Closed Loop Contol of ZCS Interleaved High Step Up Converter for Sustainable Energy Applications

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Abstract: ***The Renewable energy is the best solution to satisfy the energy shortage without environmental problems. Photovoltaic energy is the most promising energy among the renewable energies. The main advantages includes long life and maintenance free and the main disadvantages are high installation cost and low conversion efficiency. The narrow turn off period of the conventional interleaved boost converter limits its application for high step-up applications. The interleaved boost converter with built in transformer voltage multiplier cells overcomes this drawback. This converter provides an additional control freedom to achieve extremely high voltage conversion ratio and minimize the ripple current. Additional advantages are switch voltage stress and conduction losses are also reduced. To study the performance of the high step up Interleaved DC-DC converter with closed loop control, simulations has been carried out in MATLAB2013 environment. Thus these current and voltage waveforms agreed with the operating principles and the steady-state analysis.***

Keywords: boost conveter, interleaved converter,built in transformer voltage multiplier cell, regenerative diode, soft switching (zcs).

1. Introduction

Nowadays, the renewable-energy grid-connected systems with photovoltaic (PV) and fuel cells call for high step- up and large-current dc/dc topologies ,because the low voltage generated by the PV and fuel cells should be boosted to a relatively high dc bus voltage for the grid-connected generation systems. For example, in order to deliver the energy to a single-phase 220-V utility grid, a 380-V dc bus voltage is required with a full-bridge inverter. Unfortunately, the output voltage of most fuel cell stacks or the individual PV cells is lower than 40 V due to the safety and reliability issues in the household applications.

Large voltage conversion ratio with over ten times of voltage gain is necessary for the front-end dc/dc converters. As a result, non-isolated high-step-up converters are desirable to reduce the system cost and improve the power density by removing the isolated voltage or current sensors and additional auxiliary power supply in the isolated conversion systems.

In this paper, the built-in transformer voltage multiplier cell is inserted into each phase of the conventional interleaved boost converter to provide additional control freedom for the voltage gain extension without extreme duty cycle. The voltage multiplier cell is only composed of the built-in transformer windings, diodes and small capacitors. And additional active switches are not required to simplify the circuit configuration.

Furthermore, the switch voltage stress and the diode peak current are also minimized due to the built-in transformer voltage multiplier cells to improve the conversion efficiency. Moreover, there is no reverse-recovery problem for the clamp diodes and the reverse recovery current for the regenerative and output diodes are controlled by the leakage inductance of the built-in transformer to reduce the relative losses. In addition, the switch turn-off voltage spikes are suppressed effectively by the ingenious and inherent passive clamp scheme and zero current switch (ZCS) turn-on is realized for the switches, which can enhance the power device reliability.

In a closed-loop control system, a sensor monitors the system output and feeds the data to a controller that adjusts the control to maintain the desired system output and hence remain unaffected to the external noise sources. A closed loop control has high reliability, easy implementation and output short circuit and overload protection.

With the decline in the production of fossil fuels,the sustainable energy sources such as the photovoltaic (PV),fuel cells and wind energy has been taken as the promising candidate for future energy supply. This energy sources has random energy fluctuations. To absorb the random energy fluctuation the sustainable energy sources require backup storage elements [1].The PV panel and back up battery cell has low output voltage. High step up boost converters are required to lift the low voltage to high one.

In industrial applications we require high voltage gain, so we depend on step-up converter. The conventional converters has many problems such as voltage stress, diode reverse recovery problems etc. The converter proposed in this paper can solve these problems.

Conventional Interleaved converter is an excellent candidate for the power factor correction applications.

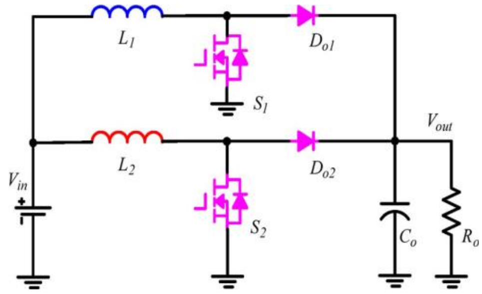

Figure 2.1: Conventional Interleaved boost Converter

For the conventional interleaved boost converter as shown in Fig. 2.1, the output voltage gain M in continuous-current mode is simplified by

$$M = \frac{1}{1-D} \quad \text{(a)}$$

which is completely determined by the duty ratio. In high-step-up applications, the duty cycle becomes extremely large. Consequently, the turn-off period is very narrow, which is not practical for the industrial design. First, it is difficult to realize a duty ratio greater than 0.9 with typical PWM controller IC. Second, the narrow turn off period leads to a large current ripple. At last, the output diode reverse-recovery losses are considerable. Furthermore, the voltage stresses of the switches and the output diodes are given by

$$V_{ds} = V_{Do} = V_{\text{out}} \quad \text{(b)}$$

The voltage stresses of the power devices are equal to the high output voltage. Therefore, the high switch voltage stress, the large current ripple, and the serious output diode reverse recovery problem are the main limitations for the conventional interleaved boost converters in high-step-up and high-output voltage conversion systems.

[2] uses an isolated dc-dc converter for high step up ratio applications. Overall efficiency is increased due to the resonance involving the transformer leakage inductance and the diode parasitic capacitances.ZVS turn ON of the main switch can be achieved due to the proper recirculation of the leakage inductance energy. In [3] to provide a large voltage conversion ratio a voltage doubler rectifier is introduced. Current fed type configuration reduces input current ripple.

To extend the converter voltage gain and to reduce the output diode voltage stress an advanced symmetrical voltage quadrupler rectifier is derived in [4].All the diodes in SVQR have same voltage and current stresses which simplifies the thermal design. The major considerations of Photovoltaic grid connected power system in the residential applications is discussed in [5].

[6] uses a novel configuration of the single phase three level PFC topology with the passive lossless snubber. To realize the soft switching of the main switches and freewheeling diodes two passive lossless snubber cells are added to the converter.[7] discusses design approach for server Power supplies for Networking Applications. The use of voltage multiplier technique in the classical non-isolated dc-dc converters to obtain high step up static gain is discussed in [8].The converter reduces the problems of EMI generation and diode reverse recovery problem.

[9] uses switched capacitor technique for high power high efficiency dc dc converter. The high pulse current at the switching transients which was the main drawback of the conventional switched capacitor techniques were overcome in the proposed converter.[10] discusses switched capacitor/switched inductor structures for getting transformerless Hybrid DC DC PWM converters. The main advantage of the new converters is their lower energy in the magnetic elements which leads to weight, size and cost saving for the inductors and thus for the power supply and less conduction losses which leads to better efficiency.

In [11] a Family of single switch PWM converters with high step up conversion ratio is discussed. The converter possesses higher voltage gain with small output voltage ripples. The main advantages of the converter are low voltage stress on the semiconductor devices, simple structure and control. The use of sepic integrated boost converter to distribute the voltage stress and to supplement the insufficient step up ratio is discussed in [12].

[14] discusses single phase improved active clamp coupled inductor based converter with extended voltage doubler cell. The secondary winding of the coupled inductor is inserted into the half wave voltage doubler cell to extend the voltage gain dramatically and decrease the switch voltage stress effectively. By introducing the extended voltage doubler cell the voltage stress of the switch and conduction losses is reduced greatly. Turns off voltage spikes on the main switch are suppressed and the leakage inductance energy is recycled.

In [15] a novel high step up DC DC converter with coupled inductor and voltage doubler circuit is proposed. Here the energy stored in the leakage inductor of the coupled inductor can be recycled.

[16] discusses High step up Boost converter integrated with a transformer assisted auxiliary circuit employing Quasi Resonant operation is discussed. The transformer leakage inductor and the balancing capacitor followed by the voltage doubler constitute a series resonant tank and thereby the sinusoidal current can considerably reduce the switch TURN OFF loss and the reverse recovery on the diode.

In [17] a highly efficient high step up converter for fuel cell power processing based on three state commutation cell is discussed. The main advantages of the converter are the size of the inductor is reduced and reduces the voltage stress across the active switches. But the drawback with the converter are 1) The frequency operation is low 2)The generation of PWM is complex because it should be implemented discretely due to the lack of dedicated integrated circuits.

[22] discusses General derivation law of non isolated converter derivation with direct energy transfer scheme has been proposed. The design considerations of an interleaved High step up interleaved High step up ZVT converter with built in transformer voltage doubler cell is discussed in [25].

This paper is organized as follows. Section II and III describes high gain sepic converter and its operation.

MATLAB simulation along with results is explained in Section IV. Finally, the conclusion is stated in Section V.

2. High Gain Interleaved Converter

The paper introduces a high gain dc-dc boost converter for renewable energy systems. The basic configuration of proposed boost converter shown in figure 3. The converter is derived from a traditional sepic converter. The high gain boost converter comprised of input inductor L_{in}, coupled inductor T1, charge pump cell, buffer capacitor, regenerative snubber, output capacitor and load resistor R_L. The charge pump cell consists of C_2, D_1, and D_o. The regenerative snubber can provide zero-voltage and zero-current switching and recycles the captured leakage energy to the capacitor C_1, which improves the efficiency of the converter.

In the proposed converter in order to achieve high gain and high step up, built-in transformer voltage multiplier cell is inserted into each phase of the conventional interleaved boost converter to provide additional control freedom for the voltage gain extension without extreme duty cycle. The voltage multiplier cell is only composed of the built-in transformer windings, diodes and small capacitors. And additional active switches are not required to simplify the circuit configuration.

Furthermore, the switch voltage stress and the diode peak current are also minimized due to the built-in transformer voltage multiplier cells to improve the conversion efficiency. Moreover, there is no reverse-recovery problem for the clamp diodes and the reverse recovery current for the regenerative and output diodes are controlled by the leakage inductance of the built-in transformer to reduce the relative losses. In addition, the switch turn-off voltage spikes are suppressed effectively by the ingenious and inherent passive clamp scheme and zero current switch (ZCS) turn-on is realized for the switches, which can enhance the power device reliability.

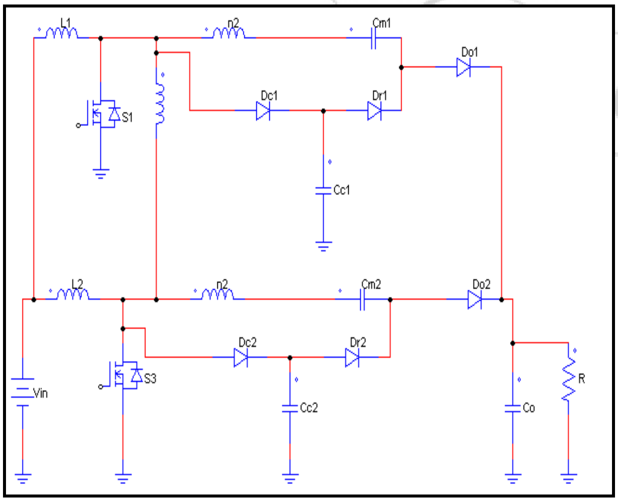

Figure 3: Circuit Diagram of the High Step Up Converter

3. Operation of the Converter

The proposed high step up interleaved converter with built in transformer voltage multiplier cell is shown in fig 4.1. S_1 and S_2 are the power MOSFETs, L_1 and L_2 are the input filter inductors, D_{o1} and D_{o2} are the output diodes, and C_o is the output capacitor. There is a built-in transformer with three winding in the proposed converter. The primary winding is n_1 turns and the turns of the secondary and third windings are both n_2 turns. L_{Lk} is the leakage summation of built-in transformer reflected to the primary winding.

There are two built-in transformer voltage multiplier cells in the proposed converter. Each of the voltage multiplier cell is composed of the transformer winding with n_2 turns, clamp diode $D_{c1(2)}$, regenerative diode $D_{r1(2)}$,clamp capacitor $C_{c1(2)}$, multiplier capacitor $C_{m1(2)}$. V_{in} and V_{out} are the input and output voltages, respectively. N is defined as the turns ratio n_2 /n_1 of the built-in transformer. There are 12 main operational stages in one switching period.

First switches S_1 and S_2 are both in the turn-on state. Clamp diodes D_{c1} and D_{c2} , regenerative diodes D_{r1} and D_{r2} , and output diodes D_{o1} and D_{o2} are all reverse-biased. Both the two input inductors L_1 and L_2 are charged by the input voltage V_{in} respectively. Now switch S_2 turns off, its parasitic capacitor C_{s2} is charged by the current of the input inductor L_2 in an approximately linear way.

The drain–source voltage v_{ds2} is charged and increased to make clamp diode D_{c2} forward-biased. Then D_{c2} begins to conduct and clamp capacitor C_I is charged by the current of the input inductor L_2 linearly. Switch S_2 turns off and its drain–source voltage v_{ds2} is clamped by capacitor C_{c2}. The voltage of output diode D_{o2} decreases to zero and it begins to turn on. As the current through D_{o2} increases, the current through clamp capacitor C_{c2} decreases. The multiplier capacitors C_{m1}, C_{m2} , the second and third windings of the built-in transformer operate as voltage sources. This is the inherent reason why the proposed converter can greatly extend the voltage gain. Meanwhile, regenerative diode D_{r1} begins to conduct. The energy stored in clamp capacitor C_{c1} starts to transfer to multiplier capacitor C_{m1} through regenerative diode D_{r1} ,second winding of built-in transformer and switch S_1 . The current through C_{c1} and C_{m1} is controlled by the leakage inductance L_{Lk} . Now, the current through clamp capacitor C_{c2} decreases to zero and clamp diode D_{c2} turns off naturally. As a result, there is no reverse-recovery problem for the clamp diodes. The energy stored in the multiplier capacitor C_{m2} continues to transfer to the load .Due to the leakage inductance L_{Lk} , S_2 turns on with zero current switch (ZCS) soft switching condition. The current falling rate through output diode D_{o2} is controlled by leakage inductance L_{Lk} , which alleviates the output diode reverse-recovery problem. This stage ends when output diode D_{o2} turns off.

4. Simulation Results

The simulation of ZCS interleaved high step up converter with built in transformer voltage multiplier cell has been carried out. An input voltage of 40V and switching frequency of 100 kHz is chosen and an output of 380V is obtained. The duty ratio of the switches are equal and the corresponding parameters are listed in Table I. Fig 4 shows the simulation waveforms of the converter (a) the input voltage, output voltage and current waveforms. (b) Voltage and current across the switch. Zero current switching is achieved. (c) Input inductor current, primary and secondary current of the coupled inductor. (d) Output diode voltage and current waveform. Fig 5, fig 6 shows the waveform of line and load regulation respectively.

Table 1: Simulation Parameters

Parameters	*value*
Input voltage V_s	40V
Output voltage V_o	380V
Output power P_o	1000W
Switching frequency f_s	100kHz
Turns ratio N_1:N_2	14:14
Input Inductor	50µH
Capacitance of C_{m1}(C_{m2})	4.7µF
Capacitance of C_{c1} (C_{c2})	4.7µF
Capacitance of C_0	470µF
Output Resistor	144.4Ω

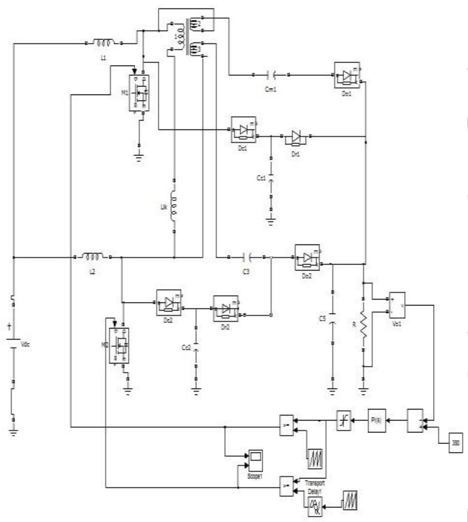

Figure 4: Simulink model of the converter

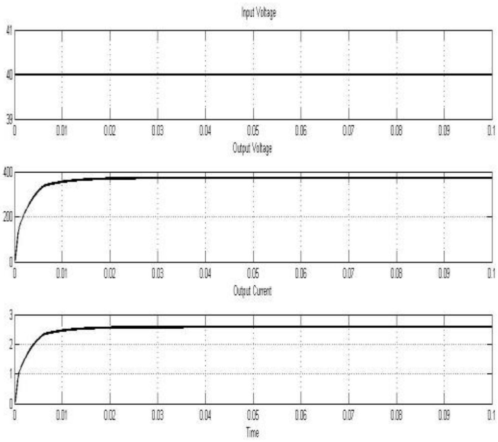

Figure a) Input voltage, Output Voltage and Output Current

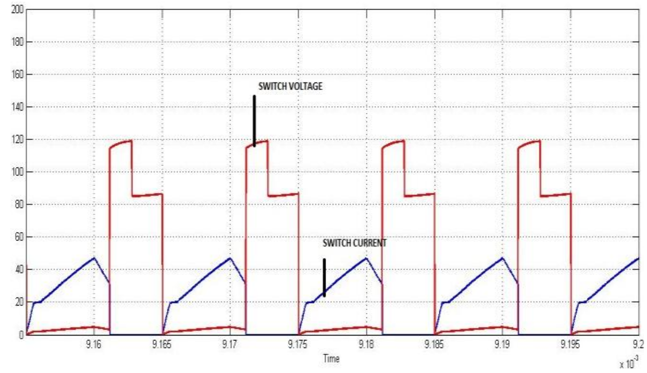

Figure b) Waveforms across the switch

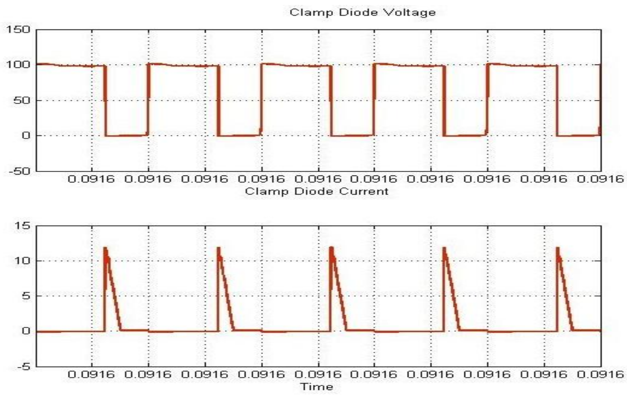

Figure c) Waveforms across clamp Diode

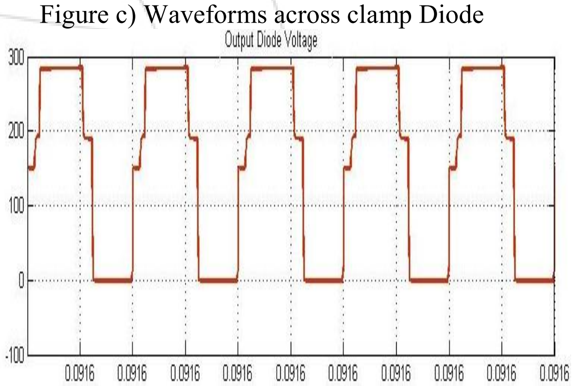

Figure d) Waveform across output Diode

Due to the leakage inductance of the built in transformer ZCS Turn on is realised for the switches. From the waveform it is clear that clamp diode turns off naturally.Consequently there is no reverse recovery problem for the clamp diodes. The current falling rate of the output diode is controlled by the leakage inductance of the built in transformer,which alleviates the diode reverse recovery problem.From the waveform it is clear that voltage stress of output diode voltage is less than the output voltage.

Fig 4: simulation results: (a) input and output voltage, output current, (b) Waveforms across the switch (c) Waveforms across clamp diode voltage (d) output diode voltage

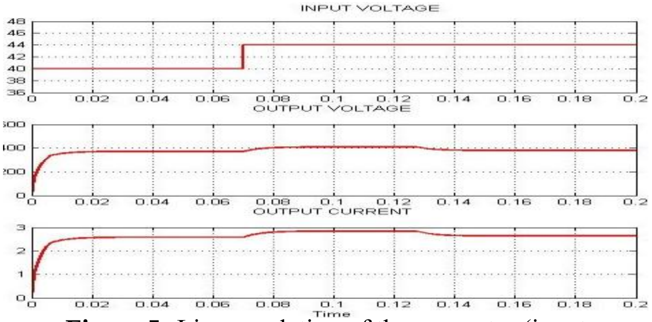

Figure 5: Line regulation of the converter (input voltage=44V)

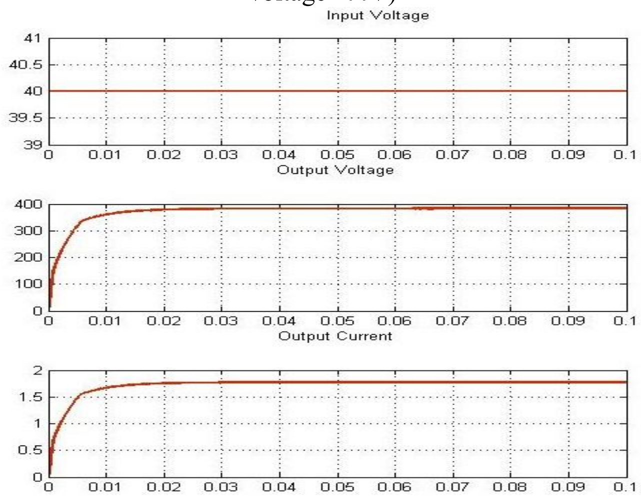

Figure 6: load regulation of the converter obtained at half load

5. Conclusion

The paper introduces closed loop control of high step up interleaved converter with built in transformer voltage multiplier cell for secondary grid connected applications. An additional control freedom is provided by the built in transformer voltage multiplier cell to achieve extremely high voltage conversion ratio and to minimize the current ripple. The switch voltage stress is reduced (26.3%) to make the low voltage rated power device and the conduction losses are reduced.ZCS is achieved for the switches and the diode reverse recovery problem is alleviated to improve the conversion efficiency. The validity is tested by using the MATLAB software and obtained the required output.

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