

Design of DC-DC Converter for PV Generation System Using A Soft-Switching Boost Converter With SARC

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Abstract

A soft switching converter poses better result in the term of efficiency and reduction of losses. Photovoltaic PV generation is the future of energy system so to improve the efficiency of energy conversion for a PV system; a simple auxiliary resonant circuit (SARC) circuit is implemented in a soft-switching boost converter. In this paper SARC is composed of an auxiliary switch, a diode, a resonant inductor, and a resonant capacitor. The conventional boost converter uses hard switching; generates losses when the switches are turned on/off which decreases the efficiency. During switching interval in the adopted circuit present in this paper all switches perform zero-current switching by the resonant inductor at turn-on, and zero-voltage switching by the resonant capacitor at turn-off. This switching pattern can reduce the switching losses, voltage and current stress of the switching device. Moreover, it is very easy to control. In this paper, the circuit is analyzed by the operational principles of the adopted soft-switching boost converter, and it is designed for PV generation system. Simulation and results are presented to validate the theoretical analysis.

Keywords: Design, PV, Soft, Switch, Converter, SARC.

1. Introduction

In the past days a lot of energy which is being utilized by the industries depends only on the energy generated by the fossil fuels due to the lack of research in the field of Renewable Energy. But now days the development and demand of renewable energy is increasing because of limited reserves, environmental pollution and depletion of fossil fuels. Some of renewable energy sources are water, wind and photovoltaic (PV) energy. Among these, PV energy is clean and is available in abundance. V-I and P-V characteristics of the solar cell are nonlinear in nature depending on irradiance, operating temperature and cell load condition [1]. Due to this reason, a dc-dc converter is proposed for controlling maximum power point variation of the solar cell output. Or maximum power point tracking (MPPT) is controlled by the duty ratio of dc-dc converter.

In this paper, soft switching boost converter is proposed which is being implemented on the auxiliary resonant circuit used for PV generation system. This converter gives us better efficiency when compared to the conventional boost converter. Also this proposed converter steps up the lower output voltage of the solar cell to the voltage as required by the load. The proposed circuit consists of a Simple Auxiliary Resonant Circuit (SARC), which helps in achieving the soft switching for all the switching devices used in the proposed circuit with the characteristics of zero voltage switching (ZVS) and zero current switching (ZCS). Thus switching losses becomes negligible in the circuit when the switch is turn on or turn off. The work carried out also includes the simulation of the soft switching boost converter on the MATLAB software which is further represented by its experimental results.

2. Operating Principle

The main objective of this section is to put light and to focus on the basic points and the operating principles of the proposed circuit on which the work has been carried out. **Modelling of proposed converter circuit:-**

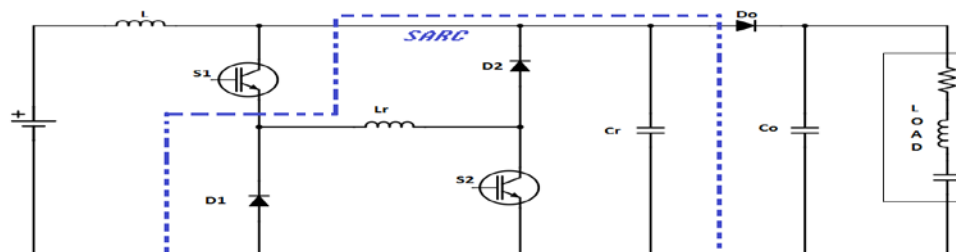


Figure 1: Proposed converter circuit with SARC configuration

The figure above shows the main circuit topology which is being proposed. This circuit shows the PV generation system whose auxiliary resonant circuit is applied with the soft-switching boost converter. The lower output voltage coming out of the solar cell is boosted up to the required voltage by the load with the use of this converter topology thus giving us better efficiency. The proposed converter circuit is provided with the Simple Auxiliary Resonant Circuit (SARC) which helps in operating all the switching devices with soft-switching under the conditions of zero-voltage and zero-current switching hence operating the circuit with negligible power loss [1]. The above proposed circuit works on the Maximum Power Point Tracking algorithm (MPPT).

The auxiliary circuit used here consists of auxiliary switch (S_2), a resonant capacitor (C_r), a resonant inductor (L_r) and two diodes (D_1 and D_2).

Converter Operation

This converter circuit has different operating modes which can be divided into six modes of operation. Thus for understanding each operating mode following assumptions are made for simpler analysis;

1. All the passive elements and switching devices used are ideal in nature.
2. All switching devices and elements have negligible parasitic components.
3. Range of the input voltage is from 150-230 V.
4. This converter operates in continuous conduction mode in all intervals.

Operating Modes

In this section, operation of the proposed converter topology during different intervals is shown. The total operating modes for this converter topology are six in number which are further discussed;

MODE 1:- Off State of S_1 and S_2 , ($t_0 \leq t \leq t_1$);

The circuit which is being proposed for the analysis of various operating modes is represented in figure 1. In this operating mode the load is provided with the energy from the main inductor (L_1). Both the switches i.e. the main switch (S_1) and the auxiliary switch (S_2) are in off state during this operating mode due to which current is not able to flow through these switches. Thus the energy which is stored in the main inductor during previous cycles is transferred to the load.

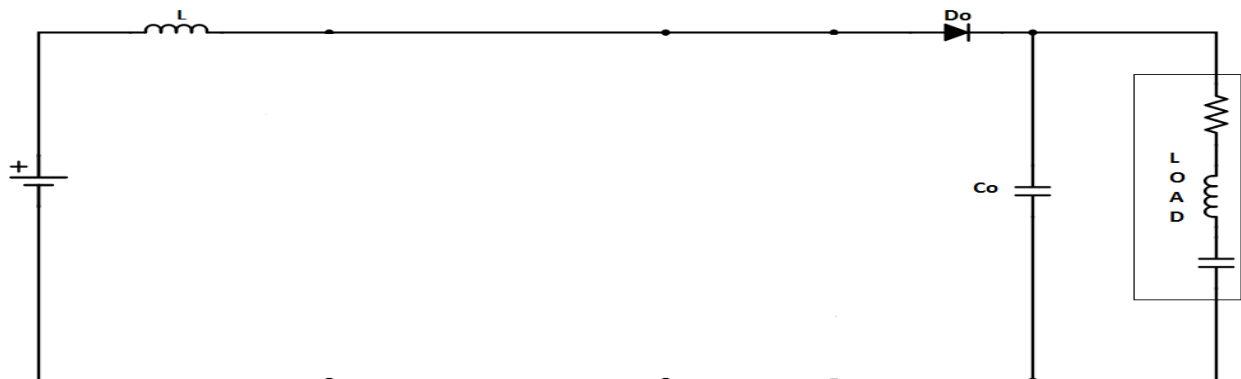


Figure 2: Equivalent circuit for the operation of mode 1.

From the above figure it is clearly seen that both the switches are in off state and the main inductor is providing the energy to the load. During this interval current of the main inductor linearly decreases. Also in this interval, no current flows through resonant inductor and the voltage across the resonant capacitor is equal to output voltage.

When the switches S_1 and S_2 are turn-on, then the end of the mode 1 takes place. The condition for this is given by;

$$v_L(t) = V_s - V_o \dots\dots\dots 1$$

$$i_L(t) = i_L(t_0) - \frac{V_o - V_s}{L} t \dots\dots\dots 2$$

$$i_{D0}(t) = i_L(t) \dots \dots \dots 3$$

$$i_{Lr}(t) = 0 \dots \dots \dots 4$$

$$v_{Cr}(t) = V_0 \dots \dots \dots 5$$

MODE 2:- Turn-On of S_1 and S_2 , ($t_1 \leq t \leq t_2$)

In this mode of operation, turning on of the switches S_1 and S_2 takes place and with this turn-on current starts flowing into the resonant inductor. In this interval turn-on of the switches S_1 and S_2 takes place under zero-current condition, and this condition is known as zero-current switching. ZCS during this interval can be achieved because of the main and auxiliary switches due to which the switching losses of this converter are lesser than the conventional hard-switching converters.

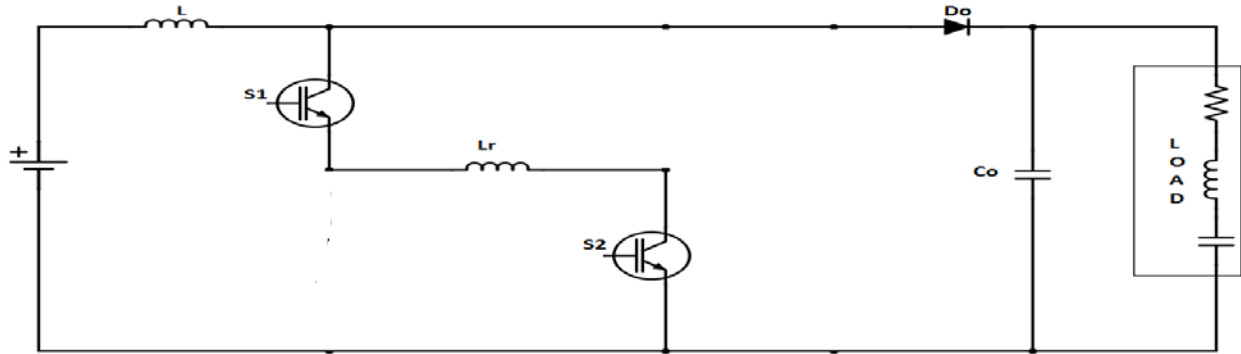


Figure 3: Equivalent circuit for the operation of mode 2.

From the above figure it is clearly seen that turn-on of the switches S_1 and S_2 is taking place and the energy is transferred to the load. There is the gradual fall in the load current with the linear increase in the resonant current. At instant t_2 , current of the main inductor equals current of the resonant inductor with zero current across the output diode. The end of the mode 2 takes place with the turning off of the output diode and when the resonant capacitor voltage equals output voltage V_0 .

$$i_{Lr}(t_1) = 0 \dots \dots \dots 6$$

$$v_{Lr}(t) = V_0 \dots \dots \dots 7$$

$$i_{Lr}(t) = \frac{V_0}{L_r} t \dots \dots \dots 8$$

$$i_L(t) = i_L(t_1) - \frac{V_0 - V_S}{L} t \dots \dots \dots 9$$

$$i_L(t_2) = i_{Lr}(t_2) \dots \dots \dots 10$$

$$i_{D0}(t_2) = 0 \dots \dots \dots 11$$

MODE 3:- ($t_2 \leq t \leq t_3$);

During this mode of operation the current which is flowing to the load through the output diode D_0 does not flows any longer. This condition occurs because at instant t_2 the resonant capacitor C_r and the resonant inductor L_r start a resonance.

The current which is fed to the resonant inductor is the total sum of current of main inductor and current through the resonant capacitor.

Total resonant current can be written as;

$$I_L(t) \approx I_{min} \dots \dots \dots 12$$

$$I_{Lr}(t) = I_{\min} + \frac{V_0}{Z_r} \sin \omega_r t \dots \dots \dots 13$$

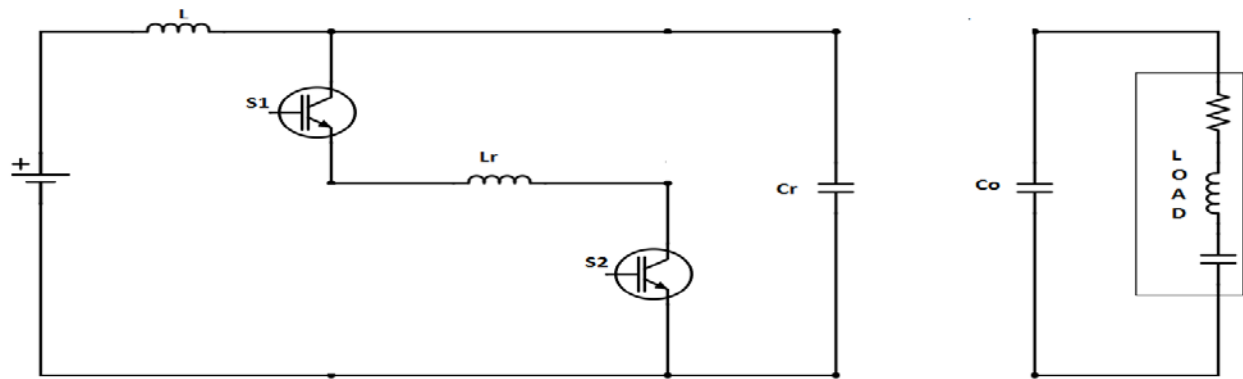


Figure 4: Equivalent circuit for the operation of mode 3.

The above figure shows operating mode between the interval t_2 and t_3 . It is clearly seen that the resonance condition is taking place through resonant capacitor C_r and resonant inductor L_r . In this resonant period, discharging of resonant capacitor C_r is taking place from V_0 to zero. This is shown below;

An equation (16) and (17) gives the resonant frequency and impedance. Mode 3 is over when the voltage across the resonant capacitor is zero.

$$v_{Cr}(t) = V_0 \cos \omega_r t \dots \dots \dots 14$$

$$v_{Cr}(t_2) = V_0 \quad v_{Cr}(t_3) = 0 \dots \dots \dots 15$$

$$\omega_r = \frac{1}{\sqrt{L_r C_r}} \dots \dots \dots 16$$

$$Z_r = \sqrt{\frac{L_r}{C_r}} \dots \dots \dots 17$$

MODE 4:- Freewheeling of D_1 and D_2 , ($t_3 \leq t < t_4$);

The beginning of this operating mode takes place when the resonance condition in mode 3 comes to an end when the voltage across the resonant capacitor becomes zero.

During this interval turning on of freewheeling diodes D_1 and D_2 takes place with the maximum value of the current through the resonant inductor.

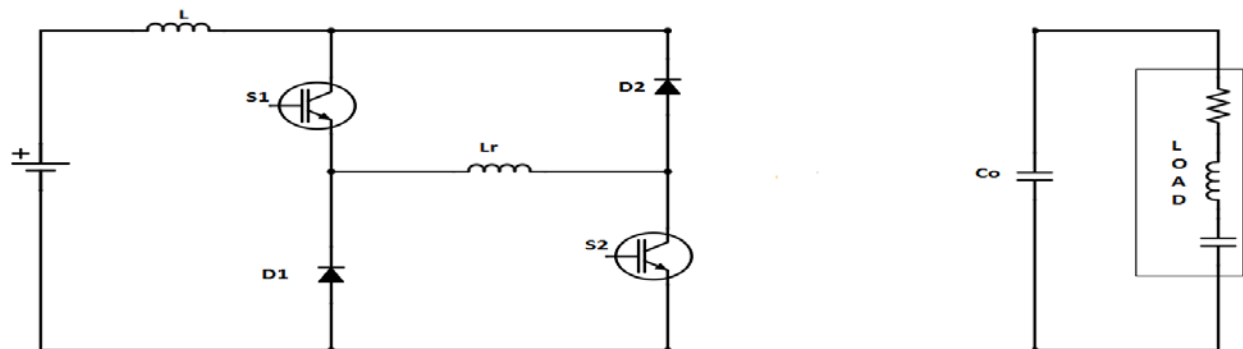


Figure 5: Equivalent circuit for the operation of mode 4.

The above figure shows the freewheeling of the diodes D_1 and D_2 . Also above shows the freewheeling paths $S_1 - L_r - D_2$ and $S_2 - L_r - D_1$ along which the current of resonant inductor is flowing to the freewheeling diodes;

$$i_{Lr}(t) = i_L(t) + i_{D1}(t) + i_{D2}(t) \dots \dots \dots 18$$

$$i_{Lr}(t_3) = i_{Lr}(t_4) = I_{Lr \max} \dots \dots \dots 19$$

In this time interval, voltage across the main inductor is equal to the input voltage with the linear increase in energy due to the accumulating current.

$$v_L(t) = V_s \dots \dots \dots 20$$

$$i_L(t) = I_{\min} + \frac{V_s}{L} t \dots \dots \dots 21$$

MODE 5:- Turn-Off condition, $(t_4 \leq t < t_5)$;

During this operating mode all of the switches in the circuit are turned off under the condition of zero voltage with the help of resonant capacitor.

In this interval, initial conditions of the current through the resonant inductor and voltage across the resonant capacitor are given as;

$$i_{Lr}(t_4) = I_{Lr \max} \dots \dots \dots 22$$

$$v_{Cr}(t_4) = 0 \dots \dots \dots 23$$

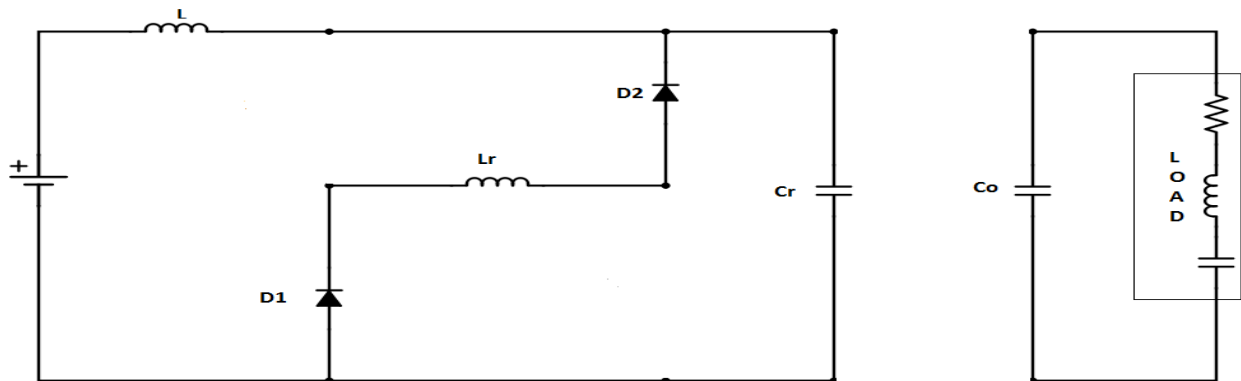


Figure 6: Equivalent circuit for the operation of mode 5.

The above figure clearly shows that during this interval all of the switches are in off state. And when turning off of all switches takes place, charging of the resonant capacitor C_r up to the output voltage takes place with two inductor currents. Also the off state of the output diode continuous, until the resonant capacitor is charged up to V_0 ;

$$i_L(t) \approx I_{\max} \dots \dots \dots 24$$

$$i_{Lr}(t) = I_{\max} - (I_{\max} + I_{Lr \max}) \cos \omega_r t \dots \dots \dots 25$$

$$v_{Cr}(t) = Z_r (I_{\max} + I_{Lr \max}) \sin \omega_r t \dots \dots \dots 26$$

$$v_{Cr}(t_5) = V_0 \dots \dots \dots 27$$

MODE 6:- $(t_5 \leq t < t_6)$;

Beginning of this operating mode takes place when the voltage of the resonant capacitor equals the output voltage V_0 and turning on of the output diode takes place with zero-voltage switching (ZVS).

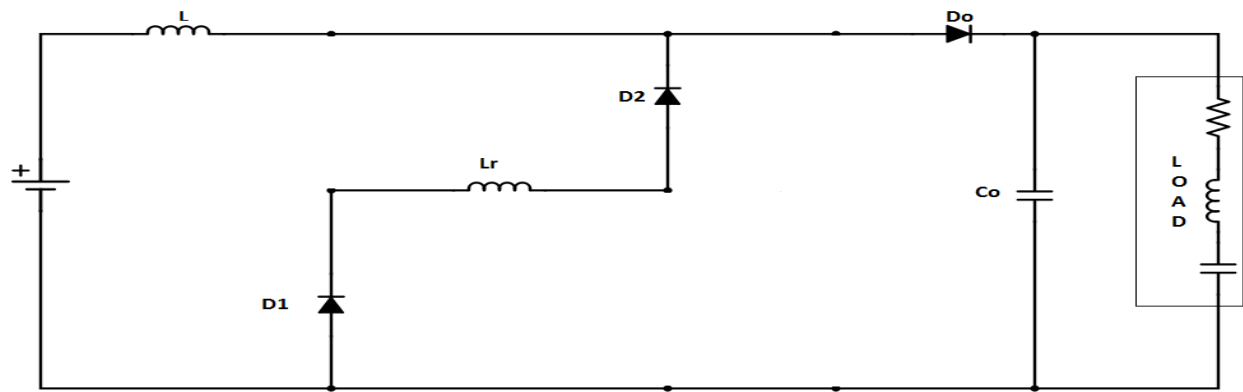


Figure 7: Equivalent circuit for the operation of mode 6.

Above figure shows the turning on of the output diode with zero-voltage switching. In this interval, current through the main inductor i_L and current through the resonant inductor i_{Lr} is flowing to the load through the output diode D_0 .

$$i_{D0}(t) = i_L(t) + i_{Lr}(t) \dots \dots \dots 28$$

$$i_{Lr}(t_5) = (I_{\max} + I_{Lr \max}) \cos \omega_r(t_5 - t_4) - I_{\max} \dots \dots \dots 29$$

$$v_{Cr}(t) = V_0 \dots \dots \dots 30$$

Ending up of the mode 6 takes place with the linear fall in two of the inductor currents and when the load is completely provided with the energy of the resonant inductor;

$$i_L(t) = I_{\max} - \frac{V_0 - V_S}{L_r} t \dots \dots \dots 31$$

$$i_{Lr}(t) = i_{Lr}(t_6) - \frac{V_0}{L_r} t \dots \dots \dots 32$$

$$i_{Lr}(t_6) = 0 \dots \dots \dots 33$$

3. Designing of the Proposed Circuit

Solar Cell and Module Characteristics:-

A solar cell can be defined as semiconductor device which is composed of p-n junction. The purpose of this device is to convert light energy to electrical energy.

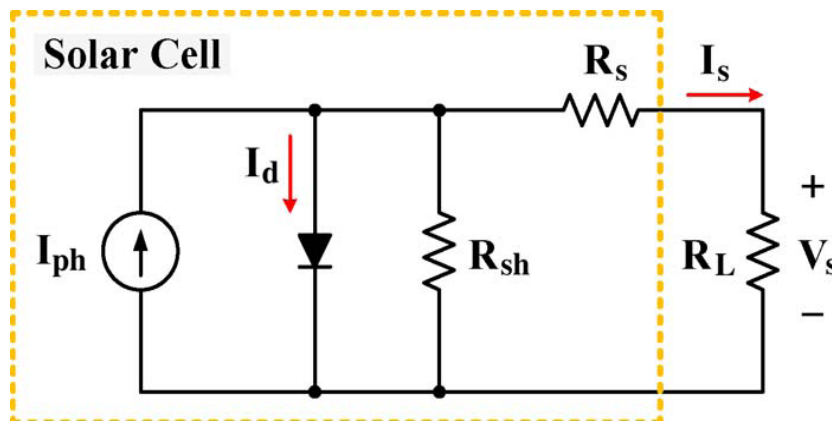


Figure 8: Equivalent circuit for the solar cell operation

As shown in the above figure, solar cell equivalent circuit comprises of internal series resistance (R_s) and the shunt resistance (R_{sh}) of the diode. Irradiance and operating temperature of the cell are the features on which the output characteristics of solar cell depend. These output characteristics of solar cell can be given as follows [2];

$$I_s = I_{ph} - I_{sat} \left[\exp \left(\frac{q(V_s + I_s R_s)}{AKT} \right) - 1 \right] - \frac{V_s + I_s R_s}{R_{sh}} \dots\dots\dots 34$$

In the above equation R_s is assumed to be zero and R_{sh} is assumed to be infinity, thus this equation can be written as [2];

$$I_s = I_{ph} - I_{sat} \left[\exp \left(\frac{qV_s}{AKT} \right) - 1 \right] \dots\dots\dots 35$$

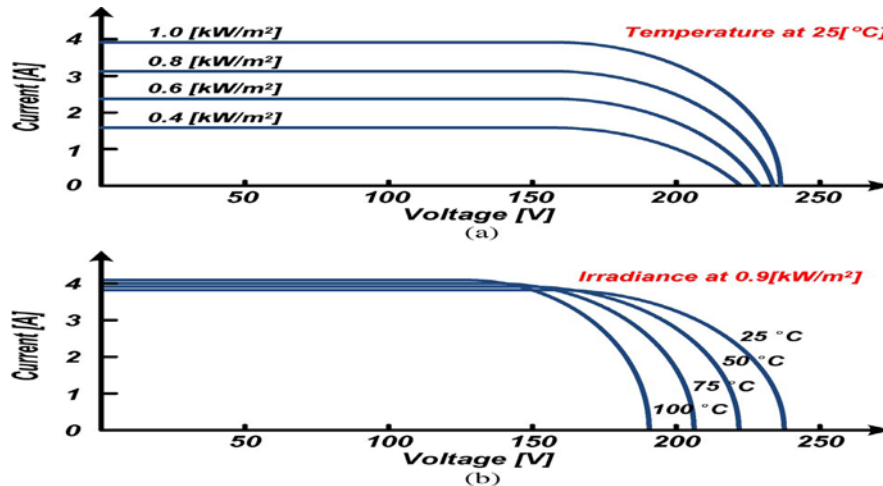


Figure 9: characteristic of solar cell

4. Resonant Inductor

The rising time of the current through resonant inductor which is shown in the above figure during the time of mode 2, is expressed by the equation below. To achieve the maximum resonant current, the duration of mode 3, which is the resonant inductor and capacitor resonant time, is only one-fourth of the whole resonant period [3]. Considering the thumb rule, the rising time of current through the resonant inductor (mode 2-3), can be set to 10% of the minimum on time. This is shown below;

$$t_3 - t_2 = \frac{L_r}{V_0} I_{min} \dots\dots\dots 36$$

$$t_4 - t_3 = \frac{T_r}{4} \dots\dots\dots 37$$

$$\frac{L_r}{V_0} I_{min} + \frac{T_r}{4} = 0.1 D_{min} T \dots\dots\dots 38$$

From the above equations the expression for resonant inductor is given as;

$$L_r < \left(\frac{2}{\pi} D_{min} T V_0 - V_{FW} D_{max} T \right) / \left(\Delta I_L + \frac{2}{\pi} I_{min} \right) \dots\dots\dots 39$$

5. Resonant Capacitor

Connection of the resonant capacitor to the switch is made in parallel. Due to this reason the waveforms of voltage across the resonant capacitor and switch are same during turn-off. The value of resonant capacitor should be ten times more than the output capacitance of the switch, so that the condition of ZVS is achieved. However, charging of the capacitor takes

place through the main inductor current and current through the resonant inductor during turn-off. Thus, the value of resonant capacitor can be twenty times more than the output capacitance of the switch. Above equation can be written as;

$$C_r = \frac{0.04 D_{min}^2 T^2}{\pi^2 L_r} + \frac{4 I_{min}^2 L_r}{\pi^2 V_o^2} - \frac{0.8 I_{min} D_{min} T}{\pi^2 V_o} \dots\dots\dots 40$$

The above two equations presents the design of resonant inductor and capacitor.

6. Result And Its Discussion

The circuit is simulated in the software of MATLAB. Simulink tool is used for the simulation.

Simulated Circuit

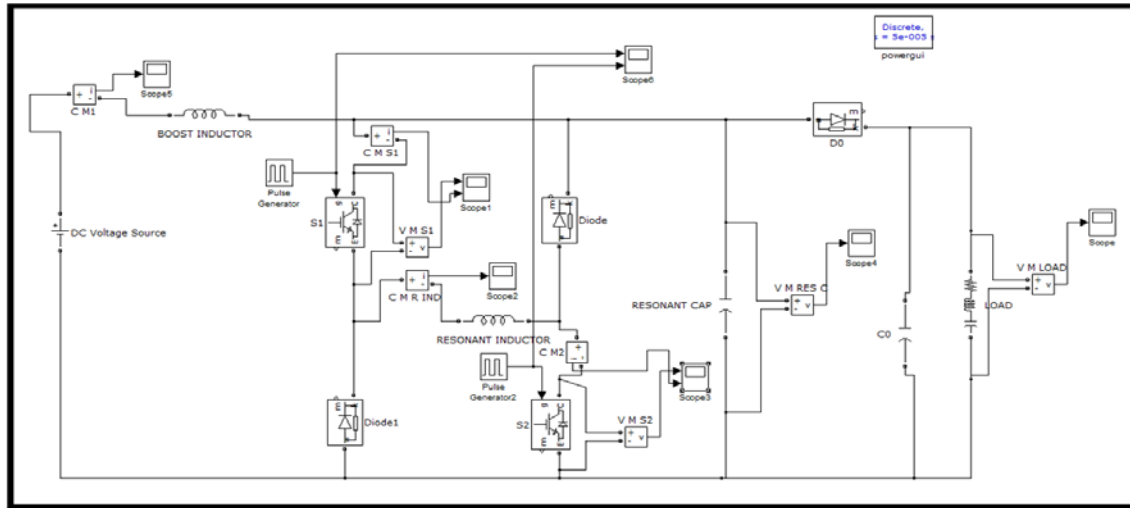


Figure 10: Proposed simulated circuit of SARC converter

The above circuit shows the proposed circuit of SARC converter which is simulated in MATLAB. **Table 1:** Converter specification and implementation detail

S.No	Component	Specification
1	Input Voltage	150 – 230 V
2	Switching Frequency	30 Khz
3	Main Switch S1	Fga15n120
4	Auxillary Switch S2	Fga15n120
5	Boost Inductor	560 Mh
6	Resonant Inductor	83 Mh
7	Resonant Capacitor	20 Nf
8	Auxillary Diodes	Dse120-12a
9	Output Diode	Dse120-12a
10	Output Capacitors	1mf

The above table shows the parameters of the simulated circuit. The circuit performs when the supply voltage is given to the circuit. The result shown below is the result when supply voltage is 160 V. the supply voltage or the voltage source taken in this is ideal DC voltage source. When the supply voltage is given to the circuit the current flows from source to the load via the boost inductor.

Switching frequency is a very important parameter for the switch. Basically switching frequency is responsible for the switching of the switches. In this work module the switching frequency is taken at 30 kHz

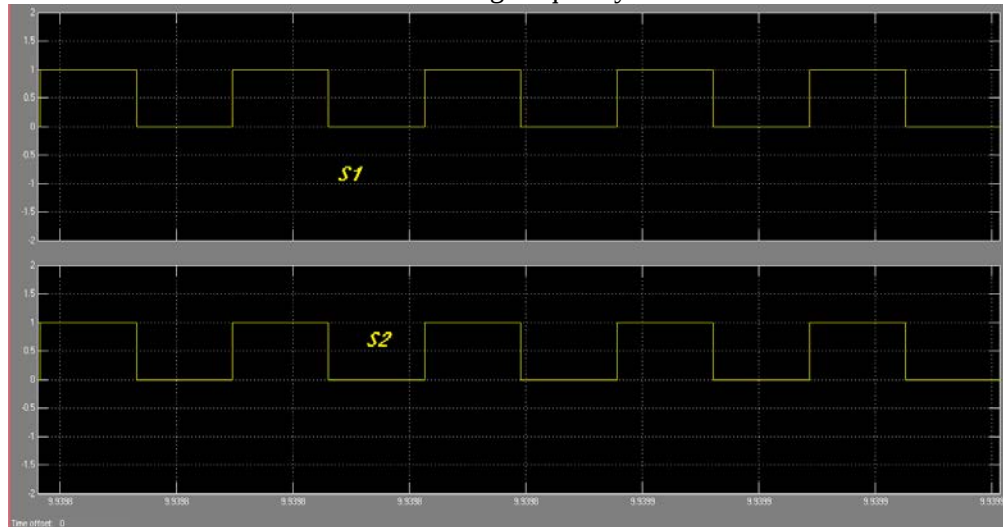


Figure 11: Switching pulse for the switch S1 and S2

The above shows the switching pulse given to the main and auxiliary switches. From the above figure we can say that the phase difference between the both switches is zero.

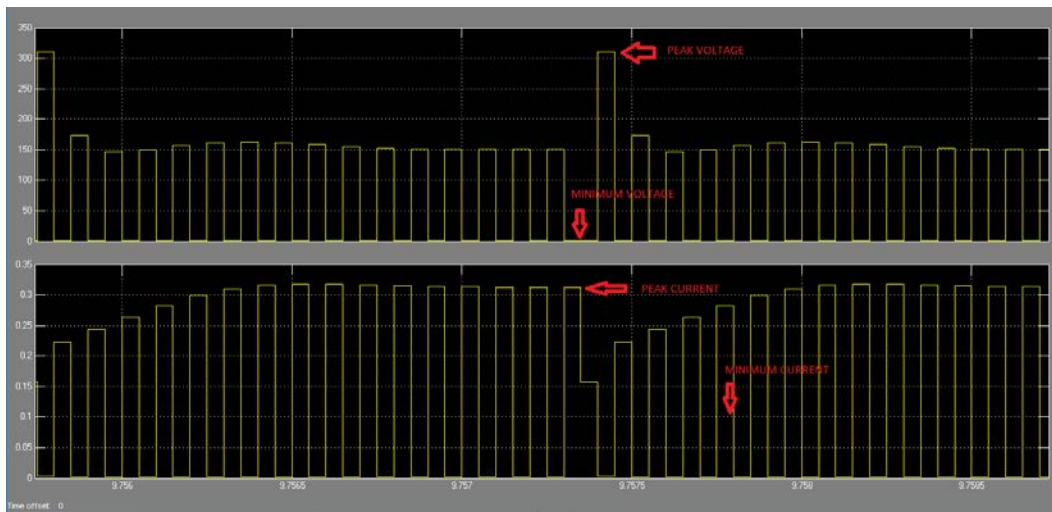


Figure: 12 Switching characteristic of switch S1

The above figure shows the voltage and current waveform of switch S1. The above figure is divided into two parts. The upper part of the figure is current characteristic of the across the switch S1 while the lower portion of the graph shows the voltage characteristic of the main switch S1. So from the figure it can be seen that when the current across the switch is maximum at that instant the voltage across the switch is minimum or zero. The same happens in the case of voltage. When the voltage across the switch is maximum then the current is minimum. And as we know that the power loss across the switch is given as the current across the switch product with the voltage across the switch at a particular instant. So if any of the above parameter is zero at the instant then the power loss due to the switching becomes zero. This technique of eliminating switching loss across the switch is known as soft switching.

The same characteristic is achieved in the auxiliary switch. The below figure shows the switching characteristic of the switch S2

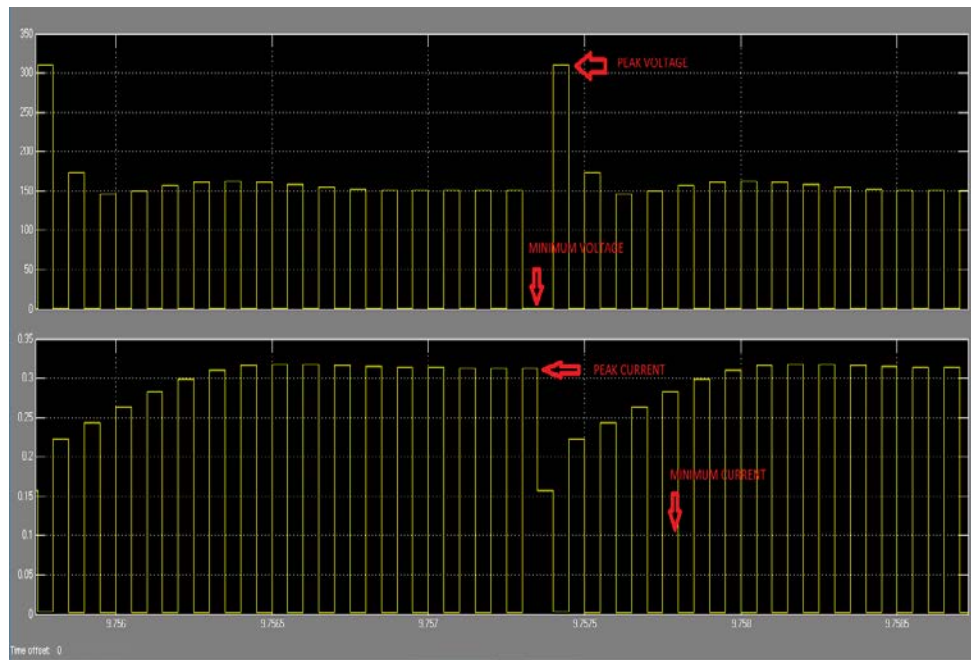


Figure: 13 Switching characteristic of switch S2



Figure: 14 Voltage across the load

The above figure shows the characteristic of load. The load connected across the converter is series RLC load. The resistance of the load is 10 ohm while the impedance is 183 ohm. The input to the circuit is 160 V and the output at the load terminal is 314 V. The above figure shows that the nature of the output voltage is almost DC as it is free from ripple.

The power output of the converter circuit can be given by:

$$\text{Power (P)} = V * I$$

Or

$$P = V^2 / Z$$

Where;

V = Output Voltage

Z = Load Impedance

As we know that the output voltage is 314 V and the load impedance is 183 ohm. So from this data the output power is given as

$$P = (314)^2 / 183$$

$$P = 538 \text{ Watt}$$

Simulated Circuit with PV Source

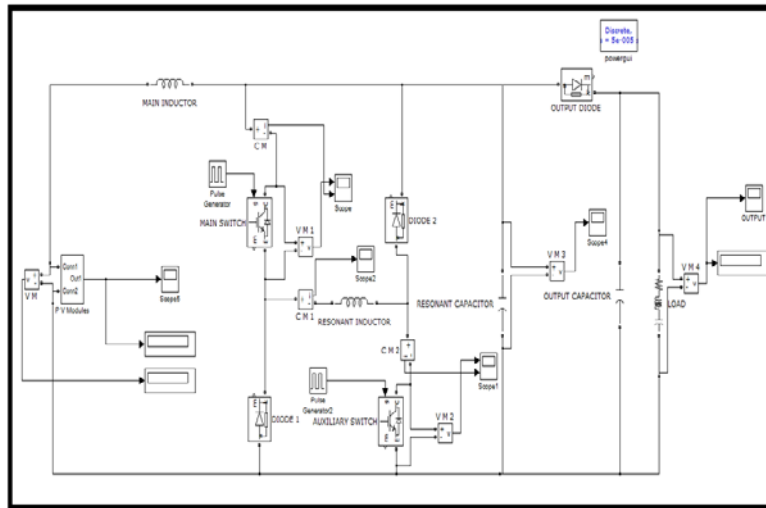


Figure 15: Proposed circuit with PV source

The above figure shown is the SARC converter with the PV source input. The output of the PV source is 12V and the supply is not always constant. Hence with help of MPPT and boost conversion it is used as supply source. To increase the output of PV a series connection of PV cell is used and hence the formation of PV array is formed. After the use of PV cell the input at source become 212 V. The behaviour of the circuit is with this supply is given in next section.

Result with PV Supply

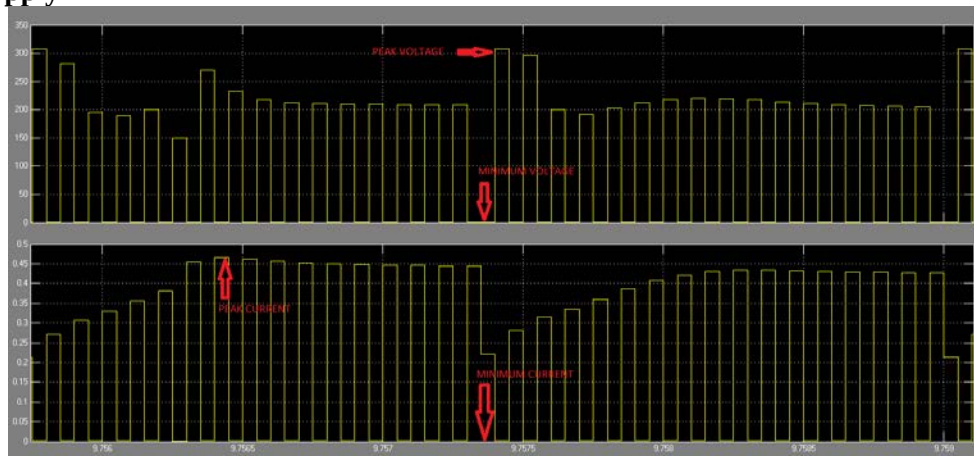


Figure 16: Switching characteristic of switch S1 with PV source

The above figure shows the voltage and current waveform of switch S1. The above figure is divided into two parts. The upper part of the figure is voltage characteristic of the across the switch S1 while the lower portion of the graph shows the current characteristic of the main switch S1. So from the figure it can be seen that when the current across the switch is maximum at that instant the voltage across the switch is minimum or zero. The same happens in the case of voltage. When the voltage across the switch is maximum, then the current is minimum. And as we know that the power loss across the switch is given as the current across the switch product with the voltage across the switch at a particular instant. So if any of the above parameter is zero at the instant then the power loss due to the switching becomes zero. The same characteristic is shown in fig 12 which indicates the process of soft switching. Hence it can be said that the soft switching is achieved in both cases of supply across the main switch.

However not only the main switch but also the auxiliary switch also perform same characteristic as with the ideal source.

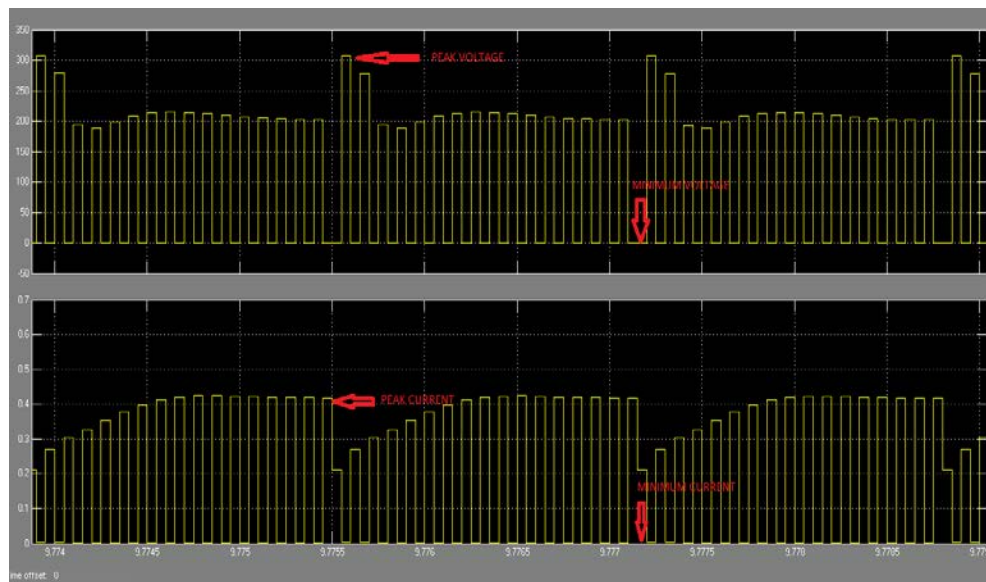


Figure 17: Switching characteristic of switch S2 with PV source

The above figure shows the voltage and current characteristic of auxiliary switch. Soft switching is occurring and that can be seen easily. So it can be seen easily that the switch behaves same as the source having ideal behaviour. However the load variation can be seen in little amount as it is compared with the ideal source.

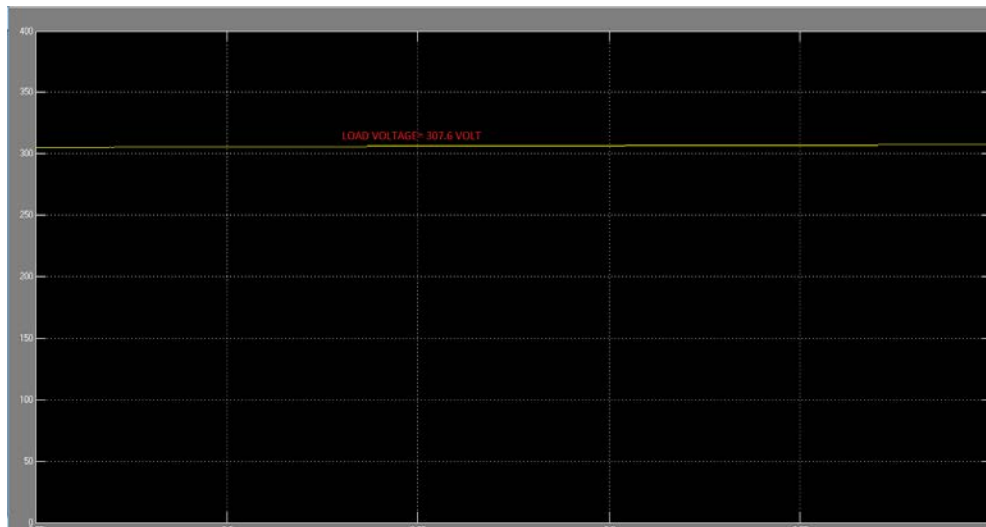


Figure 18: Load characteristic with PV source

The above figure shows the characteristic of load. The load connected across the converter is series RLC load. The resistance of the load is 10 ohm while the impedance is 183 ohm. The input supplied to the circuit is 212 V and the output at the load terminal is 307 V.

So from this data the output power is given as

$$P = (307)^2 / 183$$

$$P = 515 \text{ Watt}$$

7. Conclusion

The projected circuit is simulated and performed with help of simulation technique in the MATLAB software. The boost conversion is done properly. The soft switching is achieved with the help of resonant circuit called as SARC converter due to its simple construction. The auxiliary switches used in the SARC converter also achieve the soft switching results in lower power loss and total reduction in switching losses. The circuit is also validated with the PV source and the difference between the power output of converter and the output voltages is less than 2%.

8. Reference

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