

Soft Switching Boost Converter Solution for Increase the Efficiency of Solar Energy Systems

Alireza Kaviani-Arani^{*1}, Alireza Gheiratmand²

¹Department of Electrical Engineering, Majlesi Branch, Islamic Azad University, Isfahan, Iran

¹Shahid Rajaei Center, Department of Technical and Vocational Education in Isfahan Province

²Iran Technical and Vocational Training Organization

*Corresponding author, e-mail: A.Kaviani@iaumajlesi.ac.ir, A.Kaviani@etvto.ir

Abstract

Nowadays, renewable energies are considered as an important source of non-polluting and free energy. Solar energy in the form of photovoltaic systems is one of the most prominent of them. Using this type of energy can be an affordable and suitable solution to supply electricity to the consumers who do not have access to the distribution network due to geographical conditions. Regarding to low efficiency and high cost of installing solar panels, receiving the maximum power of them is taken into consideration. DC-DC converters are one of the key components of solar energy systems. These converters have the switching losses and their efficiency is not so high. This paper explores the switching losses in hard switching boost converter and by providing a soft switching boost converter, reduces switching losses and increases the efficiency of solar energy systems. The performance of the converter has been studied and simulations indicate its performance.

Keywords: boost converter, soft switching converters, hard switching converters, solar energy

Copyright © 2015 Institute of Advanced Engineering and Science. All rights reserved.

1. Introduction

Nowadays, with dwindling resources of fossil fuels and growth of the concerns about air pollution, the use of renewable energies is growing. Among these energies, solar energy could be a good alternative to the fossil fuels due to the availability, non-polluting, unlimited and low cost of the maintenance of the solar equipments. Besides the above advantages, the produced energy by these systems have some disadvantages such as high installation cost and low efficiency (about 9 to 16%). Since implementing solar systems are expensive and due to the nonlinearity of output characteristics of these arrays, using these systems efficiently is not possible without using power electronic converters and suitable control methods. Several methods are suggested to increase the efficiency of solar systems and receiving the maximum power of them which are referred as Maximum Power Point Tracking (MPPT). The major difference between the above mentioned methods is in the indexes such as convergence speed, oscillations around the point of maximum power in steady-state, implementation cost and complexity and number of the required measurement equipments [1].

Connecting photovoltaic systems to the electrical grid is usually done using a DC-DC converter and an inverter (Figure 1). DC-DC converter is applied with control strategy to following the maximum power point of the array. In this paper, we have used the boost converter. The efficiency of these systems are low, but the efficiency could be increased in two ways, one by using following maximum power point method and the other is using the functionality of switching supplies.

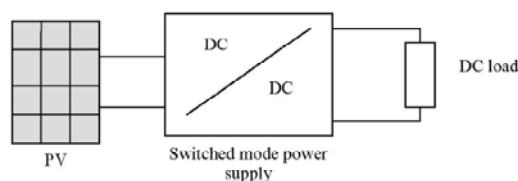


Figure 1. The components of photovoltaic system and their connection to the network

Due to the high switching losses, hard switching DC-DC converters don't have a good efficiency. Also, their switching frequency is low. By the soft switching methods, the switching frequency of the converter could be increased and the switching losses could be decreased. By increasing the frequency of the converter, the size of the converter is decreased and also the electromagnetic interference (EMI) is prevented [2].

In this paper, both hard switching boost converter and soft switching boost converter which are used in solar energy systems are studied. Switching losses in the hard switching converter are calculated and indicates that using soft switching methods, switching losses could be decreased, resulting in increased efficiency.

2. Evaluation and Selection of Indicators for DG Installation

A solar panel is a collection of photovoltaic cells that are connected in series or in parallel with each other. Each PV cell is a p-n semiconductor junction that converts solar radiation energy to the electrical energy. An equivalent circuit model for PV cell is shown in Figure 2, in which I_{ph} indicates photodiode current, R_j , R_{sh} and R_s are respectively nonlinear impedance of p-n junction, inherent shunt impedance and series resistance within the cell. R_s resistance is very small and R_{sh} resistance is very large, thus to simplify the circuit, both can be neglected.

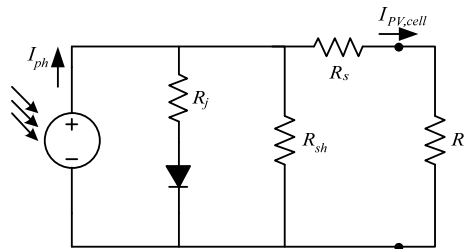


Figure 2. equivalent circuit of a solar cell

According to the equivalent circuit of the PV cell, the output current of the PV array is as follows:

$$I_{PV} = N_p I_{ph} - N_p I_{sat} \left[\exp\left(\frac{q}{nkT} \frac{V_{PV}}{N_s}\right) - 1 \right] \quad (1)$$

In which I_{PV} and V_{PV} are the current and voltage of the PV array, N_s and N_p are the number of cells in series and in parallel, q is the charge of each electron ($1.6 \cdot 10^{-19}$ Coulomb), k is the Boltzmann's constant ($1.38 \cdot 10^{-23}$ J/°K), T is the temperature of the PV array (°K) and n is the ideal p-n junction coefficient (between 1 to 5). In addition, I_{sat} refers to the inverse saturation current of a PV cell, which is dependent on the PV array temperature and can be calculated using the following equation:

$$I_{sat} = I_0 \times \left(\frac{T}{T_0}\right)^{\frac{3}{n}} \times \exp\left[\frac{qE_{gap}}{nk} \left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \quad (2)$$

In which, T_0 is the cell reference temperature, I_0 is inverse saturation current of cell at T_0 and E_{gap} is the voltage of the semiconductor air gap in PV array. In Equation (1), I_{ph} varies with changing the radiation dose S_i and array temperature T . That can be analyzed as follows:

$$I_{ph} = I_{SC T_0} \times S_i + K_i (T - T_0) \quad (3)$$

In which, $I_{sc,T0}$ is the short circuit current of the array in T_0 temperature and K_i is the temperature coefficient. According to the Equation (1), the output power of the PV array (P_{PV}) can be identified as follows:

$$P_{PV} = I_{PV}V_{PV} = N_p I_{ph} V_{PV} - N_p I_{sat} V_{PV} \left[\exp\left(\frac{q}{nkT} \frac{V_{PV}}{N_s}\right) - 1 \right] \tag{4}$$

This equation shows that the produced power P_{PV} depends on the radiation dose S_i and temperature T of the PV array [3-4].

3. Hard Switching Boost Converter

Boost converter is shown in Figure 3. Here solar cell is modeled with a voltage source. When the key is turned on, the inductor current increases linearly and the diode D is off. When the key is turned off, the energy stored in the inductor is transferred to the load through D. The input inductor must be large enough so the input current could be ripple-free. For CCM mode L should be $L > L_{min}$. While the diode is off, the capacitor provides the load current so the capacitor should be large enough so that its voltage remains constant. For boost model, we have the equations below [5]:

$$V_{dc} = \frac{V_{in}}{1 - D} \tag{5}$$

$$L_{min} = \frac{D(1 - D)^2 R}{2f_s} \tag{6}$$

$$C > \frac{D}{Rf_s \left(\frac{\Delta V_o}{V_o}\right)} \tag{7}$$

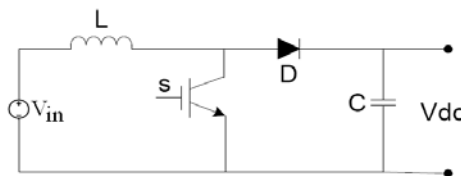


Figure 3. The boost converter

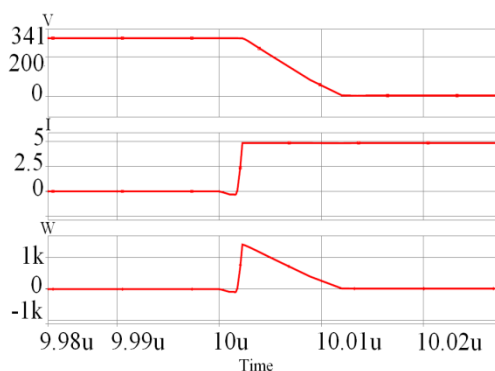


Figure 4. Voltage, current and power losses during turning on the key

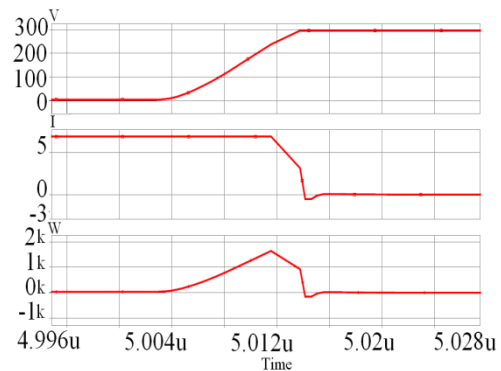


Figure 5. Voltage, current and power losses during turning off the key

In hard switching boost converter, the voltage of the key decrease and the current begins to rise, while turning on the key. And the current of the key begins to decrease and voltage to increase while turning off the key. At these switching times, there is an overlap between voltage and current of the key and thus switching losses arise. Voltage, current and power losses in the boost converter during turning on the key is indicated in Figure 4. Also the voltage, current and power losses during turning off the key is shown in Figure 5.

4. Soft Switching Boost Converter

In soft switching methods, a high frequency resonator circuit is added to the above mentioned hard switching circuit. The resonance circuit may include only L and C elements or it may include additional elements such as key and diode. Therefore, the voltage and current oscillate and cross zero point and as a result provides the soft switching conditions for the power switches. By the resonance circuit, switch waveform is built in a way that minimize the switching losses, decrease the switching stress and prevent EMI resulting in improvement in the efficiency of the circuit. Various techniques of soft switching boost converter have been proposed so far and extensive researches in this area are ongoing [6].

The proposed soft switching boost converter is indicated in Figure 6. An inductor, two capacitors and two diodes are added to the hard switching boost circuit. This converter has only one key and using resonance this key could turn on or off at zero voltage switching (ZVS) and zero current switching (ZCS) condition. The operation of the circuit includes 7 steps as follows. The waveforms of the operation of the circuit are indicated in Figure 7.

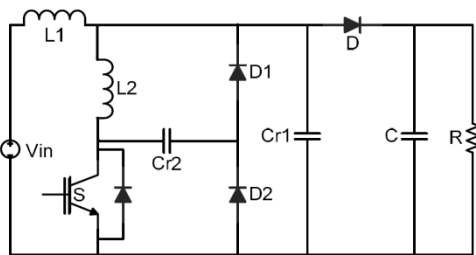


Figure 6. Soft switching boost converter

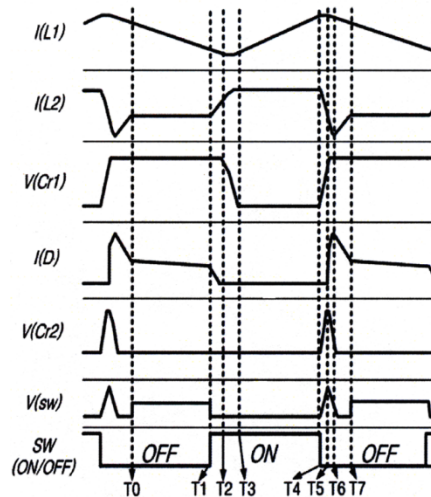
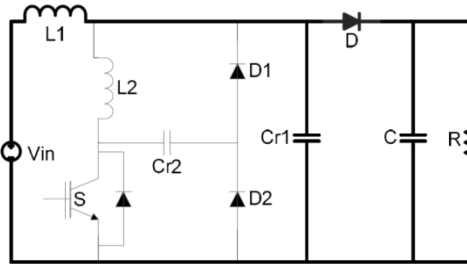


Figure 7. Waveforms of the converter

4.1. State 1- $t_0 < t < t_1$:

In this state, the key is off and the output DC current of the solar panel directly transferred to the load through L_1 and D. At this time, the current of the main inductor begin to decrease. Considering initial conditions $i_{L2}(2) = 0$, $V_{Cr1}(t) = V_o$ and $V_{Cr2}(t) = 0$ we have the following equation:

$$i_{L1}(t) = i_{L1}(t_7) - \frac{V_o - V_{in}}{L_1} t \tag{8}$$

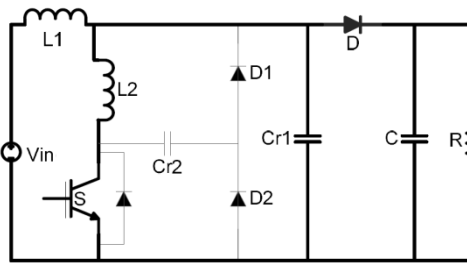
Figure 8. Equivalent circuit for each $t_0 < t < t_1$

4.2. State 2- $t_1 < t < t_2$:

At the beginning of this state, the key in the condition of ZCS (due to L_2 inductor) turns on. The current of the L_2 inductor begins to increase linearly. As the current of the L_2 becomes equal to the current of the L_1 , this state ends.

$$i_{L_2}(t) = \frac{V_o}{L_1} t \quad (9)$$

$$i_{L_1}(t) \cong I_{\min} \quad (10)$$

Figure 9. Equivalent circuit for each $t_1 < t < t_2$

4.3. State 3- $t_2 < t < t_3$:

When the current of the L_2 becomes equal to the current of the L_1 , diode D goes off and this state starts. At this moment resonance between capacitance C_{r1} and inductor L_2 is started and the voltage of the capacitance C_{r1} decreases and at the end of this state, it reaches zero. Also the current of the load is fed from the output capacitance.

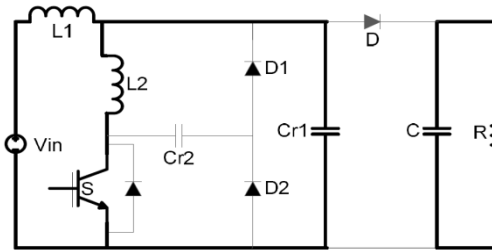
$$i_{L_1}(t) \cong I_{\min} \quad (11)$$

$$i_{L_2}(t) = I_{\min} + \frac{V_o}{z_1} \sin(\omega_1 t) \quad (12)$$

$$V_{C_{r1}}(t) = V_o \cos(\omega_1 t) \quad (13)$$

$$\omega_1 = \frac{1}{\sqrt{L_2 C_{r1}}} \quad (14)$$

$$z_1 = \sqrt{\frac{L_2}{C_{r1}}} \quad (15)$$

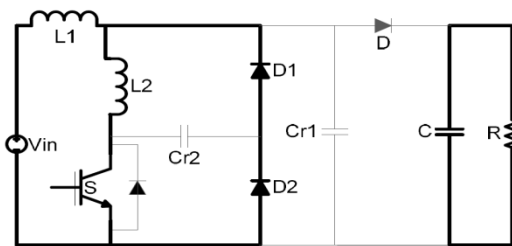
Figure 10. equivalent circuit for each $t_2 < t < t_3$

4.4. State 4- $t_3 < t < t_4$:

As the voltage of the capacitance C_{r1} becomes zero, diodes D_1 and D_2 turn on. The current of the inductor L_2 remains constant in this mode and the current of the inductor L_1 increases linearly.

$$i_{L1}(t) = I_{\min} + \frac{V_{in}}{L_1} t \quad (16)$$

$$i_{L2}(t) = i_{L2}(t_3) \quad (17)$$

Figure 11. Equivalent circuit for each $t_3 < t < t_4$

4.5. State 5- $t_4 < t < t_5$:

At the beginning of this state, we turn off the key at ZVS condition. In this case, two separate circuits are formed. The current of the L_1 inductor charges C_{r1} capacitance and make the voltage of C_{r1} capacitance to be increased to the output voltage. Also the resonance between L_2 and C_{r2} cause charging the capacitance and the current of the inductor L_2 becomes zero.

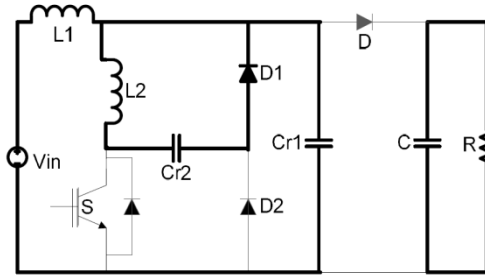
$$i_{L1}(t) \cong i_{L1}(t_4) \quad (18)$$

$$i_{L2}(t) = i_{L2}(t_3) \cos(\omega_2 t) \quad (19)$$

$$V_{Cr2}(t) = z_2 i_{L2}(t_3) \sin(\omega_2 t) \quad (20)$$

$$\omega_2 = \frac{1}{\sqrt{L_2 C_{r2}}} \quad (21)$$

$$z_2 = \sqrt{\frac{L_2}{C_{r2}}} \quad (22)$$

Figure 12. Equivalent circuit for each $t_4 < t < t_5$

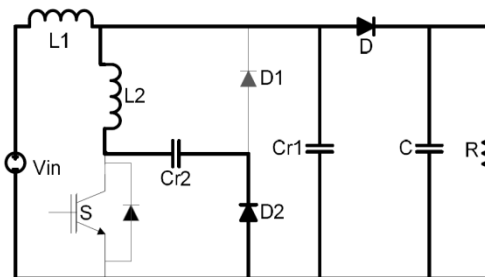
4.6. State 6- $t_5 < t < t_6$:

At the beginning of this state, the capacitance C_{r2} is charged to its maximum voltage and the current of the inductor L_2 is zero. At this moment, the resonance between L_2 and C_{r2} cause the energy of the capacitance to be transferred to the inductor and the current of the inductor L_2 begins to rise in the opposite direction. At the end of this state, the voltage of C_{r2} becomes absolutely zero.

$$i_{L1}(t) = i_{L1}(t_5) - \frac{V_o - V_{in}}{L_1} t \quad (23)$$

$$i_{L2}(t) = \frac{V_o i_{L2}(t_3)}{z_2} \sin(\omega_2 t) \quad (24)$$

$$V_{Cr2}(t) = V_o - (V_o - z_2 i_{L2}(t_3) \cos(\omega_2 t)) \quad (25)$$

Figure 13. Equivalent circuit for each $t_5 < t < t_6$

4.7. State 7- $t_6 < t < t_7$:

In this state, inverse parallel diode of the key turned on and transfer the current of the L_2 to the load and finally its current becomes zero. In addition L_1 transfer energy to the load by diode D and its current decreases [7].

$$i_{L1}(t) = i_{L1}(t_6) - \frac{V_o - V_{in}}{L_1} t \quad (26)$$

$$i_{L2}(t) = \frac{i_{L2}(t_6)}{L_2} t \quad (27)$$

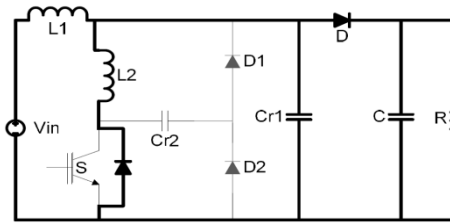


Figure 14. Equivalent circuit for each $t_6 < t < t_7$

5. Control Circuit

Measured values of the output voltage and current of the solar cell and output voltage of the boost converter are given to the controller. The output power of the solar cell and reference power MPPT are compared and after passing the controller, the converter output reference voltage is made. This value is compared with the output voltage of the converter and the pulses for the switch gate are made. Overview diagram is shown in Figure 15 [8-9].

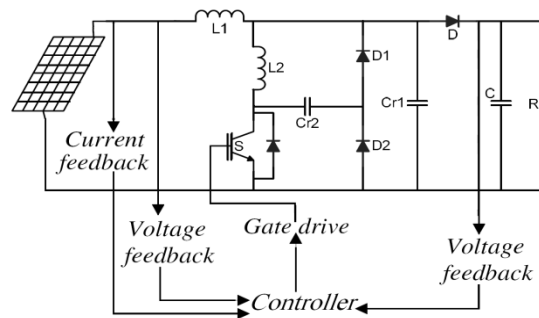


Figure 15. Overview diagram of the solar cell connected to the converter

6. Simulation

The simulation is performed by PSIM software. Voltage and current of the key is indicated in Figure 16. As it is obvious, the key is turned on in ZCS mode and is turned off in ZVS mode. Therefore the switching losses are minimized [10].

The current of the L_2 is indicated in Figure 17 and Figure 18 shows the current of the L_1 . Based on the status of the key, the current of L_1 is increased and decreased linearly. Also based on the resonance the current of L_2 is increased and absorbs the energy and by turning off the key, this energy returns back to the circuit.

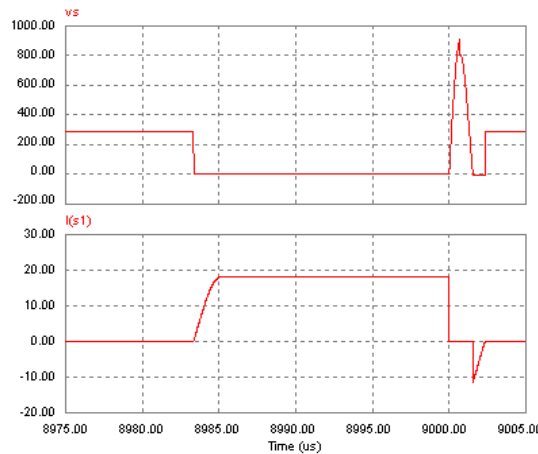
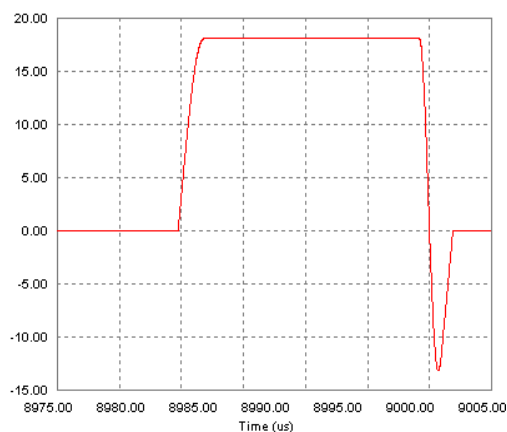
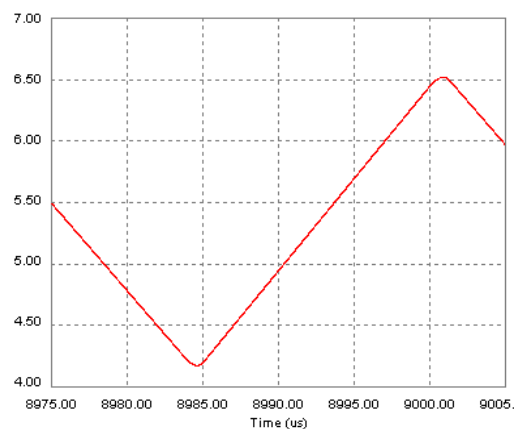


Figure 16. Voltage (above) and Current (below) of the key

Figure 17. Current of the inductor L_2 Figure 18. Current of the inductor L_1

7. Conclusion

Switching losses in hard switching boost converters which is used in solar cells are high and because of this, solar power systems have low efficiencies. By using soft switching methods these losses can be eliminated, thus the efficiency of the converter could be increased. Suggested converter has only one key and is turned on and off in soft mode. The performance of the converter is fully described and simulations affirm its performance.

References

- [1] Samosir, Ahmad Saudi, NFN Taufiq, Abdul Halim Mohd Yatim. Simulation and Implementation of Interleaved Boost DC-DC Converter for Fuel Cell Application. *International Journal of Power Electronics and Drive Systems (IJPEDS)*. 2011; 1(2): 168-174.
- [2] Carrasco, Juan Manuel, Leopoldo Garcia Franquelo, Jan T Bialasiewicz, Eduardo Galván, RC Portillo Guisado, Ma AM Prats, José Ignacio León, Narciso Moreno-Alfonso. Power-electronic systems for the grid integration of renewable energy sources: A survey. *Industrial Electronics, IEEE Transactions on*. 2006; 53(4): 1002-1016.
- [3] Shahinzadeh, Hossein, Mohammad Moien Najaf Abadi, Mohammad Hajahmadi, Ali Paknejad. Design and Economic Study for Use the Photovoltaic Systems for Electricity Supply in Isfahan Museum Park. *International Journal of Power Electronics and Drive Systems (IJPEDS)*. 2013; 3(1): 83-94.
- [4] Shahinzadeh, Hossein, Farhad Maghzian, Sayed Amin Feghhi, Omid Nematollahi, Mohammadreza Radmanesh. Reduction of Energy Consumption Through using Solar Heating and Ventilation. *International Journal of Engineering Research and Applications (IJERA)*. 2012; 2(3): 1260-1264.
- [5] Yao, Gang, Alian Chen, Xiangning He. Soft switching circuit for interleaved boost converters. *Power Electronics, IEEE Transactions on*. 2007; 22(1): 80-86.
- [6] Park, Sang-Hoon, Gil-Ro Cha, Yong-Chae Jung, and Chung-Yuen Won. Design and application for PV generation system using a soft-switching boost converter with SARC. *Industrial Electronics, IEEE Transactions on*. 2010; 57(2): 515-522.
- [7] Shangguan, Xuanfeng, Huimin Yang, Yongliang Wang, and Benlong Shi. The Design and Simulation of Improved and Multiplex Boost Converter. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(4): 2599-2605.
- [8] Galam, Sesha Giri Rao, S Raghu, N Rajasekaran. Design of Feedback Controller for Boost Converter Using Optimization Technique. *International Journal of Power Electronics and Drive Systems (IJPEDS)*. 2013; 3(1): 117-128.
- [9] Soomro, Amir Mahmood, Amjad Ali Syed, Shahnawaz Farhan Khahro, Xiaozhong Liao, Farhan Manzoor. A Stable Control Strategy for Input-Series Output-Series Connected Boost half Bridge DC-DC Converter. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(1): 72-79.
- [10] Kumar, K Vinoth, S SURESH KUMAR, S DAISON STALLON. High Efficient Module of Boost Converter in PV Module. *International Journal of Electrical and Computer Engineering (IJECE)*. 2012; 2(6): 758-765.