

## MODELLING AND ANALYSIS OF PARALLEL BOOST CONVERTER FOR PHOTOVOLTAIC APPLICATIONS

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### ABSTRACT

The main objective of this paper is to develop a mathematical modelling and design a high efficient photovoltaic (PV) application with proposed parallel boost converter. This model is based on mathematical equations and is described through an equivalent circuit including a PV source with MPPT, a diode, a series resistor, a shunt resistor and a dual boost converter with active snubber circuit. This model can extract PV power and boost by using dual boost converter with active snubber. By using this method the overall system efficiency is improved and also the switching losses is reduced.

**Key Words:** MPPT, SEPIC Converter, PV module, Parallel Boost Converter

### 1. Introduction

Solar power is a renewable energy source that might replace fossil fuel dependent energy sources. However, for that to happen, solar power cost per kilowatt-hour has to be competitive with fossil fuel energy sources. Currently, solar panels are not very efficient, it has 12-20% efficiency to convert sunlight to electrical power. The efficiency can drop further due to other factors such as solar panel temperature and load conditions. In order to maximize the power derived from the solar panel, it is important to operate the panel at its optimal power point. To achieve this, a type of charge controller called a Maximum Power Point Tracker should be designed and implemented.

The MATLAB/PSPICE model of the PV module is developed [1-4] to study the effect of temperature and insolation on the performance of the PV module. MATLAB-based modelling and simulation scheme which is suitable for studying the  $I-V$  and  $P-V$  characteristics of a PV array under a non-uniform insolation due to partial shading [5] was proposed. The mathematical model of solar PV module is useful for the computer simulation. The power electronics interface connected between a solar panel and a load or battery bus, is a pulse width modulated (PWM) DC-DC converter or their derived circuits is used to extract maximum power from solar PV panel [6]. The main drawback of PV systems is that the output voltage of PV panels is

highly dependent on solar irradiance and ambient temperature. Therefore it is not possible to connect the PV panels outputs directly to the load. To improve this, a DC-DC boost converter is required to interface between PV panels and loads [7]. The boost converter decides the output voltage of the PV system. Converter receives the variable input voltage which is the output of PV panels and give up constant output voltage across its output capacitors where the loads can be connected. In general, a DC-DC boost converter operates at a certain duty cycle. In this case, the output voltage depends on that duty cycle. If the input voltage is changed while the duty cycle is kept constant, the output voltage will vary. Duty cycle is varied by using a pulse width modulation (PWM) technique [8].

Silicon carbide (SiC) represents an advanced silicon technology because it allows a larger energy gap. SiC is classified as a wide-band-gap (WBG) material, and it is the mainstream material for power semiconductors [9] [10]. Among the different types of power semiconductors, the power diode was the best device to adopt SiC technology. The main advantage of SiC is high-breakdown voltage and reverse-recovery current is small [11]-[13]. As a result, higher efficiency and higher power density can be brought to power electronic systems in different applications [14]-[16]. In this research, a new active snubber circuit is proposed to contrive a new family of PWM converters. This

proposed circuit provides perfectly ZVT turn ON and ZCT turn OFF together for the main switch of a converter by using only one quasi resonant circuit without an important increase in the cost and complexity of the converter. This paper is organized as follows. In Section 2, MATLAB model of L1235-37W Solar PV module is presented. In Section 3 Mathematical Model for Parallel Boost Converter with Active Snubber Circuit is presented and in Section 4 Proposed Parallel Boost Converter for PV application is presented. Simulation Results and Discussions are given in Section 5. Finally conclusion is presented in Section 6.

**2. MATLAB MODEL OF L1235-37W SOLAR PV MODULE**

A solar cell is the building block of a solar panel. A photovoltaic module is formed by connecting many solar cells in series and parallel. Considering only a single solar cell; it can be modelled by utilizing a current source, a diode and two resistors. This model is known as a single diode model of solar cell. Two diode models are also available but only single diode model is considered here [1],[2],[4],[17],[18] [19].The equivalent circuit of PV module is shown in figure 1.

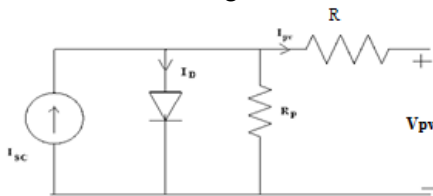


Figure 1: Equivalent Circuit of Solar PV Module

From the figure 1, the current equation is given by

$$I_{sc} = I_D + I_{pv} + (V_D / R_p) \tag{1}$$

$$V_{pv} = V_D - (I_{pv} * R_s) \tag{2}$$

Where diode current is,  $I_d = I_o + (e^{(V_D / V_T)} - 1)$ .

The load current is given by

$$I = I_{sc} - I_{pv} \left( \exp \left( \frac{q(V_{pv} + RI)}{NKT} \right) - 1 \right) - \frac{(V_{pv} + RI)}{R_p} \tag{3}$$

In this equation  $I_{pv}$  denotes the photo voltaic current,  $I_{sc}$  is the diode reverse saturation current,  $q$  is the electron charge,  $V_{pv}$  is the diode across the voltage,  $K$  is the Boltzmann's constant.  $T$  is the temperature of the junction,  $N$  is the diode identity factor,  $R$  and  $R_p$  are the series and shunt resistors of the solar cell. The complete physical behaviour of the PV cell depends upon  $I_{sc}$ ,  $I_{pv}$ ,  $R$ ,  $R_p$  and with

two environmental parameters as the temperature and solar radiation. The model is developed in MatLab/simulink based on the above equations. For a given radiation, temperature,  $R$  and  $R_p$ , the I-V and P-V curves are generated [20]. Based on the electrical equation (1) and (2), the solar PV module is modelled in MATLAB shown in figure 2, which is used to enhance the understanding and predict the V-I characteristics and to analyze the effect of temperature and irradiation variation. If irradiance increases, the fluctuation of the open-circuit voltage is very small. But the short circuit current has sharp fluctuations with respect to irradiance. However, for a rising operating temperature, the open-circuit voltage is decreased in a Non-linear fashion [1]

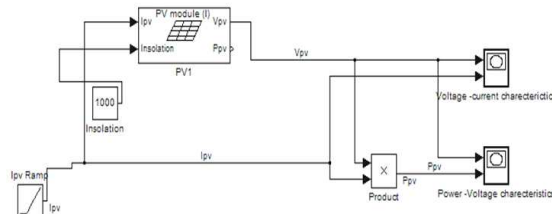


Figure 2: MATLAB Model for Single PV Module

The V-I characteristics are validated experimentally in the L1235-37Wp solar module shown in figure 3. The table I shows the technical specifications of L1235-37W solar module under test. The figure 4 shows the V-I characteristics based on the experimental results under irradiation (G) =1000W/m<sup>2</sup>, temperature =25°C.



Figure 3: L1235-37W Solar Module Under Test

Table I: Specifications of L1235-37W Single Solar PV Panel

Short circuit current ( $I_{sc}$ )	2.5A
Voltage at MPP( $V_m$ )	16.4
Current at MPP( $I_m$ )	2.25
Open circuit voltage ( $V_{oc}$ )	21V
Length	645mm
Width	530mm
Depth	34mm
Weight	4kg
Maximum power ( $P_{max}$ )	37W

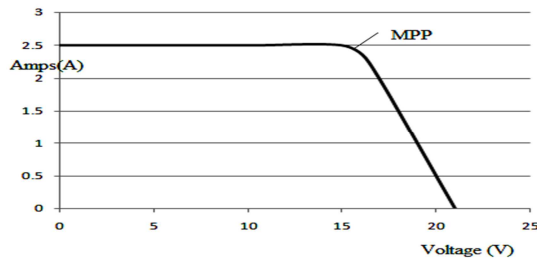


Figure 4: V-I Characteristics of L 1235-37W Solar Panel

2.1 PV Array

In order to require power an array of PV modules has been constructed. These PV modules are interconnected in series and all of them are connected to the external control block as shown in figure 5.

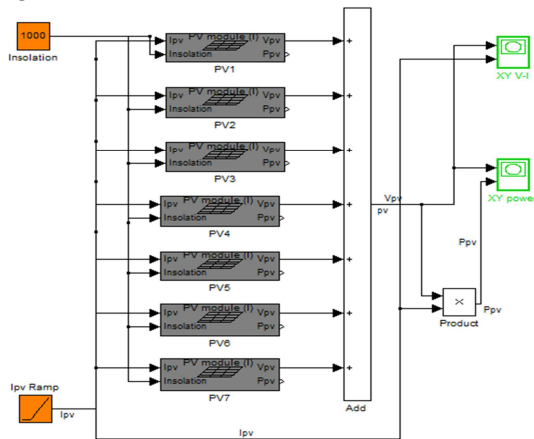


Figure 5: PV Array Model

The PV array model was simulated in Matlab/Simulink. The above model includes two subsystems for calculating the PV cell photocurrent which depends on the radiation and the temperature according to equation (3) [22].

$$I_{ph} = [I_{sc} + K_i(T - 298)] \frac{\beta}{1000} \quad (4)$$

where  $K_i=0.0017 \text{ A/}^\circ\text{C}$  is the cell's short circuit current temperature coefficient and  $\beta$  is the solar radiation ( $\text{W/m}^2$ ).

3. MATHEMATICAL MODEL FOR PARALLEL BOOST CONVERTER WITH ACTIVE SNUBBER CIRCUIT

Usually, boost converters are used for boosting purpose. Here two boost converters are connected in parallel. By using a parallel scheme, where inductor  $L_{f1}$  and switch  $S_1$  are for main converter while  $L_{f2}$  and  $S_2$  are for active filtering. The filtering circuit serves dual purpose as to improve the quality of line current and to reduce the total switching loss. The reduction in switching losses occurs due to different values of switching frequency and current amplitude for the two switches. The parallel connection of switch mode converter is a well known strategy. It involves phase shifting of two or more boost converters connected in parallel and operating at the same switching frequency [23]. The overall advantages of using this approach is to improve the efficiency and reliability, reduce the development cost, reduce current ripples, reduce conduction losses and reduce the size of active and passive components as boost inductor.

The purpose of Parallel Boost Converter is to avoid twice power process in two-stage scheme. Two converters can be connected in parallel to form the parallel boost scheme. Here, power from the PV to the load flows through two parallel paths. The main path is a filter, in which power is not processed, whereas the other path processes the input power. Therefore, high efficiency can be obtained by this method. The snubber circuit reduces or eliminates voltage or current spikes, enables limitation of  $dI/dt$  or  $dV/dt$ , shape the load line to keep it within the safe operating area (SOA), transfer power dissipation from the switch to a resistor or a useful load. The advantages of parallel boost converter with active snubber circuit is to improve overall efficiency, high reliability, reduced development cost due to the modular design, low harmonics and conduction loss.

The main aim of this work is to develop mathematical model for parallel boost converter with active snubber circuit modelled as shown below. Figure 10 represents the circuit diagram of the parallel boost converter with active snubber. It

consists of five inductors  $L_{f1}$ ,  $L_{f2}$ ,  $L_{R1}$ ,  $L_{R2}$ ,  $L_n$  and three capacitors  $C_s$ ,  $C_r$ ,  $C_o$ ,  $V_g$  and  $V_o$  represent supply and output voltage respectively, S ( $S_1$ ,  $S_2$ ) is an active primary switch, D ( $D_{f1}$ ,  $D_{f2}$ ) is a freewheeling diode,  $D_s$  ( $D_1$ ,  $D_2$ ,  $D_3$ ) is a Snubber diode and  $R_L$  is the load resistance. S ( $S_1$ ,  $S_2$ ,  $S_3$ ) operates at a switching frequency  $f_s$  with duty ratio  $d$ .

$$\frac{dV_o}{dt} = \frac{1}{C_o} \left[ -\frac{V_o}{R_L} \right] \quad (10)$$

By using state-space averaging method the state equations during switch-on and switch-off conditions are

$$\dot{x}_1 = \frac{-(1-d_1)}{L_F} x_2 - \frac{(1-d_2)}{L_F} x_2 + \frac{V_g}{L_F} \quad (11)$$

$$\dot{x}_2 = \frac{-1}{R_L C_o} x_2 + \frac{(1-d_1)d_2}{C_o} x_1 + \frac{(1-d_1)(1-d_2)}{C_o} x_1 \quad (12)$$

Where  $x_1$  and  $x_2$  are the moving averages of  $i_{LF}$  and  $V_o$  respectively.

Figure 6: when  $S_1=S_2=0$  and  $S_3=1$

Choose the switching frequency of switches  $S_1=S_2=100$  KHz and  $S_3=200$  KHz.

When  $S_1=S_2=0$  and  $S_3=1$  as in figure 6

$$\frac{diL_F}{dt} = \frac{1}{L_F} [V_g - V_o] \quad (5)$$

$$\frac{dV_o}{dt} = \frac{1}{C_o} \left[ iL_F - \frac{V_o}{R_L} - iL_S \right] \quad (6)$$

Also the switches  $S_1=S_2=S_3=1$  as in figure 7

Figure 7: when  $S_1=S_2=S_3=1$

$$\frac{diL_F}{dt} = \frac{1}{L_F} [V_g - V_o] \quad (7)$$

$$\frac{dV_o}{dt} = \frac{1}{C_o} \left[ iL_F - \frac{V_o}{R_L} \right] \quad (8)$$

Figure 8: when  $S_1=S_2=1$  and  $S_3=1$  or 0

Similarly, the switches  $S_1=S_2=1$  and  $S_3=1$  or 0 as in figure 8

$$\frac{diL_F}{dt} = \frac{V_g}{L_F} \quad (9)$$

#### 4. PROPOSED PARALLEL BOOST CONVERTER FOR PV APPLICATION

Figure 9 shows the Block Diagram of a PV Based Parallel Boost Converter with Active Snubber. It is the combination of new active snubber circuit with parallel boost converter. Three switches are used in which switch  $S_1$  and  $S_2$  act as main switch and  $S_3$  act as an auxiliary switch.  $S_1$  and  $S_2$  are controlled by ZVT and ZCT respectively. Also  $S_3$  is controlled by ZCS. This circuit operates with the input of 148 V solar power.

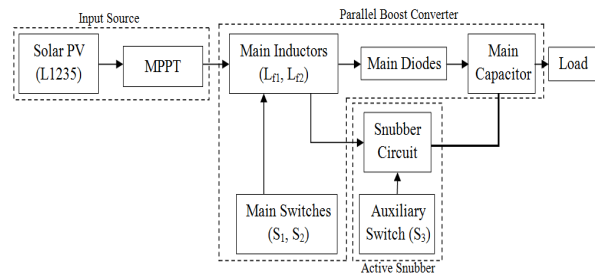


Figure 9: Block Diagram of PV Based Parallel Boost Converter with Active Snubber

Assume both the Main Switches ( $S_1$  and  $S_2$ ) operates in the same frequency. The features of proposed parallel boost converter as follows:

- All the Semiconductors work with soft switching in the proposed converter.
- The main switches  $S_1$  and  $S_2$  turn on with ZVT and turn off with ZCT.
- The secondary switch turn on with ZCS and turn off with ZCS.
- All other components of the parallel boost converter function based on this soft switching.
- There is no additional current or voltage force on the main switches  $S_1$  and  $S_2$ .
- There is no additional current or voltage force on the secondary switch  $S_3$ .

- Also there is no additional current or voltage force on the main Diodes  $D_{f1}$  and  $D_{f2}$ .
- According to the ratio of the transformer, a part of the resonant current is transferred to the output load with the coupling inductance. So there is less current stress on the secondary switch with satisfied points.
- At resistive load condition, in the ZVT process, the main switches voltage falls to zero earlier due to decreased interval time and that does not make a problem in the ZVT process for the main switch.
- At resistive load condition, in the ZCT process, the main switches body diode ON-state time is increased when the input current is decreased. However, there is no effect on the main switch turn-OFF process with ZCT.
- This parallel boost converter operates in high-switching frequency.
- This converter is easily controllable because the main and the auxiliary switches are connected with common ground.
- The most attractive feature of this proposed converter is using ZVT and ZCT technique.
- The proposed new active snubber circuit is easily adopted with other basic PWM converters and also in switching converters.
- Additional passive snubber circuits are not necessary for this proposed converter.
- SIC (Silicon Carbide) is used in the main and auxiliary diodes and so reverse recovery problem is not arise.
- The proposed active snubber circuit is also suitable for other dc-dc converters.

#### 4.1 Procedure for Constructing A Proposed Converter

Steps to obtain a system level modeling and simulation of proposed power electronic converter are listed below.

- Determine the state variables of the proposed power circuit in order to write its switched state- space model, e.g., inductance current and capacitance voltage.
- Assign integer variables (ON-1 and OFF-0 state) to the proposed power semiconductor to each switching circuit.
- Determine the conditions controlling the states of the proposed power semiconductors or the switching circuit.
- Assume the main operating modes, apply Kirchhoff's Current law and Kirchhoff's Voltage law and combine all the required

stages into a switched state-space model, which is the desired system-level of the proposed model.

- Implement the derived equations with MatLab Simulink.
- Use the obtained switched space-state model to design linear or nonlinear controllers for the proposed power converter.

Perform closed-loop simulations and evaluate performance of proposed converter. The algorithm for solving the differential equations and the step size should be chosen before running any simulation. This step is only suitable in closed-loop simulations [21]

#### 4.2 Operation of Proposed Boost Converter with Snubber Circuit

The proposed PV based converter is shown in figure 10, and it is based on a dual boost circuit where the first one (switch  $S_1$  and choke  $L_{f1}$ ) is used as main chock of boost converter circuit and where the second one (switch  $S_2$  and choke  $L_{f2}$ ) is used to perform an active filtering. The proposed converter applies active snubber circuit for soft switching. This snubber circuit is built on the ZVT turn-ON and ZCT turn-OFF processes of the main switches. Specification of proposed parallel boost converter with active snubber is in table II.

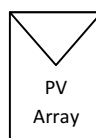


Figure 10: Circuit Diagram Of PV Based Parallel Boost Converter With Active Snubber With Resistive Load

The power from the solar flows through the two parallel paths. High efficiency was obtained by this method. So as to reach Soft Switching (SS) for the main and the auxiliary switches, main switches turn on with ZVT and turn off with ZCT. The proposed converter utilizes active snubber circuit for SS. This snubber circuit is mostly based on the ZVT turn-ON and ZCT turn-OFF processes of the main switch.  $C_S$  is the parasitic capacitors added to the main switch  $S_1$  and the main diode  $D_f$ .  $L_{R2}$  value is limited with  $(V_{out} / L_{R2}) t_{riseS2} \leq I_{imax}$  to conduct

maximum input current at the end of the auxiliary switch rise time ( $t_{riseS_2}$ ) and  $L_{R1} \geq 2L_{R2}$ . To turn OFF  $S_1$  with ZCT, the duration of  $t_{ZCT}$  is at least longer than fall time of  $S_1$  ( $t_{fallS1}$ )  $t_{ZCT} \geq t_{fallS1}$ . Though the main switches are in OFF state, the control signal is functional to the auxiliary switch. The parasitic capacitor of the main switch should be discharged absolutely and the main switches anti parallel diode should be turned ON. The ON-state time of the anti parallel diode is named  $t_{ZVT}$  and in this time period, the gate signal of the main switch would be applied. So, the main switch is turned ON below ZVS and ZCS with ZVT.

Whereas the main switches are in ON state and ways input current, the control signal of the auxiliary switch is applied. After the resonant starts, the resonant current should be higher than the input current to turn ON the anti-parallel diode of the main switch. The ON-state time of the anti-parallel diode ( $t_{ZCT}$ ), has to be longer than the main switches fall time ( $t_{fS1}$ ). After all these terms are completed, while anti-parallel diode is in ON state, the gate signal of the main switch should be cutoff to provide ZCT for the main switch. The auxiliary switch is turned ON with ZCS for the coupling inductance limits the current rise speed.

Table II. Specification Of Parallel Boost Converter With Active Snubber

Main Inductor $L_{f1}$	750 $\mu$ H
Main Inductor $L_{f2}$	750 $\mu$ H
Upper Snubber Inductor $L_{R1}$	5 $\mu$ H
Lower Snubber Inductor $L_{R2}$ ( $L_m+L_d$ )	2 $\mu$ H
Magnetization Inductor $L_M$ ( $L_n+L_{o1}$ )	3 $\mu$ H
Parasitic Capacitor $C_s$	1 $\mu$ F
Snubber Capacitor $C_R$	4.7nF
Output capacitor $C_o$	330 $\mu$ F/450 V
Output Load Resistance $R=R_L$	530 $\Omega$

The current passes through the coupling inductance, must be partial to conduct maximum input current at the end of the auxiliary switch rise time ( $t_{rS3}$ ). So, the turn-ON process of the auxiliary switch with ZCS is offered. To turn OFF the auxiliary switch with ZCS, though the auxiliary switch is in ON state, the current passing through the switch should fall to zero with a new resonant. Then, the control signal will be cut-off. If  $C_s$  is ignored,  $L_{R1}$  value should be two times added than  $L_{R2}$  to make the auxiliary switch current fall to zero. As the current cannot stay at zero as long as the auxiliary switch fall time ( $t_{fS3}$ ), the auxiliary switch is turned OFF nearly with ZCS.

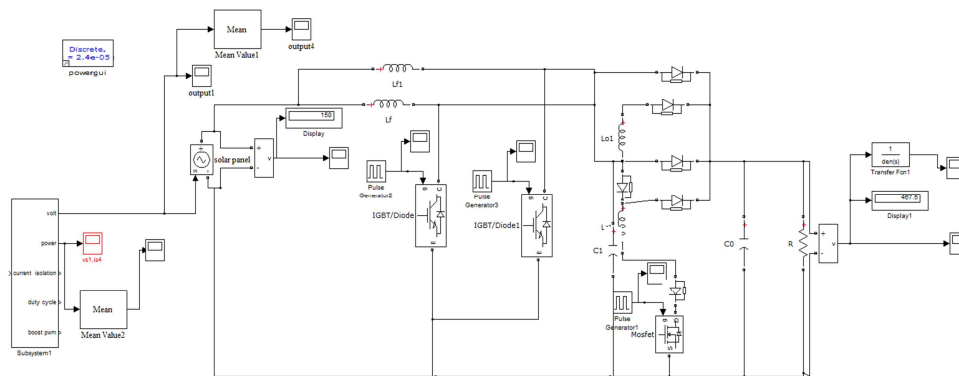


Figure 11: Simulink Model Of Proposed PV Based Parallel Boost Converter With Active Snubber Circuit

The proposed simulink topology is shown in figure 11. The inductors  $L_{f1}$  &  $L_{f2}$  have the similar values, the diodes  $D_{f1}$ - $D_{f2}$  are of the same type and the same guess was for the switches ( $S_1$  &  $S_2$ ). All inductor has its individual switch and thus it's like the paralleling of both single/classic converters.

A modular solar PV based dc-dc converter using parallel boost converter with active filter is simulated using MatLab Simulink program. The input waveform  $V_{in}$  of the converter is shown in figure 12. The output dc voltage ( $V_o$ ) is shown in figure 13 and the control signals of the switches are shown in figure 14 and 15 respectively. The

6. RESULTS AND DISCUSSIONS

simulation results show the proposed PV based soft switched parallel boost dc-dc converter has the proper response.

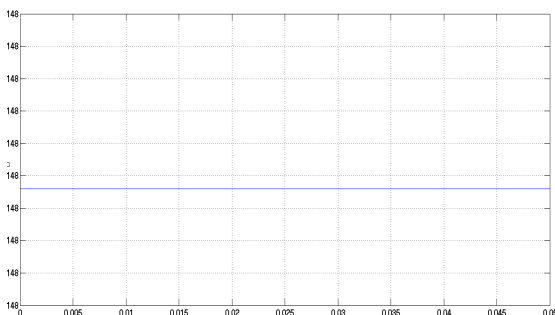
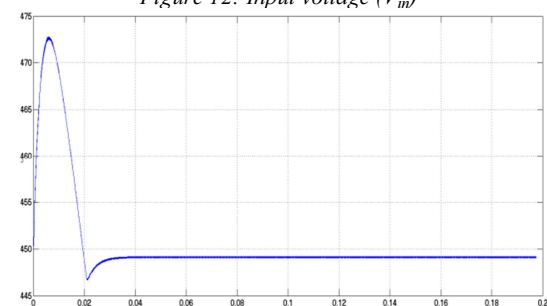
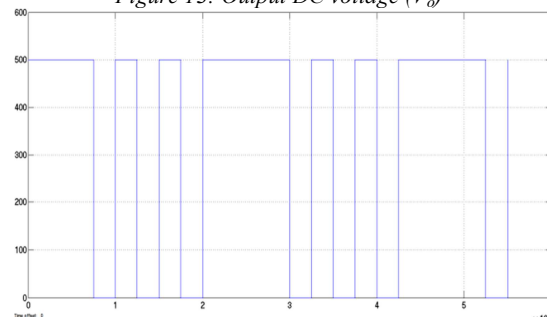
Figure 12: Input voltage ( $V_m$ )Figure 13: Output DC voltage ( $V_o$ )

Figure 14: Control Signals of Switch S1 and S2

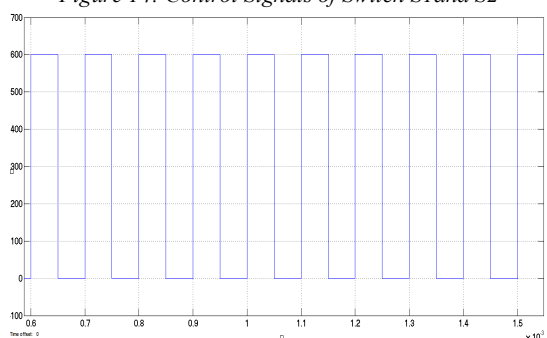


Figure 15: Control Signals of Switch S3

## 7. CONCLUSION

The main objective of this research was to improve the efficiency of the solar PV based parallel boost converter and reduce the switching

losses. Simulations were initially done for conventional boost converter with snubber circuit. The changes in the input current waveform were obtained. A parallel boost converter was designed with soft switching which is provided by the active snubber circuit. For this idea, only one auxiliary switch and one resonant circuit was operated. The main switches and all the other semiconductors were switched by ZVT and ZCT techniques. The active snubber circuit was applied to the parallel boost converter, which is fed by solar input line. This latest converter was achieved with 148 V input and produces 448V output. The diode was added in the auxiliary switch path in order to avoid the incoming current stresses as of the resonant circuit to the main switch. As the main and the auxiliary switches have a common ground, the converter was controlled easily. The proposed new active snubber circuit can be simply functional to the further basic PWM converters and to all switching converters. Here the overall tracking efficiency is 98.6% without considering the efficiency of the solar PV panel and converter. The converter conversion efficiency is increased from 86% to 91.47%

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