Voltage Gain Enhanced Step-Up Converter Using Switched Capacitor Cell Topology

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Abstract-*This paper develops a novel single switch step up converter adopting switched capacitor cell for renewable energy generation applications. By integrating the advantages of resonant conversion and switched capacitor cell topology energy efficient high voltage gain can be achieved. Single switch topology will reduce the cost of conversion and complexity of control circuits. The circuit topology consisting of resonant converter with zero voltage switching with an energy blocking diode having zero current switching. The energy blocking diode with DC output filter filters the output stage of converter. Integration of switched capacitor cell topology will boost the output voltage. The basic idea of switched capacitor cell is that, when the switch is off, the energy released from the inductor is used to charge the capacitors in parallel. When the switch is on, the capacitors are connected in series to supply the load. Thus, the voltage gain is increased. Operating principles are derived, and analyses are carried out based on the equivalent circuits for the proposed power converter under different operating modes. Given appropriately chosen circuit parameters, the active power switch can be operated with ZVS and ZCS. Simulation and experimental results demonstrate a satisfactory performance of the proposed topology.*

Keywords-*Photovoltaic (PV), resonant power converter, zero-current switching (ZCS), zero-voltage switching (ZVS). high voltage gain, switched capacitor (SC)*

I.   Introduction

The recent growth of battery powered applications and low voltage storage elements are increasing the demand of efficient step-up dc–dc converters. Typical applications are embedded systems, renewable energy systems, fuel cells, mobility applications and uninterrupted power supply (UPS). These applications demand high step-up static gain, high efficiency and reduced weight, volume and cost.

We can improve the voltage gain by increasing the turns ratio of the transformer in isolated converters. But, too large turns ratio will lead to a large leakage inductance. Hence voltage stress of the switch will be increased, which will result in degraded efficiency[1-3].

In case of the non-isolated dc–dc converters, the boost converter is usually used for voltage step-up. But as the output voltage increase, duty cycle will approach to unity. Which increase the current ripple and turn off current. Which will lead to large conduction loss, switching loss, and thus lowefficiency [4]&[5]. Cascading of boost converter can improve the voltage gain. But increased component count will increase the cost and lowers the efficiency[6].

Coupled inductor having appropriate turns ratio can increase the voltage gain effectively. However, a snubber circuit is needed to absorb the energy stored in the leakage inductor. This will lead to circuit complexity and low efficiency. In [7]–[9], the active-clamp technique is incorporated to suppress the voltage spike of the switch and regenerate the energy stored in the leakage inductor to the load, which leads to improved efficiency. But, in this circuitry, input current will be having pulsating nature. Another problem is the resonance between leakage inductor and parasitic capacitor of the output diode.

Voltage gain can be drastically increased using switched capacitor cell topology. Which will result in poor line and load regulation and input current pulsation. Meanwhile, the voltage gain is predetermined by the circuit structure [10]. Incorporation of SC structure into the switching-mode dc–dc converters can increase the voltage gain with an appropriate duty cycle. By this topology, we can achieve good voltage regulation [11]–[12]. Moreover, the pulsating input current can be reduced.

While discussing about energy efficient conversion, the first thing we have to do is minimizing the losses. Real devices dissipate power when they are used in various applications. If they dissipate too much power, the
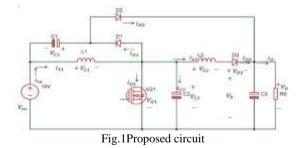
devices can fail and in doing so will not only destroy themselves, but may also damage the other system components.The simplest method for controlling power semiconductor switches is pulsewidth modulation (PWM) [13]–[15].The PWM approach is to control power flow by interrupting current or voltage by switching with control of the duty cycles.Conventionally, the voltage across or current through the semiconductor switch is abruptly altered; this approach is called hard-switching PWM. Because of its simplicity, relatively low current stress, and ease of control, hard-switching PWM approaches have been preferred in modern power electronics converters. Increased switching frequency lead to increased loss of the system. In the last few decades, various research studies havebeen performed to improve the switch transition to overcomethis inherent problem of hard-switching PWM converters. Bysolving these high voltage and current stress problems, energyconversions using resonant converters have been important inensuring both high performance and supporting energy conservation applications in renewable energy generation systems. To minimize the switching losses in high frequency systems we are using soft switching techniques.Zerovoltageswitching (ZVS) and zero-current switching (ZCS)techniques are two commonly used soft-switching methods[16]–[18]. In these techniques, either voltage or current iszero during the switching transition, substantially reducing theswitching loss and increasing the reliability of resonant converters. In this paper we are integrating resonant conversion in SC based switched mode DC-DC converter. Hence we can obtain energy efficient high step up converter[19]&[20].

II.   Study Of Proposed System

This work integrates a novel current-fed resonant converter with switched capacitor cell topology in order to increase the voltage level. Resonant converter with ZVS and ZCS operations of both the active power switch and the rectifying diode for energy conversion. Fig.1 shows a basic circuit diagram of the proposed novel ZVS and ZCS single-switch step up converter for renewable energy generation applications.

The circuit comprises a choke inductor L_1 , a metal–oxide–semiconductor field-effect transistor (MOSFET) that operates as a power switch Q_1, The capacitor C_1 is connected in series to source voltage and load resistor through diode D_2 ,a shunt capacitor C_2, a resonant inductor L_2, an energy-blocking diode D_3, and a filter capacitor C_3. The capacitor C_3 and the load resistance R_0 together form a first-order low-pass output filter, which reduces the ripple voltage below a specified level. The MOSFET is a favored device because its bodydiode can be used as anantiparallel diode D_E ,   for a bidirectional power switch. Notably, the shunt capacitance C_2, includes the power switch parasitic capacitance and any other stray capacitances (such as the winding capacitance of the choke L_1). Careful design of the circuit parameters guarantees that the power switch Q_1 is switched by ZVS and the energy-blocking diode D is switched by ZCS, optimizing the operation of the converter.

Fig.1Proposed circuit

III.   Circuit Operating Principles

The novel ZVS single-switch step up converter for renewable energy generation applications is analyzed using the following assumptions.

- The switching elements of the converter are ideal, such that the drop in forward voltage across the resistance of the power switch in the ON state is negligible.
- The equivalent series resistance of the capacitance and stray capacitances is negligible.
- The characteristics of the passive components are linear, time invariant, and independent of frequency.
- The filter capacitance C_3 at the output terminal is typically very large; theoutput voltage across capacitor C_3 can therefore be treated as an ideal dc voltage in each switching cycle.

The key waveforms for each mode of the proposed converter are shown in Fig.2 One switching cycle is divided into six modes, which are described as follows.
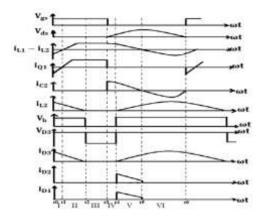
Fig. 2 Key Waveforms

Mode I—Between t_0 and t_1: Prior to Mode I, the active power switch Q_1 is off. The resonant tank current i_{L2} is positive and exceeds the dc input current i_{L1}. The power switch must be turned on only at zero voltage. Otherwise, the energy stored in the capacitor C_2 will be dissipated in the active power switch Q_1. To prevent this situation, the antiparallel diode D_E must conduct before the power switch is turned on. Since the capacitor current i_{C2} is negative, it flows through capacitor C_2. When the capacitor voltage V_{C2} falls to zero, a turn-on signal is applied to the gate of the active power switch Q_1. Therefore, the active power switch Q_1 turns on under ZCS and ZVS conditions.
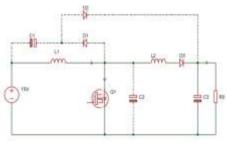

Fig.3. Mode 1 Operation

At the beginning of this mode, the antiparallel diode D_E conducts because the difference between currents $i_{L1} - i_{L2}$ isnegative. In this mode, the energy-blocking diode D_3 is turnedon because the resonant tank current i_{L2} is positive. Diodes D_1 and D_2 is reverse biased. Fig.3 presents the equivalent circuit of this mode. This mode ends as soon as the antiparallel diode D_E is reverse biased by a positive current $i_{L1} - i_{L2}$.

Mode II—Between t_1 and t_2: In this period, the switch Q_1 remains in the ON state. Fig. 4 shows the equivalent circuit. The line voltage is applied to the choke inductor L_1, and i_{L1} increases continuously. In this mode, the current $i_{L1} - i_{L2}$ naturally commutates from the antiparallel diode D_E to the active power switch Q_1. Accordingly, the voltage across the capacitor C_2 is clamped at zero.
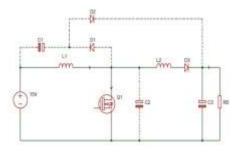

Fig.4 Mode 2 Operation

The resonant current i_{L2} passes through the energy-blocking diode D_3. The circuit operation enters Mode III when the inductor current i_{L2} falls to zero.

Mode III—Between t_2 and t_3: In Mode III, the active power switch Q_1 remains in the ON state, and the input dc current i_{L1} continuously increases. The choke inductor current i_{L1} flows through the active power switch Q_1. The inductor current i_{L2} falls until it reaches zero and is prevented from going negative by the energy-blocking diode D_3. Notably, the dc input source is never connected directly to the output load in the novel single-switch converter. Energy is stored in the choke inductor L_1 when the active power switch is turned on and is transferred to the output load when the active power switch is turned off. Fig.5 displays the equivalent circuit of this mode.
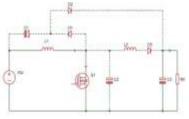

Fig.5. Mode 3 Operation

Mode IV—Between t_3 and t_4: At the beginning of Mode IV, the active power switch Q_1 is switched off. The capacitor current i_{C2} becomes i_{L1}. Then, the capacitor voltage v_{C2} rises from zero to a finite positive value. For ZVS operation, Q_1 is switched off at zero voltage, and the capacitor voltage v_{C2} increases linearly from zero at a rate that is proportional to i_{L1}. The capacitor current i_{C2} flows through capacitor C_2 to charge C_2, transferring the energy from the dc input source to capacitor C_2. During this mode, the output power of load resistor R_0 is supplied by the output capacitor C_3. Fig .2 reveals that the active power switch Q_1 is turned off under the ZVS condition. Fig.6 presents the equivalent circuit. This mode ends when the energy-blocking diode D_3 is forward biased ($v_{C2} > V_0$). Then, the circuit operation enters Mode V.
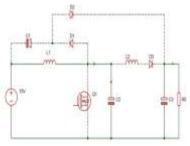

Fig.6. Mode 4 Operation

Mode V—Between t_4 and t_5:: In ModeV, the active power switch Q_1 remains in the OFF state. The inductor current i_{L2} is positive, and the energy-blocking diode D_3 is turned on, yielding a resonant stage between inductor L_2 and capacitor C_2. In this interval, the capacitor current i_{C2} is still positive. Hence, the capacitor voltage v_C continues to increase to its peak value. Diodes D_1 and D_2 in the conducting state. The capacitor C_1 discharges it's energy to the load via diode D_2. Fig.7 presents the equivalent circuit. Mode V ends when capacitor current i_{C2} resonates to zero at t_5, and operating Mode VI then begins.

Mode VI—Between t_5 and 2π: This cycle begins at t_5 when capacitor voltage v_{C2} resonates from negative values to zero. The active power switch Q_1 is turned on when $\omega t = 2\pi$ to eliminate switching losses. Fig.8 illustrates the equivalent circuit.
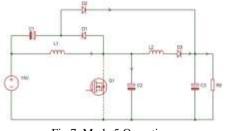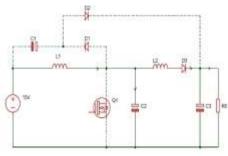

Fig.7. Mode 5 Operation

Fig.8. Mode 6 Operation

Before the cycle of the resonant inductor current i_{L2} oscillation ends, the active power switch Q_1 is kept off condition, constraining the positive current to flow continuously through the energy-blocking diode D_3. In addition to the active power switch, the energy-blocking diode in the novel converter is also commutated under soft switching. This feature makes the novel single-switch ZVS step up converter topology particularly attractive for high-efficiency energy conversion applications.

When the driving signal Vgs again excites the active power switch Q_1, this mode ends, and the operation returns to Mode I in the following cycle.

IV. Design Parameters

Accordingly, the relationshipsbetween switching frequency f_s and resonant frequency f_0 must satisfy the following equation:

$$f_s \leq f_o = \frac{1}{2\pi \sqrt{LC}} \tag{1}$$

During the time that the inductor current i_{L2} is positive, the power is fed to the load through the energy-blocking diode D_3. When the energy-blocking diode D_3 is turned on, the resonant circuit must be under damped to achieve resonant operation. That is,

$$R \leq 2\sqrt{\frac{L_S}{C}} \tag{2}$$

The following equation gives the efficiency of the proposed novel single-switch resonant power converter:

$$\eta = \frac{V_O I_0}{V_{in} I_{in}} \tag{3}$$

The other components can be designed according to following equations. The input inductor can be designed according to equations (4) and (5)

$$L_1 = \frac{V_{in} D}{\Delta i_{L1} f_s} \tag{4}$$

$$\Delta i_{L1} = \frac{V_{in} D T_s}{L1} = \frac{V_O (1-D) D T_s}{2L1} \tag{5}$$

In the converter circuit, the SC is regarded as a voltage source. In fact, there exists a small voltage ripple at the switching frequency on the capacitor. When the switch is on, the sum of voltages of C_1 and the voltage source is slightly larger than the output voltage. Then, C_1 and the voltage source are in series to supply the load. Moreover, the voltage difference is added to the equivalent series resistor (ESR) of the capacitor, which results in large pulsating current. Hence, the voltage ripple should be limited to a small range in case of too large current. As the average current of the branch of filter capacitor C_3 is zero, the average current that C_1 output to the load when the switch conducts is I_0, where I_0 is the load current. The ripple voltage is set to 1% of the output voltage. Then, the voltage ripples are

$$\Delta V_{C1} = \frac{I_0 T_S}{C_1} \tag{6}$$

The output filter capacitor can be designed according to following equation. It is assumed that the output is connected to the input of an inverter.
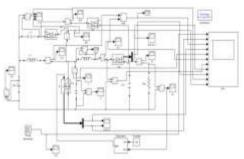
$$C_3 = \frac{P_o}{2\pi f_{line} \Delta V_o V_o} \tag{7}$$
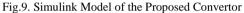
V.   Simulation Results And Analysis

To verify the feasibility and validity of the proposed converter, MATLAB/Simulink software is applied for the simulation of the converter. The input of the proposed novel ZVS single-switch step up power converter can be connected to a small-scaled solar energy generation system that consisting of a dc source with an output voltage of 15 V. Fig.9 shows the Simulink model of the proposed converter.

A.   SIMULATION PARAMETERS

The following parameters are used in this simulation model. DC input voltage of 15V. $L_1 = 25\mu H$, $L_2 = 19\mu H$, $C_1 = 0.82\mu F$, $C_2 = 0.1\mu F$, $C_3 = 220\mu F$, $P_0 = 16W$, $V_0 = 55V$, $f_s = 70kHz$

Fig.9. Simulink Model of the Proposed Convertor

B.   FEEDBACK CIRCUIT

In this Simulink model, we are using closed loop PWM control using PI controller. Fig. 10 shows the feedback loop.In this loop we are comparing output voltage with constant reference voltage and the error signal is fed to PI controller. PI controller block is shown in Fig.11. This value is limited to a particular range using saturator .Saturator output is compared with the repeating sequence and output is given as gating pulse.
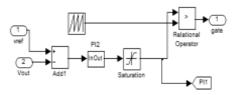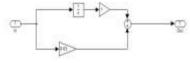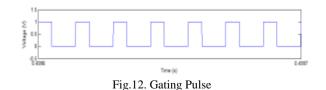

Fig.10. Feedback loop

Fig.11. PI Controller

C.   SIMULATION RESULTS

The gating pulses are generated by closed loop PI controller. This pulse is given to the gate of power switch, which is shown in Fig.12.

Fig.12. Gating Pulse

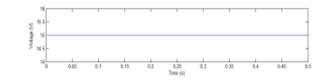The input to the converter is 15 V. Fig .13.shows the input voltage.

Fig 13. Input voltage

The following figures illustrates the satisfactory operation of the convertor. Fig.14 shows the voltage and current waveforms across the switch. From the figure, it is clear that the switch transition occurs at zero voltage and zero current.
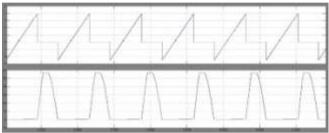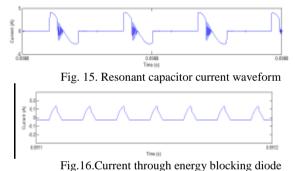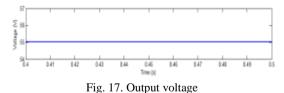

Fig. 14. ZVS and ZCS switching

Fig. 15 shows the resonant capacitor current. Resonant transition of inductor capacitor pair is clear from this current waveform. Fig. 16 shows the current through energy blocking diode.

Fig. 15. Resonant capacitor current waveform

Fig.16.Current through energy blocking diode

For an input voltage of 15V, the output voltage is boosted to 55V with a single switch converter which operated in zero voltage and zero current conditions. Fig. 17.shows the output voltage waveform.

Fig. 17. Output voltage

VI. Conclusion

Energy efficient and economical power conversion, can be obtained by proposed single switch step up resonant converter. In this topology we are integrating the advantages of resonant conversion and switched capacitor cell topology. To reduce the cost of conversion and complexity of control circuits, we used only one active power switch. The structure of the proposed converter is simpler and cheaper than other resonant power converters, which require numerous components. The novel step up converter is analyzed, and performance characteristics are presented. For an input voltage of 15V, obtained boosted output of 55V with 16W output power. The developed novel single-switch resonant power converter offers the advantages of soft switching, reduced switching losses, and increased energy conversion efficiency along with voltage boost up. The output power can be determined from the characteristic impedance of the resonant tank by adjusting the switching frequency of the converter. The novel single-switch resonant power converter is supplied by a solar energy generation system to yield the required output conditions. The experimental results reveal the effectiveness of the developed novel single-switch resonant boost converter in solar energy generation.

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