A High Voltage Gain SEPIC DC-DC Converter With Coupled Inductor And Active Clamping For Renewable Energy Applications

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Abstract- A high voltage gain SEPIC DC-DC converter is suitable for renewable energy applications. A high step up converter should be used in these systems with renewable energy sources having low output DC voltage. The presented topology consists of a SEPIC based DC-DC converter with coupled inductor and an active clamp circuit for obtaining high voltage gain. To increase the voltage gain, voltage multiplier cells are also added to the converter circuit. The active clamp circuit not only increases voltage gain, but also reduces the voltage stress on main switch compared to conventional SEPIC converters. The converter also has the advantage of low ripple continuous input current which is an important factor in maximum power point tracking of renewable energy systems. The SEPIC converter with active clamping circuit has reduced losses and increased overall efficiency compared to topology with passive clamping circuit. Performance study of the converter is carried out with MATLAB/Simulink. The switching pulses for the control circuit are generated using PIC16F877A microcontroller and the output of the microcontroller is fed to driver IC TLP250. The prototype is implemented on a design of 5 V DC input and 20 kHz switching frequency.
Keywords –DC-DC converter, High voltage gain, Coupled inductor

I. INTRODUCTION

Renewable energy sources have attracted most researchers' attention now a day. Renewable energy sources are more advantageous than fossil fuels due to their abundance, pollution-free and sustainability. However, application of renewable energy sources has some challenges [5]. For instance, the low output voltage of the PV panels must be increased to be suitable for grid integration. Output voltage and power regulations of FCs are another issue that must be resolved. The output voltages of these sources are not large enough for connecting to ac utility voltage so, a high step-up DC-DC converter should be used in these systems [7]. Maximum power point tracking (MPPT) is required for PV panels ,to realize MPPT, the converter should have a continuous input current. Fuel Cells are also required to have a continuous output current so that their output power can be regulated. A DC/DC converter with continuous input current will also increase the dynamic performance of the system. Totally, in order to use a DC/DC converter in renewable energy sources, it should have a high voltage gain and continuous input current with low ripple.

Conventional boost converters can achieve high voltage gain with an extremely high duty ratio [12]. However, the performance of the system will be worsened with a high duty cycle due to several problems such as low conversion efficiency, reverse-recovery etc.

There have been some techniques such as switched capacitors [9] and voltage lift [10] to obtain high voltage gain. Flowing high charging current through the main switch is an important drawback of these converters which decreases the efficiency. Coupled inductor based boost converters solve the above mentioned problems [11]. The leakage current of the coupled inductor is restored through active or passive clamps.

In this paper, the modified high voltage gain SEPIC based DC-DC converter benefits from various advantages such as high output voltage gain, low ripple continuous input current and lower voltage stress. The presented converter which is the modified version of converter [1], consists of a coupled inductor, an inductor and an improved voltage multiplier cell. An active clamping circuit is also used to increase the voltage gain. This cause the number of components to be high. The power is transferred to the load with some steps from input to output. Since both sides of the coupled inductor charge the capacitors of voltage multipliers, the voltage gain of the proposed converter in comparison other converters with same number of components to be very high. Thus, higher voltage gain can be achieved with low duty ratio. The voltage stress on the output diode in the converter is less which helps solving reverse recovery problem [1].

This paper presents the SEPIC converter with active clamping circuit which has reduced losses and increased overall efficiency compared to topology with passive clamping circuit so that a switch with low on-resistance to be used in this converter which reduces the conduction loss.

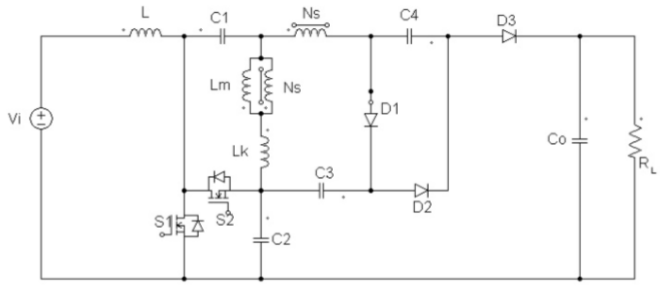

Figure 1. The circuit prototype of the proposed converter

The circuit configuration of the proposed converter is shown in Fig. 1.Capacitors C3 and C4 are charged by both sides of the coupled inductor. The voltage across the main switch is clamped by switchS2 and capacitor C1. The operation principle of the proposed converter under steady state condition is discussed in the section II.

II. OPERATING MODES OF CONVERTER

The operation principle of the converter is in Continuous Conduction Mode (CCM) consists of five intervals. Since operating in Discontinuous Conduction Mode (DCM) has some disadvantages such as slow dynamic response, dependence on frequency of the output power and the value of inductors and also high current stress on the semiconductors, the converter should be designed to operate under CCM condition.The SEPIC based DC-DC converter with active clamping circuit has high voltage gain, continuous and low-ripple input current. It consists of two switches S1 & S2 , diodes D1, D2, D3 ,inductor L1, magnetizing inductor Lm, and leakage inductor Lk , one coupled inductor, four capacitors C1, C2 , C3,C4 and one output capacitor Co. Vi is the input voltage and output voltage is denoted as Vo. The only difference of this modified converter with passive clamp SEPIC converter [1] is that diode D1 is replaced by switch S2. This helps to reduce the diode losses and also reduces input current ripple. Operations are described as follows [1]:

Mode 1[t0 – t1]:In this mode, switch S1 is turned on. Diodes D2, D4 are also turned on. The current of the leakage inductor is increased rapidly. The voltage across the leakage inductor is high and also its inductance is very low. So, the slope of this current will be high. Therefore, this time interval is too small. The secondary side current of the coupled inductor becomes zero when the currents of leakage and magnetizing inductor become equal. At this point of time, diodes D2, D4 are turned off.

Mode 2[t1 – t2]: In this time interval, the switch S1 is on. As mentioned, this mode begins when the currents of leakage and magnetizing inductor become equal. Secondary side current of the coupled inductor reaches zero and diodes D2 and D4 are turned off. Once the current of the leakage inductor becomes greater than the magnetizing inductor current, the direction of the secondary side current of the coupled inductor changes and turns diode D3 on. Inductor L is charged by the input source. The magnetizingand leakage inductors and capacitor C1 are charged by the energy stored in capacitor C2. Capacitor C3 and secondary side current of the coupled inductor charge capacitor C4. The output capacitor provides energy to the load. This mode ends by turning the switch off.

Mode 3[t2 – t3]:In this mode, switch S1 is turned off. The current of inductor L flows through S2 and charges capacitor C2. In this mode, the leakage inductor is demagnetized. So, the energy stored in the leakage inductor is recycled to capacitor C1 through S2.Because of high negative voltage across the inductor and low value of inductance, its current slope to be high and so this causes mode 3 like mode I to be too small.

Mode 4[t3 – t4]:In this time interval, switch S2, diodes D2 and D4 are on. Recycling the energy of the leakage inductor is continued in this mode. Once the leakage inductor current become smaller than the magnetizing inductor current, the direction of the secondary side current of the coupled inductor reversed and turns diode D2 and D4 on. In conventional voltage multipliers, just the secondary side of the coupled inductors becomes in parallel with the capacitors but, in this converter, both sides of the coupled inductor become in parallel with capacitor C3. This makes the voltage across capacitor C3 and as a result, the voltage gain to be increased.

Mode 5[t4 – t5]:The energy of the leakage inductor has been recycled to capacitor C2 in modes 3 and 4. The energy of inductors and the input source energy charge the output capacitor and provide energy to the load through diode D4. Diode D2 is still on and capacitor C3 is in parallel with both sides of the coupled inductor. Avoiding current ripples of inductors L and Lm, the current slope of leakage inductor and diodes D2 and D4 are almost zero. So, the voltage across the leakage inductor in this mode is zero.

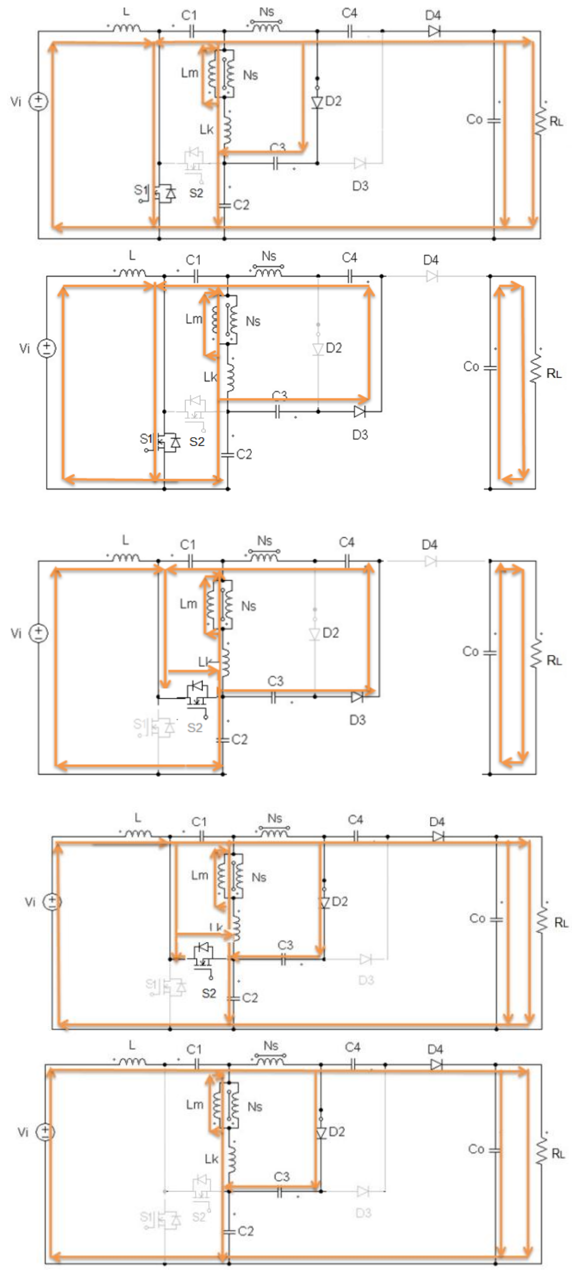

Figure 2. Modes of Operations

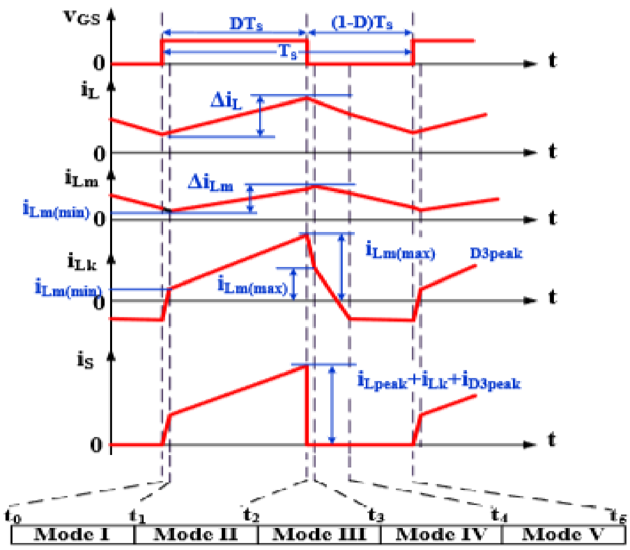

Figure 3. Theoretical waveforms [1]

III. DESIGN CONSIDERATIONS

In order to operate a converter properly, its components should be designed appropriately. Input voltage is taken as 20 V. The pulses are switched at the rate of 50 kHz with a duty ratio of 0.65. The design is done so as to get a voltage gain of 16. Turns ratio of coupled inductor is taken as 2. Taking Po as 245 W and output voltage as 320 V, Load resistance is calculated.

$$R_o = \frac{V_o^2}{P_o} = \frac{320^2}{245} = 420 \qquad (1)$$

Duty ratio D of the converter is given by the equation,

$$D = \frac{n+2-M}{-M-n-1} \qquad (2)$$

Where M is the voltage gain.Duty ratio of the converter is designed as 0.65 for the desired voltage gain of 16.

In order to operate the converter in CCM, the value of Lm should be calculated and designed properly. If the average current value of the inductor is more than half of its ripple, the converter will operate in CCM. Therefore, for a switching frequency fs=50kHz,Assuming current ripples 10 % less than average value,

$$I_L = MI_o \qquad (3)$$

$$L = \frac{DV_i}{\Delta I_L f_s} \qquad (4)$$

The value of L is set at 320 μH.Similarly for magnetizing inductor Lm,

$$I_{Lm} = (n+1)I_o \qquad (5)$$

$$Lm = \frac{DV_i}{\Delta I_{Lm} f_s} \qquad (6)$$

The value of Lm is set at 100 μH.Considering certain voltage ripple, the output capacitor value can be found.

$$C_o = \frac{DV_o}{\Delta V_o f_s R_L} = \frac{0.65 * 320}{0.06(50 * 10^3)420} = 180uF \qquad (7)$$

IV. SIMULATION RESULTS

Simulation parameters for the SEPIC based DC-DC converter is given in Table 1. An input voltage Vin of 20 V gives an output voltage Vo of 320 V for an output power Po of 245 W. The switches are MOSFET/Diode with constant switching frequency of 50 kHz. The duty cycle of switches is taken as D=0.65.

Table-1. SIMULATION PARAMETERS

Parameters	Specification
Input voltage V_{in}	20 V
Switching frequency f_s	50 kHz
Output voltage	320 V
Inductor L	320 µH
Capacitors C_1, C_2, C_3, C_4	47µF
Inductor Lm	100 µH
Capacitor Co	180 µF
Load Resistor	420 Ω

The SEPIC converter is simulated in MATLAB/SIMULINK by choosing the parameters listed in Table 1 and the simulink model is shown in figure 4.

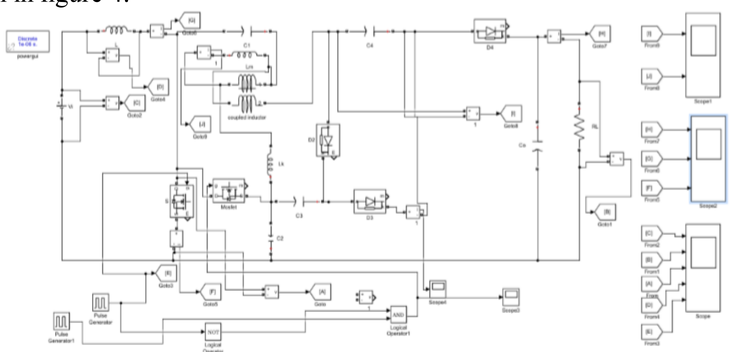

Figure. 4. Simulink Model Of Active clamp SEPIC converter

The simulation results of SEPIC based DC-DC converter are shown in the following figures. Simulation of input voltage, input current, output voltage, output current, switching pulses, voltage across switches, voltage across input inductor and voltage across output diode of the converter are shown.

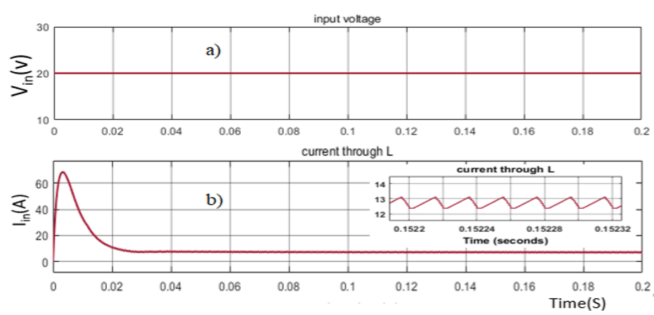

Figure 5.(a)Input Voltage and (b) Input Current

It can be seen that the input voltage Vin is 20 V and the input current ripple is about 0.4A.

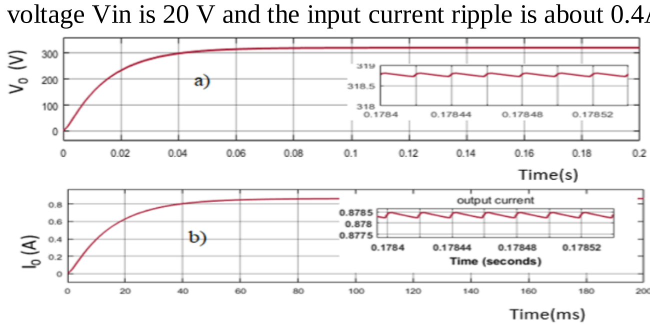

Figure 6. (a)Output Voltage and (b) Output Current

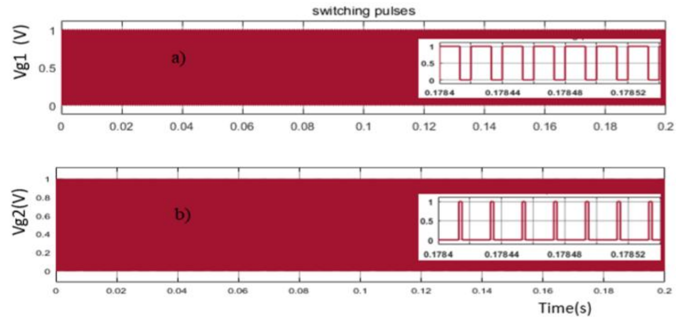

Figure 7. (a) Switching pulses (Vg1) and (b) switching pulse (Vg2)

The switching frequency is chosen to be 50 kHz and the duty ratio of S1 is equal to 0.65. The voltage stress obtained across the main switch is 60V.

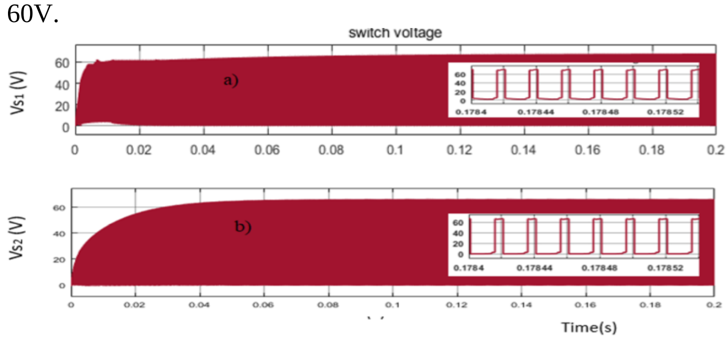

Figure 8.(a) Switch voltage (Vs1) and (b) switch voltage(Vs2)

The voltage stress on the output diode is less which alleviates the reverse recovery problem.

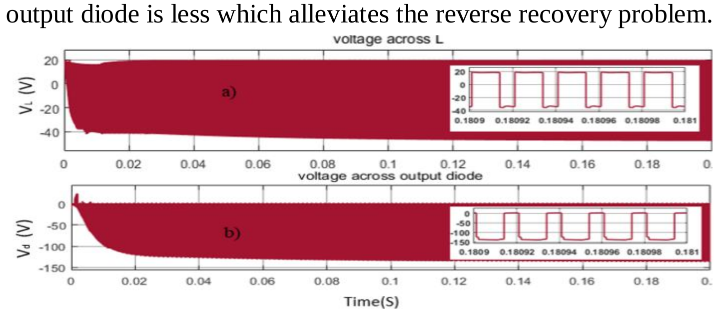

Figure 9. (a) Input inductor Voltage (VL) and (b) Output diode voltage (Vd)

Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. The efficiency tells us the fraction of the input power delivered to the load. A typical curve for the variation of efficiency as a function of output power is shown in Figure. The eff ficiency obtained is 94.3% for 245 W power output.

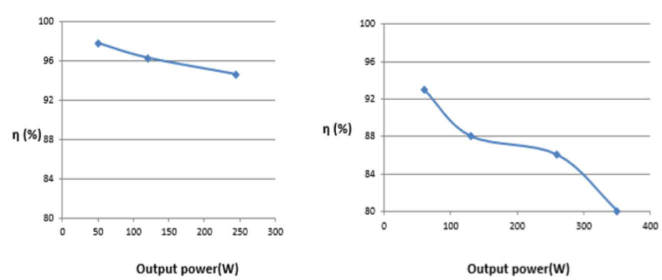

Figure 10.Efficiency Vs output power a) For R load b)For RL load

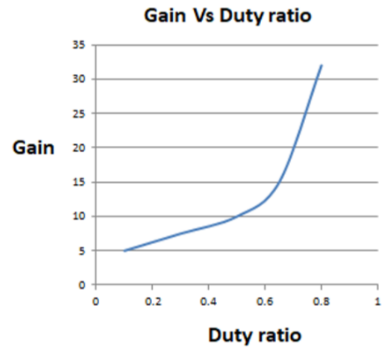

Figure 11. Gain Vs Duty Ratio

V. PROTOTYPE

An input voltage Vin of 5V gives an output voltage Vo of 80V for an output power Po of 20 W. The switches are MOSFET/Diode with constant switching frequency of 20 kHz. The duty cycle of switches is taken as D=0.65. The experimental setup of SEPIC DC-DC converter is done through two stages. First the program is written in micro C for generating gate pulses for switching devices. The program is verified and frequency is checked by simulating it in the Proteus software. The program is burned to the microcontroller (PIC16F877A) using the software micro programming suit for PIC. The switches used are MOSFET IRF540 along with its driver TLP250.The output voltage obtained by applying the above gate signals is shown in Figure. For the hardware prototype a 150 µF capacitor and 320 Ω 20W load resistor are used. The switches used are IRF540.

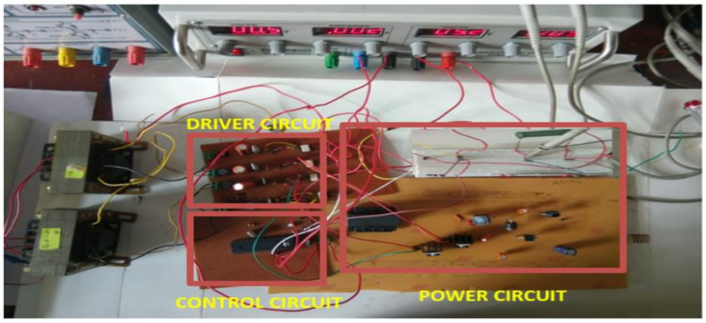

Figure 12 Experimental setup

It is observed from the experimental result that the output voltage is 16V for an input of 1.18V.The gain obtained is slightly lesser than that obtained in simulation.Gain remains constant for any input voltage. Since ideal switches with no voltage drop and no resistance are considered in simulation, so this slight variation in output voltage is appreciable. This confirms that the output voltage closely matches simulation results.

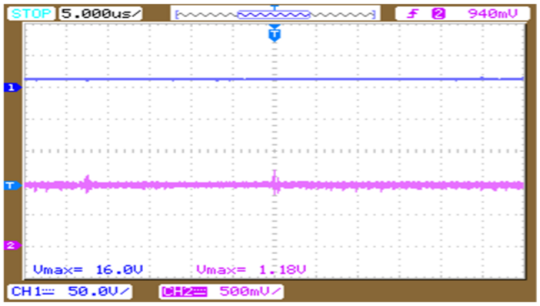

Figure 13. Output voltage of prototype

VI. CONCLUSION

The SEPIC based DC-DC converter has high voltage gain , continuous and low-ripple input current. An active voltage clamp and two voltage multipliers are added to the converter to achieve high voltage gain. Since both sides of the coupled inductor charge the capacitors of voltage multipliers, the voltage gain of the converter in comparison other converters with same number of components to be higher. Thus, higher voltage gain can be achieved with low duty ratio. The main disadvantage is higher number of components. The converter is suitable for renewable energy applications. According to the simulation results obtained the converter has a voltage gain of 16 for a duty ratio of 0.65. The converter provides an efficiency of 94.3 % for an output power of 245 W.

VII. REFERENCES

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