the boost converter and the transformer of the flyback converter are integrated into a coupled inductor. The two converters share the same switch. The outputs of boost and flyback converters are in series to extend the voltage gain.

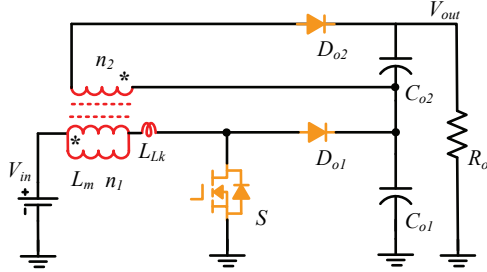


Fig.7. High step-up flyback-boost converter with coupled inductor.

(B): High step-up converters with switched capacitors

The capacitor can be taken as another voltage source, so high step-up converter can be achieved by switched capacitors. Fig.8 is a N-stage high step-up converter with switched capacitors [15]. Each switched capacitor cell is composed of a capacitor, a diode and two switches. Each capacitor can be taken as a voltage source, which is switched and recombined by the switches. The current path is provided by the diode when the switches turn off. High step-up and wide range voltage gain can be realized by in series N switched capacitor cells.

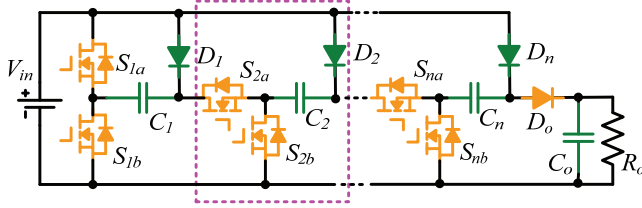


Fig.8. High step-up converter with switched-capacitors.

Besides the serial switched capacitor structure, high step-up converter with switched capacitors can be derived by the general multi-level converter concept. Fig.9 is an example of high step-up converter with the general multi-level cell [16]. Each basic cell is composed of a clamp capacitor and two switches operated in complementary mode. High voltage gain can be obtained by the parallel or serial structure of the basic cell. This circuit is a high efficiency high power density bi-directional converter, which is suitable for vehicle applications.

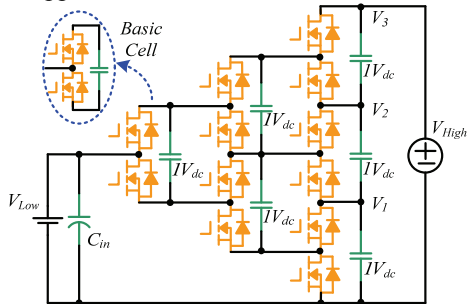


Fig.9. High step-up converter with general multi-level cell.

The magnetic components, such as the inductor or transformer, are not required in the switched capacitor converters to reduce the circuit size. And the switching frequency can be pushed to a high level, even to MHz range,

to improve the power density. However, a lot of power MOSFETs are necessary to realize a high voltage gain and the gate driver circuit is complex, which increases the cost. And the voltage gain can be only lifted integral times, which has some limitations in many applications.

(C): High step-up converters with inductor and switched capacitors

The switched capacitor converter and the boost converter can be integrated together to obtain a stepless voltage gain. Cuk converter has two inductors in the input side and the output side, which can minimize the input and output current ripples. N-stage switched capacitor cells can be inserted into the Cuk converter to achieve a high voltage gain. The schematic of high step-up Cuk converter with inductors and switched capacitors is given in Fig.10 [17]. Stepless voltage gain can be realized and input and output current ripples are small to reduce the EMI noise. The main limitation of the converter is that the diode D1, D2, D3 and Do should sustain a high voltage stress, which increases the conduction losses. And the output diode reverse-recovery problem is serious.

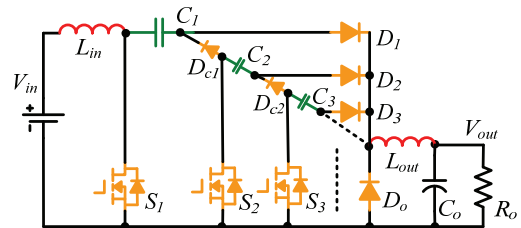


Fig.10. High step-up Cuk converter.

(D): High step-up converters with coupled inductor and switched capacitors

The concept of coupled inductor and switched capacitor can be combined to derive high step-up converters, which can improve the power density and the circuit efficiency.

A high step-up converter with coupled inductor and switched capacitor is shown in Fig.11 [18-20]. This converter has the following performances: a) The voltage gain is extended by the coupled inductor and the switched capacitor; b) The leakage energy is recycled and the voltage spikes on the MOSFET are absorbed by the passive lossless clamp circuit; c) The switch voltage stress is low to reduce the conduction losses; d) The output diode reverse-recovery problem is alleviated by the leakage inductance of the coupled inductor.

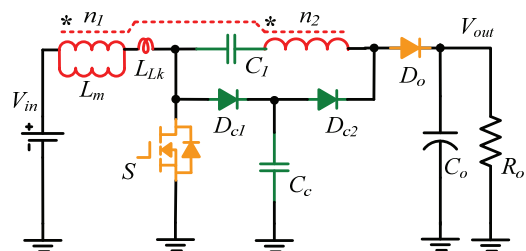


Fig.11. High step-up converter with coupled inductor and switched capacitor.

(E): High step-up interleaved boost converters

A high step-up interleaved boost converter is proposed by inserting the switched capacitors into the conventional

boost converter. The circuit schematic is shown in Fig.12 [21-22]. The interleaved structure can be used to increase the power level, minimize the current ripple, reduce the passive component size, improve the transient response and realize auto-current sharing. High voltage gain can be realized by the switched capacitor cell. The main disadvantage is that the power devices operate with hard switching performance, which leads to large switching losses.

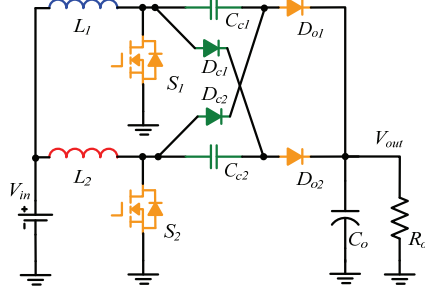


Fig.12. High step-up interleaved boost converter with inductors and switched-capacitor.

The two separate inductors in Fig.12 can be replaced by a coupled inductor, which can optimize the magnetic core and improve the magnetic utility. The high step-up interleaved boost converter with coupled inductor and switched capacitor is shown in Fig.13 [23-24]. The magnetic component is minimized to improve the power density. ZCS turn-on is achieved to reduce the switching losses. However, many switched capacitor cells are required to get a very high step-up gain.

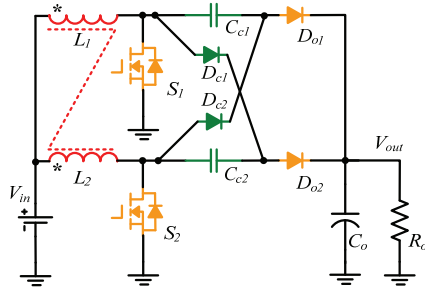


Fig.13. High step-up interleaved boost converter with coupled inductor and switched capacitor.

A family of high step-up interleaved DC/DC converters with Winding-Cross-Coupled Inductors (WCCIs) is proposed in [25-28]. A modified coupled inductor with three windings is proposed and its third winding is inserted into another phase, which is named as Winding-Cross-Coupled Inductors (WCCIs) in [27] as shown in Fig.14. Each WCCI has three windings. The second winding with n_2 turns couples to the inductor in its phase with n_1 turns (L_{1b} versus L_{1a} and L_{2b} versus L_{2a}) and the third winding with n_2 turns couples to the inductors in another phase (L_{1c} versus L_{1a} and L_{1b} , L_{2c} versus L_{2a} and L_{2b}). The coupling references of the WCCIs are marked by “ \circ ” and “*” as shown in Fig. 14. The primary windings L_{1a} and L_{2a} have the similar performance as the filter inductors in the conventional interleaved boost converter. The second and the third windings of the WCCIs serve as the DC voltage sources and are in series to the circuit to achieve a high step-up conversion and to reduce the switch voltage stress. The active clamp scheme is applied to the

converter to recycle the leakage energy and to suppress the voltage spikes [25], which is shown Fig.14. With the active clamp circuits, ZVT performance for the main switches and the auxiliary switches are achieved during the whole switching transition, which reduces the switching losses greatly. Meanwhile, the leakage energy is recovered and the switch voltage is clamped effectively, so high performance MOSFET with low R_{DS_ON} can be employed to reduce the conduction losses. The output diode reverse-recovery problem is alleviated by the leakage inductance to minimize the relative reverse-recovery losses and to reduce the EMI noise.

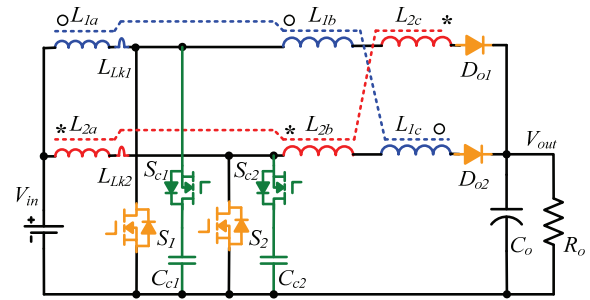


Fig.14. High step-up active-clamp ZVT interleaved boost converter with WCCIs.

With some topology variations, the active clamp scheme can be replaced as the passive lossless clamp scheme. The derived proposed boost converter with passive-lossless clamp circuits is shown in Fig.15 [26]. ZCS turn-on can be realized and the clamp circuits are simple but effective to reduce the circuit complexity.

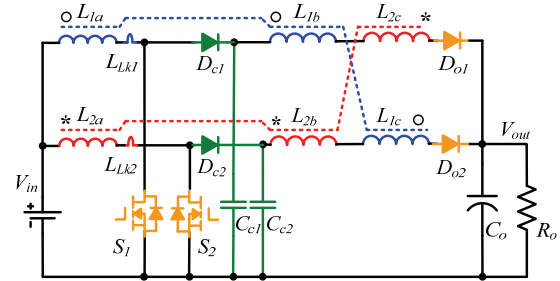


Fig.15. High step-up passive-lossless clamp interleaved boost converter with WCCIs.

Another type of high step-up interleaved boost converter with WCCIs is presented in [29] as shown in Fig. 16. The topology is derived from its isolated counterpart. And only one set of active clamp circuit composed of an auxiliary switch and a small capacitor is necessary for the interleaved two phases to recycle the leakage energy and to suppress the voltage spikes. The voltage gain is extended and the switch voltage stress is reduced. The output diode reverse-recovery problem is alleviated by the leakage inductance. By changing the turns of the third winding $L_{1c}(L_{2c})$ from (n_2-n_1) to n_2 , adding two additional clamp capacitor $C_{d1}(C_{d2})$ and making some topology variation, the converter shown in Fig.16 can be improved to another one, which is shown in Fig.17 [30]. The voltage ringing on the output diode is clamped by the additional capacitors and a built-in LC low pass output filter is formed by the leakage inductance and the additional capacitors. So the output current ripple is cancelled and the EMI noise is reduced.

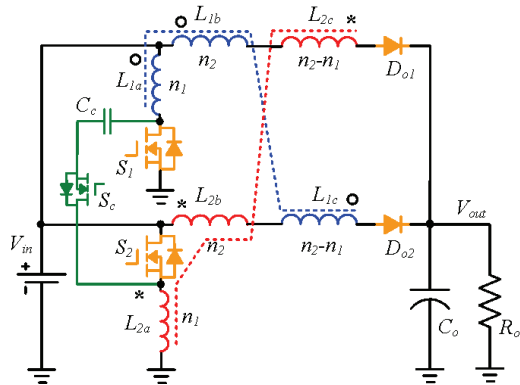


Fig.16. High step-up ZVT interleaved boost converter with WCCIs and reduced clamp switch number.

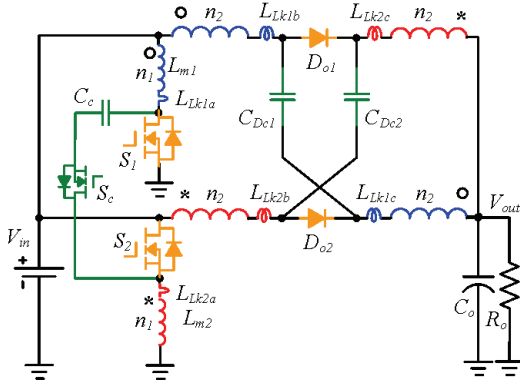


Fig.17. Improved High step-up ZVT interleaved boost converter with reduced clamp switch number and built-in output filter.

The detailed analysis and design procedure of the converter shown in Fig.15 are given in [26]. The experimental results of a 1kW 40V-to-380V interleaved boost converter with WCCIs and passive lossless clamp circuits operating with $f_s=50\text{kHz}$ is given in the following. The gate signals and the MOSFET switching voltage are given in Fig. 18. The equivalent duty cycle is about 0.5. The extreme duty cycle is avoided. The MOSFET voltage stress is about 165V, which is far lower than the high output voltage. The current through the output diode D_{o1} , the current of switch S_1 and the switching voltage of S_1 are given in Fig. 19. ZCS turn-on of the main switches is achieved and the output diode reverse-recovery problem is alleviated by the leakage inductance. The efficiency at full load is 90.7% and the maximum efficiency is 92.6%. Over 5% efficiency improvement at full load is realized over the conventional interleaved boost converter.

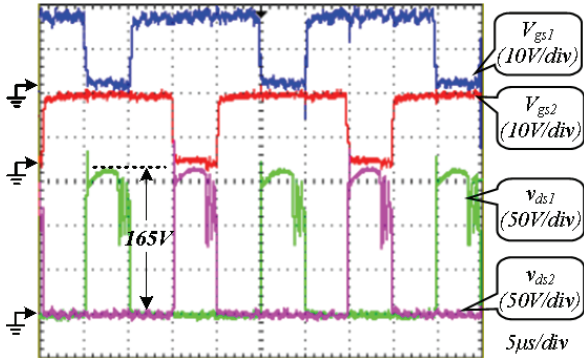


Fig.18. Gate signal and switching voltage of Fig.15.

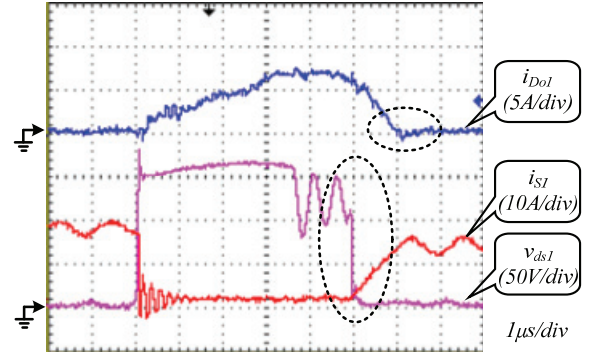


Fig.19. ZCS turn-on and output diode turn-off current of Fig.15.

IV. CONCLUSION

The limitations of the conventional boost converter in high step-up renewable energy applications are analyzed and a lot of topologies, which are published in previous papers, are summarized and classified. From the above analysis, the major challenges in high step-up DC/DC converters are the following:

- 1:) How to extend the voltage gain and avoid the extreme duty cycle to reduce the current ripple and the conduction losses;
- 2:) How to reduce the switch voltage to make low voltage MOSFETs available;
- 3:) How to realize soft switching performance to reduce the switching losses;
- 4:) How to alleviate the output diode reverse-recovery problem;
- 5:) How to increase the power level easily and reduce the passive component size.

The conceptual solution for high step-up conversion is proposed and some topologies satisfied the major challenges in high step-up DC/DC converters are given. A clear picture on the general law and framework for the next generation non-isolated high step-up DC/DC converters is made in this paper.

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