Design and Implementation of Buck-Boost Converter for Residential PV Application

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Abstract: Solar based renewable power generation is more important to compensate fossil fuel power generation. It is necessary to implement Maximum Power Point Tracking (MPPT) system to reduce cost of PV array system by decreasing the number of solar panel required to generate the power. Since the solar power fluctuates with the sunlight's intensity, it requires conversion to maintain the desired voltage like inverters. In this paper, a series compensation scheme is suggested. Perturbation and observation (P&O) algorithm of MPPT. A single stage architecture of photovoltaic generators which is used for residential applications are incapable to boost the voltage of the PV modules and also provides deficient input voltage range in spite of providing deplete power loss. This research work proposes a series connection of buck-boost converter which operates only in buck mode and also processes a fraction of the power input from the inverter while operating at high efficiency. This inverter focused SPWM pulses and produces pure sine wave as output. The duty ratio is decreased to less than 0.5 hence switching losses also reduced. The proposed logic is carried out in simulation and hardware setup of 480W prototype and the results were analyzed to enhance the advantage of the series compensation approach.

Keywords: Buck-Boost Converter, Solar Panel, Battery, Inverter, Series Compensation, MPPT

1. Introduction

Solar power generation has a greater perspective in our country. Due to atmospheric concerns, residential applications of continuous administrative strategy Solar Photovoltaic (PV) technology have been enhanced. Government has taken efforts to upgrade the power demand for the nation. But Generation of electricity is not as much the demand due to the shortage of generation. The rural areas are mainly affected without electricity. To compensate the demand Photovoltaic power has gained more attention by its quality of power which is provided to residential and industrial customers. Gujarat has a greater capacity in solar power generation in which sunlight is converted into electricity without pollutant emission and includes solar radiation and cell temperature of PV as the environmental parameters.

Power conditioners are used to enhance the solar power generation in single stage or two stage configurations exclusively for residential areas [1-2]. Single stage utility has lower power level (< 5kW) and has single phase PWM inverter between PV module and grid. It gives higher efficiency and power density with low cost. The single stage configuration is generally tailored around a single phase PWM operated by full bridge inverter. No electrical isolation is provided between the PV modules and the grid. Moreover, the grid inverter is tasked either to invert the PV string dc output voltage, or to accomplish the MPPT (Maximum Power Point Tracking). Resonant type converters, which are zero current switching or zero voltage switching, has a good solution to obtain high efficiency [3-4]. Particularly, the resonant converter is suitable for the dc-dc converter because the dc-dc converter requires high switching frequency in order to realize downsizing and high speed output voltage response. However, the number of parts in the circuit increases since the resonant converters requires an additional inductor or capacitor. Moreover, the voltage and current rating of the dc-dc converter are dominated by the output voltage and current rating in conventional dc-dc converters.

Received: October 12nd, 2017. Accepted: December 23rd, 2017

DOI: 10.15676/ijeei.2017.9.4.15

Power conversion in high frequency is done in two stage configuration which includes cascade connection of dc-dc step up converter and bridge inverter with dc link in the middle. DC-DC converter can be a transformer less non-isolated type or a high frequency transformer isolated type. Non isolated single stage power conditioners are generally more efficient than their two stage counterparts. When the strings of PV modules are directly connected to the grid inverter, the numbers of power processing steps are basically halved and a greater efficiency is achieved. However, some additional problems in practice arise when such configuration is used in PV plants for residential applications. In fact, due to the small power size generally less than 3 kW, only a limited amount of PV modules can be connected in series to form a string feeding the power conditioner. As a result, the inverter input dc voltage may be insufficient for a direct dc/ac inversion, especially when the temperature of the PV modules exceeds at 40-45^{O}C. In order to expand the input voltage range, a step-up dc-dc converter is often introduced between the PV array and the inverter, for a two stage configuration. It enables the implementation of the MPPT which is independent from the delivery of the electrical power to the grid.

Further alternatives are represented by single stage configurations with an inner voltage boosting capability [5-6] as the flying inductor converter or by some topologies mixing single and two stage operational modes. An example of the last type is the time-sharing dual mode single-phase quasi-sine wave PWM inverter [7]. It is composed of cascaded connection of a boost converter and a full bridge inverter, but it features a quasi-single stage operational mode. In fact, when the input dc voltage is insufficient to produce the required grid ac voltage. The power optimizer activates only one of the two stages at a time to control the output ac voltage. In some battery applications, the output voltage is regulated by the dc-dc converter as the output voltage which is close to the input voltage. In this case, the conventional dc-dc converter has to convert all power regardless of the output voltage because the conventional converter is connected in parallel to power supply and a load. A further viable solution is this paper based on the series compensation approach [8-9].

A series compensation approach of buck-boost type dc-dc converter is projected in which PV string series are connected than cascaded connection. Difference between the PV string output dc voltage and inverter input voltage is provided by converter. Transfer of electric power takes place mostly between PV modules to the inverter. Power rating of the converter is less than PV generator but has greater efficiency by delivering lossless power to the inverter. When PV string output voltage increases, power processed by converter reduces and hence voltage is sufficient for dc/ac inversion. In this similar way battery can be used for charging and discharging purpose when PV failure occurs. This type of system is particularly used in residential applications.
The organization of the paper is as follows: The need of solar power is explained in section 1 and the process description is explained in section 2. The Series compensation method has been explained in section 3 and the operation of series compensation topology discussed in section 4 .The operation of series compensation scheme buck-boost converter is discussed in section 5. The results and conclusion are discussed in section 6 and 7.

2. System Description

The block diagram of the testing system is shown in figure 1. The system consists of the following major components such as the solar panel, dc-dc converter with MPPT, battery, single phase inverter with SPWM and transformer. Constant voltage is maintained at the inverter by varying PV output voltage in accordance with the load. DC-DC converter and inverter input are connected to PV panel. Converter and PV source are connected in series. To maximize the power output from PV module, MPPT is connected to dc-dc converter. Electrical storage batteries are used in the system to store electrical energy when it is produced by the PV array and to supply energy to electrical loads as needed or on demand. Here the single phase inverter is used. The gate pulse to the inverter is given by SPWM technique which decreases the harmonics at the output of the inverter. To get a pure sinusoidal waveform, passive filter is connected after the inverter. Voltage from the inverter is not sufficient to run the loads, because the output voltage from inverter is around 72 volts. Since all loads are designed to 230 volts, to step up the voltage from inverter output to 230 volts, it requires the use of transformer. Here the 51/230V step up single phase transformer is used to run loads, as voltage from inverter is not sufficient for practical conditions.

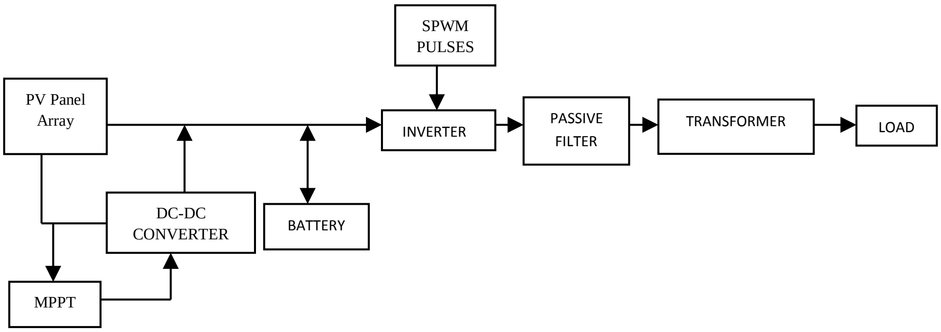
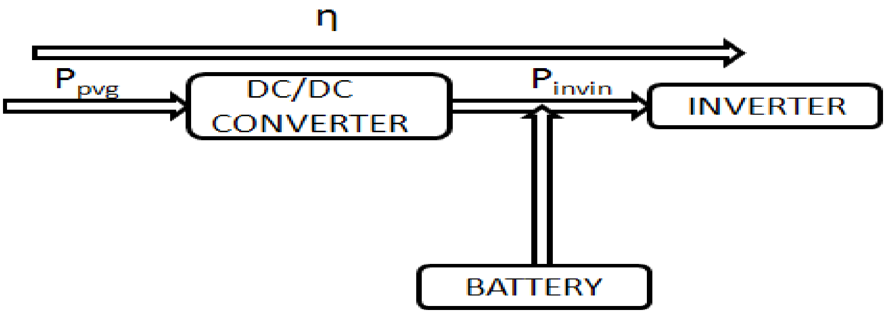


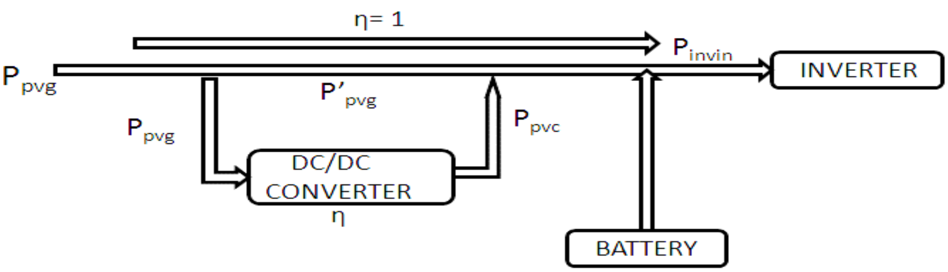
Figure 1. Block diagram of the system

DC-DC converter is used as a cascade of step-down converter and step up converter. It operates as boost converter when duty cycle is more than 0.5 and it operates as buck converter when duty cycle is less than 0.5. The boost chopper is used to generate the output ac waveform, when ac voltage exceeds the input dc voltage. It produces a segment of sinusoidal voltage. Inverter gives the polarity to the output voltage at line frequency which gives sinusoidal output voltage. Boost chopper is activated when the inverter is operated at direct dc output voltage of the PV string. During boost chopper circuit activation and deactivation there is no power or switching losses produced. The total efficiency of the power processor is similar to that of single stage configuration.

3. Series Compensation Method

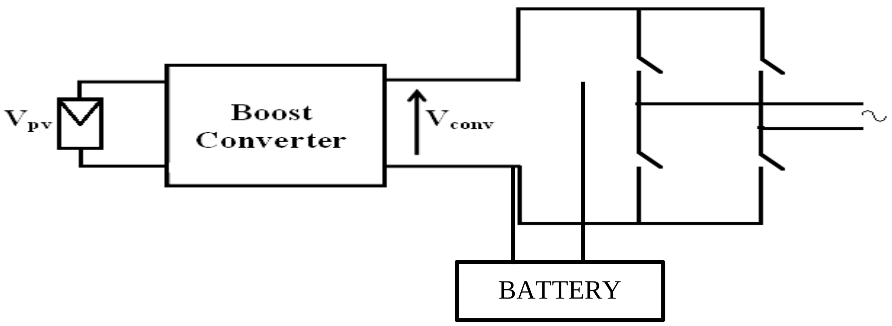


(a). Conventional scheme

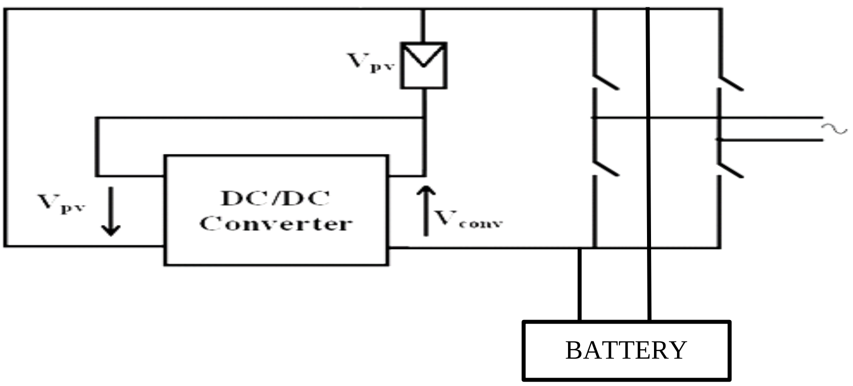


(b). Series compensation Method
Figure 2. Power flow diagram

Figure 2 shows power flow diagram of the conventional scheme dc-dc converter with battery and the proposed series compensation dc-dc converter with battery. The configuration of conventional and the proposed series compensation scheme of the circuit are shown in figure 3. The power rating of boost chopper is analogous to the entire power processor. The PV array gives DC input voltage to dc-dc converter; output voltage from DC/DC converter gives the required input voltage to the inverter. It also provides the variations in PV string dc output voltage and the needed inverter input voltage as conventional system. In standalone photovoltaic systems, the electrical energy produced by the PV array cannot always be used when it is produced since the demand for energy does not always coincide with the energy generation. Thus the storage batteries are commonly used in this system. The output power supplied by the dc-dc converter in conventional and series compensation scheme is discussed. Only least amount of electric power is transferred from PV module to the inverter which is processed by the converter.



(a). The conventional cascade scheme



(b) The series compensation approach.

Figure 3. Circuit diagram of the conventional and proposed scheme for System

Inverter input power P_{invin} in the conventional system is given by

$$P_{invin}=\eta_{con} P_{pvg} \quad (1)$$

where η_{con} is the DC-DC converter efficiency and P_{pvg} is the PV modules power generation. Inverter input power P_{invin} in series compensation approach is given as

$$P_{invin} = P'_{pvg} + \eta \left(P_{pvg} - P'_{pvg}\right) \quad (2)$$

PV modules power generation is denoted as P_{pvg}, where P'_{pvg} is the fraction of the power generated by the PV modules that is delivered directly to the inverter. In equation (1) & (2) the output power is high in second case. While the power processed by the converter decreases, series compensation increases the input power to the inverter. Considering lossless mode of delivering power to the inverter, the conventional and series compensation system has total efficiency which is given as

$$\eta = P_{out} / P_{in} = P_{out} / P_{pvg} \tag{3}$$

$$\eta = P_{out} / P_{in} = [P'_{pvg} + \eta_{con}(P_{pvg} - P'_{pvg})] / P_{pvg} \tag{4}$$

Better efficiency is attained in second case while converter efficiency is assumed to be constant in the above two expressions. However when slightly lower converter efficiency is assumed the efficiency of series compensation based system gives better result. The input and output power determines the voltage rating of power switches equipped with dc-dc converter. Switch current rating depends upon the output power for a given topology of input and output voltage. So, same topology is assumed in the two cases which are shown in Figure .2a. The proposed series compensation power converter gives low conduction as well as lesser switching losses when compared to conventional power converter while operating in reduced power and output voltage. Hence there is a remarkable reduction in the switch off-state voltage and on-state current. The voltage rating depends on input and output voltage of the DC/DC converter. The battery is directly connected to the output of buck-boost converter. The output from buck-boost always maintains at a voltage of 72V and the current flowing is varied depending on the load and source. The battery is charging in constant voltage mode. The excess current flows through battery when the source power is more than the load requirement. The power required by the load may exceed more than the power generated by the PV. During night time, power generated from PV is zero, so total power demand is supplied by the battery only. To improve life time of battery discharging capacity of battery is considered.

4. Operation of Series Compensation Topology

Boost chopper type dc-dc converter and full bridge single phase inverter are used along with LPF, LCL, and LC when it is connected to utility grid. Boost chopper is used to amplify dc voltage to a required level which is suitable for grid ac voltage. If the obtained dc input voltage is found to be suitable for direct inversion, the boost chopper is neglected and hence an inductor is by passed by additional diode. Boost chopper causes power dissipation due to switching and conduction losses. In the conventional cascade scheme the inverter voltage is obtained by dc-dc converter. Moreover, as shown in figure .2, all the output power is supplied through the dc-dc converter in the conventional configuration. In the proposed series compensation scheme dc-dc converter provides the difference between the available PV string output dc voltage and required inverter input voltage and not full inverter input voltage. The inverter input voltage is the sum of dc input voltage and dc-dc converter output voltage. The effectiveness of the series compensation approach increases when power processed by dc-dc converter decreases. This compensation approach is used to realize a series compensated power processor as it produces output voltage with an inverted polarity when compared with input voltage. With high frequency transformer there is an additional cost and power loss added to it. DC-DC converter in PV residential application for a series compensated power provides voltage attenuation.

DC-DC converter topology has series connection of input and output side for designing a series compensation converter. Isolation between input and output is provided by high frequency transformer isolated with converter topologies which requires high cost and low power loss. Buck- Boost converter in series compensation and power processor use non-isolated topology. From Figure .3 and Figure. 4 the input stage of dc-dc converter is connected to PV, while output stage is connected in series with input. Assume 320V as inverter input voltage V_{out} and PV string output voltage V_{in}. When V_{in} is 235V, the series connected converter is activated and generates an output voltage V_{outC} which is given by

$$V_{outC} = V_{out} - V_{in} \tag{5}$$

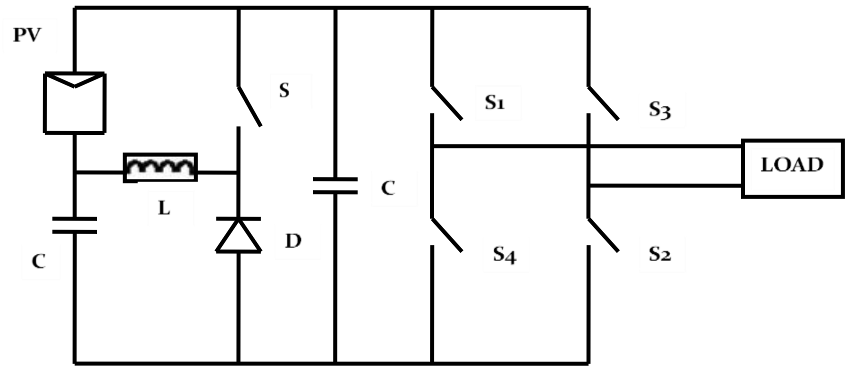


Figure 4. Circuit Diagram of Series Compensation topology

5. Operation of Series Compensation Scheme Buck-Boost Converter

The dc-dc switch mode converters are used to convert an unregulated dc input voltage to regulated dc output at required voltage level. They achieve the voltage regulation by varying the on-off time or duty ratio of the switching element. There are two main applications. It provides ac power supply with adjustable output voltage for general use. This application often requires the use of an isolating transformer. The other application of dc-dc converter is to transfer power from a fixed dc supply which can be rectified from ac to the armature of a dc motor in the form of adjustable direct voltage. There are basically three types of dc-dc converters. (i)Buck converter.(ii) Boost converter and (iii) Buck-Boost converter.

A buck-boost converter is nothing but cascade connection of the two basic converters: the step-down converter and the step up converter. The main application of such converter is in regulated dc power supplies, a negative polarity output which can be desired with respect to common terminal of the input voltage and the output voltage can be either higher or lower than the input voltage. If the duty ratio is more than 0.5 it operates as boost converter, if the duty ratio is less than 0.5 it operates as buck converter. In the conventional method buck-boost converter is connected in cascade with the source. But in the series compensation scheme buck-boost converter is connected in series with the source shown in figure .5. Operating principle of series converter is same as conventional converter.

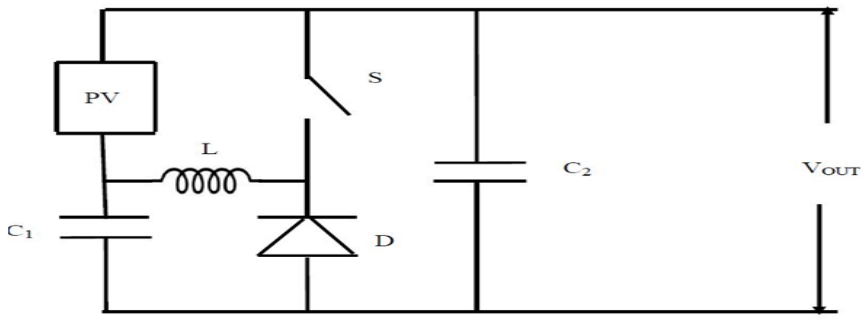


Figure 5.Series Compensation of Buck-Boost converter

When the switch's' is turned on, the inductor gets charged and inductor voltage is denoted as

$$V_{Lson}=V_{in} \tag{6}$$

The diode voltage is given by

$$V_{Dson}= V_{out} \tag{7}$$

If the switch 's' is turned off, the inductor voltage is given by

$$V_{Lsoff} = V_{outC} = V_{out} - V_{in} \tag{8}$$

The voltage across the buck boost output capacitor is V_{outC}. If the off-state switch voltage is

$$V_{Soff} = V_{out} \tag{9}$$

Series connected buck-boost converter has some special key features when comparing with conventional buck-boost converter. The off-state voltage of the switch and diode reduces the switching voltage and switching power losses is denoted by V_{out}, rather than $V_{in}+|V_{out}|$. The output voltage of the power processor V_{out} is higher than the input voltage V_{in} and operates as a step down converter which is in series connection with buck-boost converter. The Efficiency of series connected buck-boost converter is higher and the input/output voltage ratio is different. The cascaded buck boost converter operates in step up mode to generate the same output voltage. The voltage gain is given by

$$V_{out}/V_{in} = 1/(1-\delta) \tag{10}$$

While in a standard buck-boost converter the voltage gain is given by

$$V_{out}/V_{in} = \delta/(1-\delta) \tag{11}$$

Thus the series compensated power processor acts as boost converter from the input/output voltage gain. The power obtained by processor is fully equivalent to the cascaded boost chopper structure which is shown in figure .5. Thus the converter processes only a part of the input power.

6. Results and Discussion

A buck-boost based series compensation power processor has been designed and realized using specifications shown in Table 1. Technical specifications of the buck-boost converter are shown in Table 2. The series compensation method is verified by conducting simulation studies on MATLAB/Simulink environment and validated in the prototype unit built in the laboratory which is available in the Department of Electrical and Electronics Engineering, NIT Trichy, India. The MPPT control based pulses to the converter are generated using DSPIC30F4011 microcontroller and SPWM pulses to the inverter are generated using LM318 op-amp.

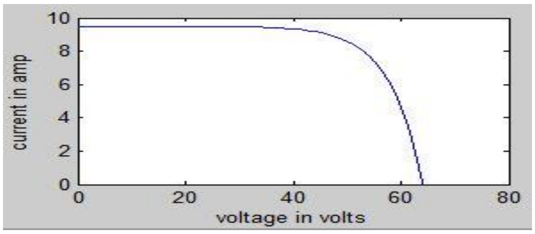
Table 1.

PV array ratings	
Open circuit voltage	21V dc
Short circuit current	5.6A
Max power output	80W
Series resistance	0.9206

Table 2.

Buck-boost Technical data	
Input voltage	40-45V dc
Output voltage	5-15V dc
Switching frequency	22kHz
Capacitor	470μF
Inductor	5mH

For simulation studies all these results are taken at an isolation condition of 700 W/m^2



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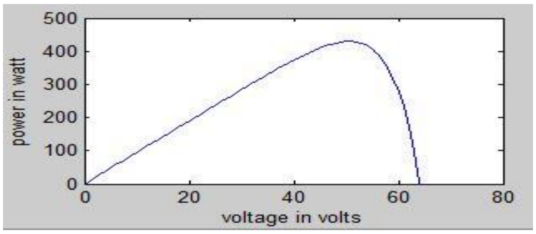

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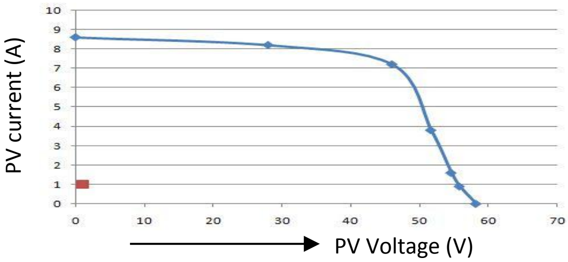

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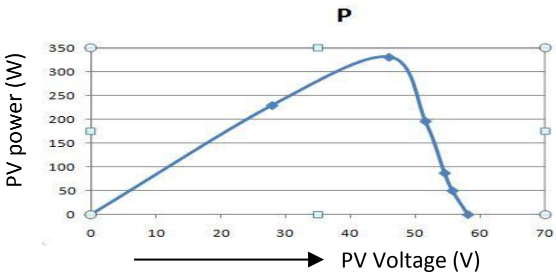
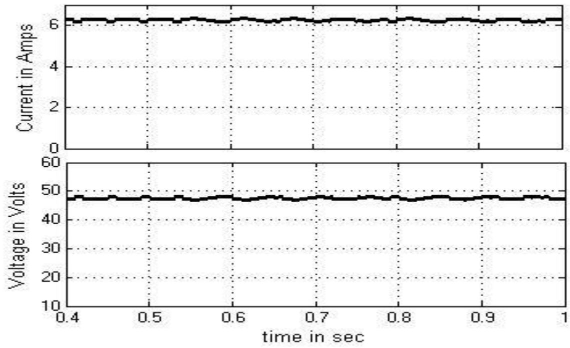


d.

Figure 6. Simulation results of PV a) V-I characteristics, b) P-V characteristics and Hardware results of PV c) V-I characteristics, d) P-V characteristics.

The variation of PV voltage, current and power during load variations from open circuit condition to short circuit condition is shown in figure 6. The proposed system proved that hardware results are found to match in close proximity with simulation results. But variation is due to the internal resistance of PV and variation of irradiation.



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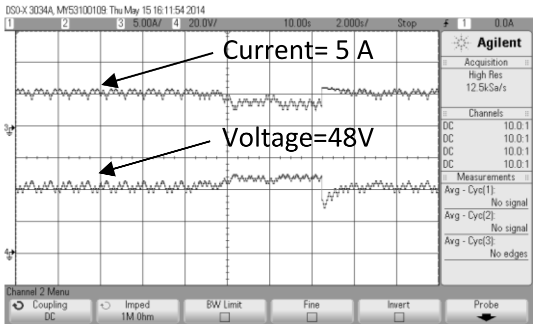
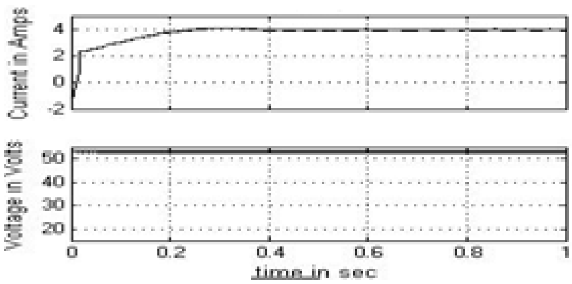


b.

Figure 7. Output current and voltage waveforms of PV a) simulation, b) hardware



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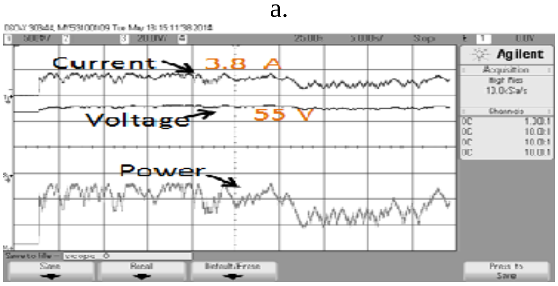


b.

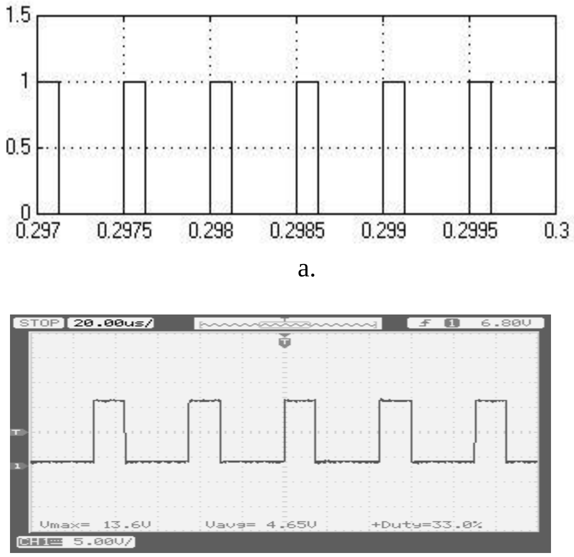
Figure 8. DC link current and voltage to the inverter a) simulation studies, b) Real time hardware

The PV voltage and current corresponding to MPPT at insolation of 700 W/m^2 with maximum power rating of 480 Watts is shown in figure 7. MPPT technique is implemented using

P&O algorithm. The voltage and current obtained from simulation are 47 V and 6.2 A respectively. Power is extracted as 291 Watts at an insolation of 700 W/m^2. At this insolation a maximum power of 336 (0.7*480) W is obtained. Efficiency of MPPT system is increased to 87%. In hardware the voltage and current ratings of MPPT are 48 V and 5.0 A respectively. Total power extracted from the PV is 240 watts. The proposed system is validated with hardware setup which is available at department of Electrical and Electronics engineering, NIT Trichy, India. Hence it is proved that hardware results are similar to simulation results, and also power extracted in hardware is less than the power extracted in simulation studies.

The total output current and output voltage from the combination of PV and Buck-Boost converter circuit of DC link is shown in figure 8. This voltage and current are given to the inverter to drive the load and remaining power goes to charge the battery. In simulation studies the current output is 4 A and voltage is 53 V gives the total power of 212 Watts, as shown in figure 8. The power extracted from PV is 292 Watts. Efficiency of the Buck-Boost converter is 73%. The simulation results are validated with hardware setup is shown in Figure 8. b). The voltage and current are 55V, 3.8 A respectively, which gives the total power of 209 Watts.

The gating pulses of Buck-Boost converter corresponding to the switching frequency of 22kHz is shown in figure 9. The operating voltage of MPPT of PV is 78%. So input of Buck-

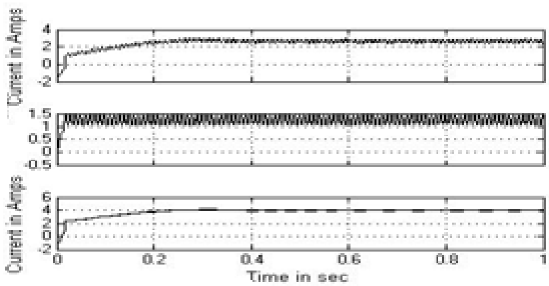


a.

b.

Figure 9. Gating pulses of Buck-Boost converter
a) Simulation studies, b) Real time Hardware setup

Boost converter is varied from 35-45V and voltage always maintains around 48-50 because of battery output. If the input to the dc-dc converter is 40 V then output is 50 V. According to the system configuration to get 50 V output, has to step down the voltage of dc-dc converter to 10 V. This 10 V aids with the input voltage to give the total 50 V. The gating pulse to the switch should be around 30% duty ratio to obtain the 10V from the converter. Hence it is proved that the proposed system is validated with hardware. The same gating pulses are obtained from simulation studies and hardware is shown in figure 9.



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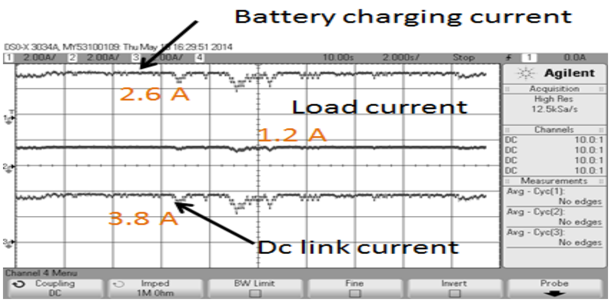
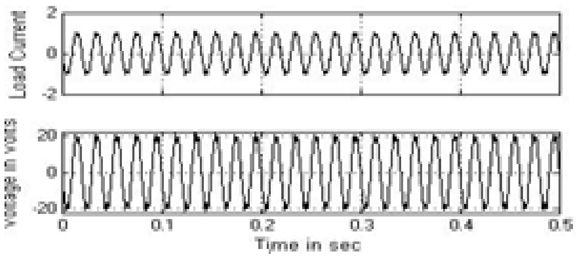


b.

Figure 10. Battery charging current, Inverter input current, DC link input current
a) Simulation studies, b) real time hard ware setup



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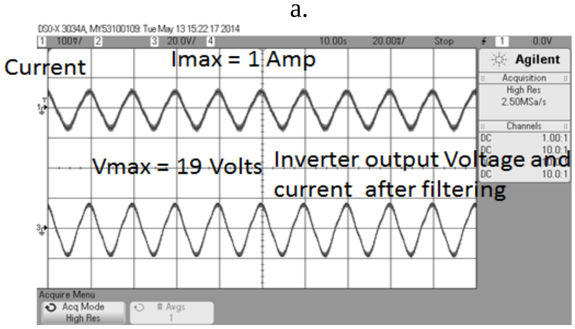
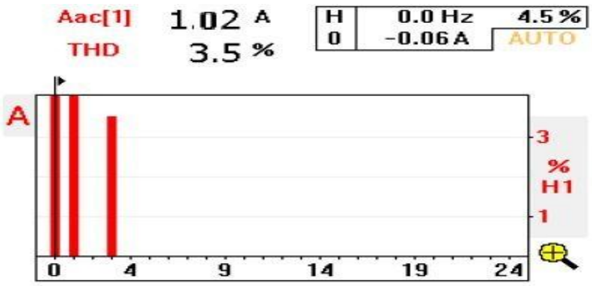


b.

Figure 11. Load current, Load voltage a) simulation, b) hardware.

Total power extracted from the PV is connected to the load and for charging the battery when load requirement is less than the power extracted. As shown in Figure 10. a) in the simulation studies, input current to the dc link is 4 A, the load requirement is around 1.3A and remaining current 2.7A which is used to charge the battery. The proposed system is validated with hardware setup, the results have similar pattern when DC link input current is 3.8 A, load current is 1.2 A and battery charging current is 2.6 A. Hence it is proved that the result of simulation studies and hardware setup are same, the proposed system is successfully validated.

SPWM pulse drives the inverter and reduces the harmonics of output voltage and current. Analog elements are used to develop SPWM pulses. LM318 Op-Amp is used as comparator to compare sinusoidal and triangular signals. Open loop pulse is developed as which is used to maintain constant voltage at DC link. At the inverter side of the system 20 ohms resistor is connected as load. Input voltage to the inverter is 48V and output RMS voltage is 19V as the modulation index is taken as 0.4. The current flowing through the load is 1A. LC filter is used to give pure sine wave and with reduced harmonics. Hardware results are also similar to the simulation. Because of filter there is some voltage drop across the inductor. So the chosen inductor value is 5mH.



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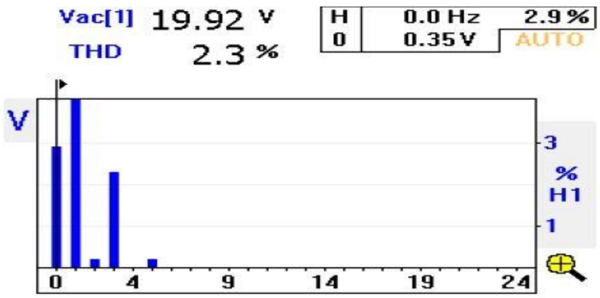

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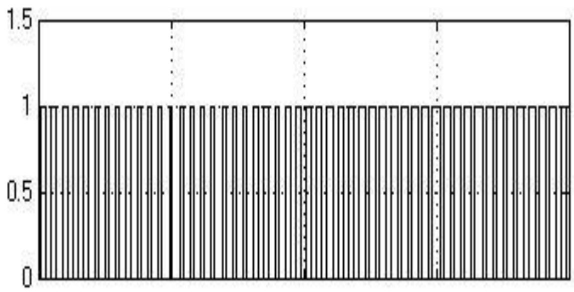
Figure 12. Total harmonic distortion of a) load current, b) load voltage



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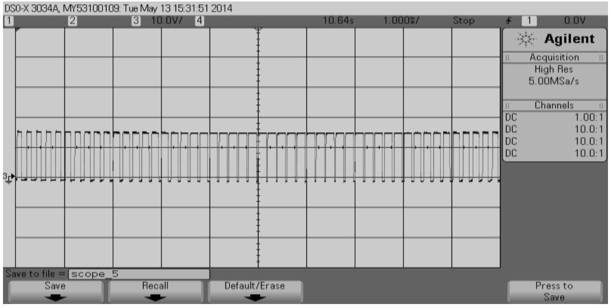

b.

Figure 13. SPWM pulse to the inverter a) Simulation studies b) Real-time hardware setup

Figure 12 a) & b) shows THD of current and voltage and the THD values are 3.5% and 2.3% which represents the high quality of power. In inverter, gating pulse gives quality output and good reliability. The pulse should be continuous and should have minimum gate driving voltage and current. The turn on voltage for IGBT switch is 5 V. From figure 13. b) It is observed that magnitude of signal is 5 V which follows the SPWM pulse pattern like simulation studies graph.

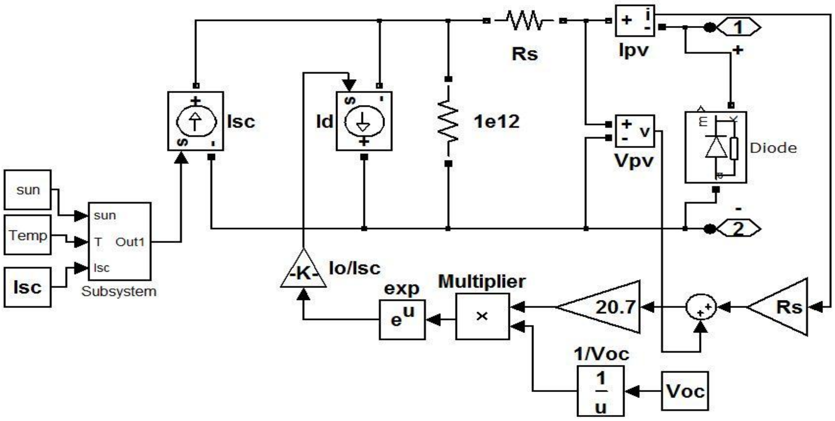

Figure 14. Simulink model of PV panel

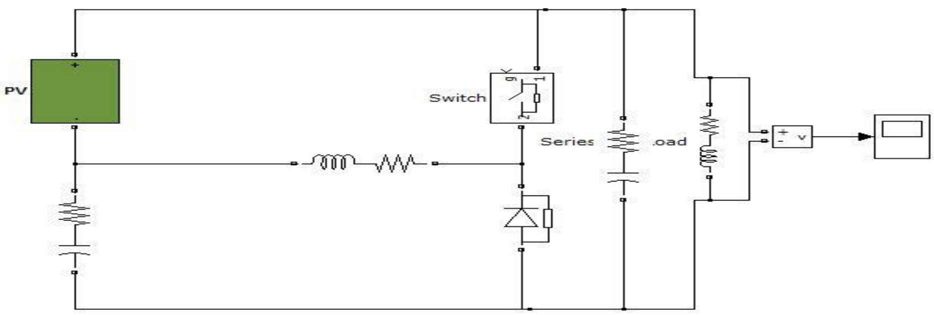

Figure 15. Simulink model of Buck-Boost Converter.

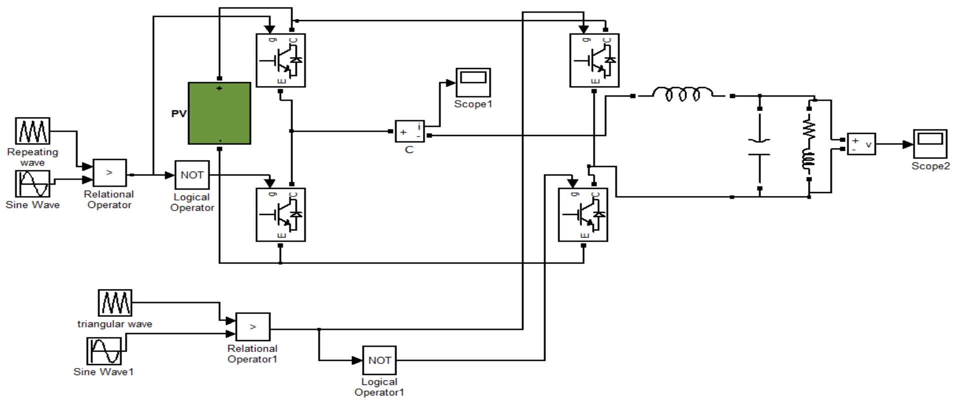

Figure 16.Simulink model of Single Phase Inverter.

Figure.14 shows the Simulink model of PV panel. In order to validate the PV characteristics; simulations were carried out for different operating points. I-V characteristics of a PV under different insolation conditions such as 1000W/m^2, 800W/m^2 and 400W/m^2 were performed. Figure .15 shows the Simulink model of Buck-Boost converter and Figure .16 shows Simulink model of a unipolar SPWM based single phase inverter. Figure .17 shows the real time hardware setup of proposed system.

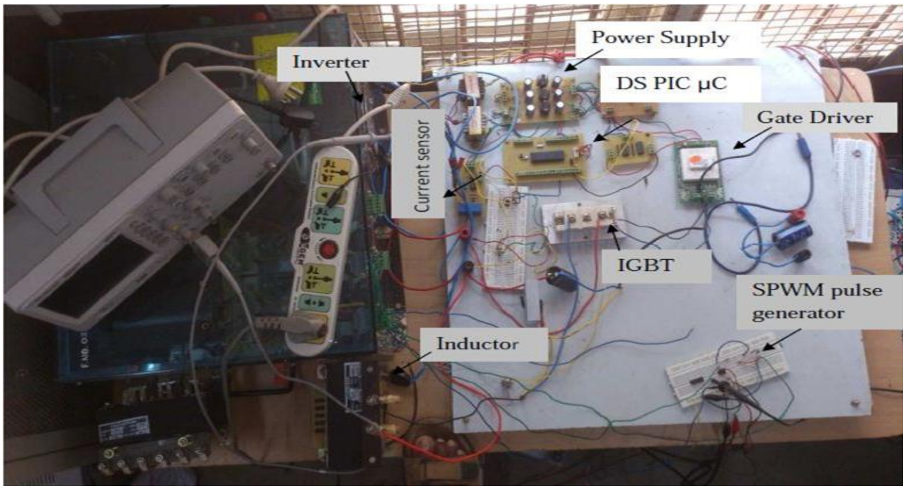

Figure .17 Hardware Setup of Series Compensation Method

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7. Conclusion

In this work the PV residential applications using series compensated power processor is proposed. It has a buck-boost converter whose output is connected in series to the PV string to form the inverter input voltage. As a result of the series connection, the buck boost converter generates the difference between the voltage delivered by PV modules and the inverter input voltage processing only a part of the power delivered to the inverter. Ratings of the buck boost converter and the efficiency of the power processor has a positive effects. The proposed scheme is implemented in simulation studies and results were validated with real-time experimental setup of 480W prototype which is available in the department of Electrical and Electronics Engineering, NIT Trichy, India. The proposed system is increases the efficiency of the system by reducing the losses. Hence it can be used for PV residential application where the constant voltage is required and it enhances the advantage of series compensation approach.

8. References

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