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A Voltage Controller in Photo-Voltaic System with Battery Storage for Stand-Alone Applications

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ABSTRACT

This paper proposes the new voltage controller in photo-voltaic system for Stand-Alone Applications with battery energy storage. The output of the PV array is unregulated DC supply due to change in weather conditions. The maximum power is tracked with respect to temperature and irradiance levels by using DC-DC converter. The perturbation and observes algorithm is applied for maximum power point tracking (MPPT) purpose. This algorithm is selected due to its ability to withstand against any parameter variation and having high efficiency. The solar cell array powers the steady state energy and the battery compensates the dynamic energy in the system. The aim of the control strategy is to control the SEPIC converter and bi-direction DC-DC converter to operate in suitable modes according to the condition of solar cell and battery, so as to coordinate the two sources of solar cell and battery supplying power and ensure the system operates with high efficiency and behaviors with good dynamic performance. The output of DC-DC converter is converted to AC voltage by using inverter. The AC output voltage and frequency are regulated. A closed loop voltage control for inverter is done by using unipolar sine wave pulse width modulation (SPWM). The regulated AC voltage is fed to AC standalone loads or grid integration. The overall system is designed, developed and validated by using MATLAB-SIMULINK. The simulation results demonstrate the effective working of MPPT algorithm, control strategy and voltage controller with SPWM technique for inverter in AC standalone load applications.

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1. INTRODUCTION

Solar energy has become a promising alternative source because it has many advantages such as abundance, pollution free and renewability. The solar photovoltaic (PV) power will play an important role in alleviating the energy crisis and reducing the environmental pollution and has a bright prospect of applications.

Due to the nonlinear relationship between the current and the voltage of the photovoltaic cell, it can be observed that there is a unique maximum power point (MPP) at a particular environment, and this peak power point keeps changing with solar illumination and ambient temperature. In recent years, a large number of techniques have been proposed for maximum power point tracking (MPPT), such as the constant voltage tracking (CVT), the incremental conductance (INC) method, the perturb-and-observe (P&O or hill-climbing) method [1,2]. Perturbation and Observation (P&O) method has a simple feedback structure and fewer measured parameters. It operates by periodically perturbing (i.e. incrementing or decreasing) the array terminal voltage and comparing the PV output power with that of the previous perturbation cycle. In this manner, the peak power tracker continuously seeks the peak power condition.

MPP is tracked by using DC-DC converters [3]. Much attention has been given to the single ended primary inductor converter (SEPIC) topology recently because output voltage may be either higher or lower than input voltage .The output is also not inverted as is the case in a fly back or Cuk topology. The input and output voltages are DC isolated by a coupling capacitor and the converter works with constant frequency PWM.

Inverters are static power converters that produce an ac output waveform from a dc power supply. The dc power from SEPIC is fed to inverter to get ac output power [4, 5]. A Bi-Directional DC-DC Converter (BDC) is connected between the Sepic Converter and Inverter. BDC is used to store the dynamic energy in battery and supply to load when there is overcast sky or at night [6, 7, 8, 9]. For sinusoidal ac outputs, the magnitude and frequency should be controllable. This is done by comparing a sinusoidal wave of the same frequency as inverter output against triangular carrier frequency wave. This technique called sinusoidal pulse width modulation (SPWM) mainly used because of its simplicity and ease of implementation. The output voltage magnitude is controlled by closed loop control system using PI controller [10].

A micro PV system structure in which two PV modules connected in series is considered and it provides an output power of nearly 160 Watts. To address the micro PV system structure, this paper proposes a novel MPPT algorithm, which is based on the improved research on the characteristics of the PV array to track the global MPP even under non-uniform insulation. Battery charging and discharging is done using BDC (Bidirectional converter). BDC is operated in three modes namely; Buck, Boost and Bidirectional. The algorithm was verified with MATLAB-SIMULINK that it can track the real MPP very fast when the temperature changes. The closed loop operation of proposed system is verified with MATLAB simulations including Load and source disturbances.

2. PROPOSED SYSTEM CONFIGURATION

The block diagram schematic of the proposed solar energy conversion scheme is shown in Fig. 1. It consists of a solar cell array, a battery, SEPIC Converter, bi-directional DC-DC converter (BDC) and single phase Inverter. The solar cell array and battery are connected to the same DC Bus through the Sepic Converter and bi-directional DC-DC converter respectively. The system has several advantages: (1) The charging and discharging currents of the battery are only controlled by the BDC and the system structure is simpler. (2) The over-load power is supplied by the battery (3). The energy management can be realized through the control of the UDC and BDC, ensuring the system to work with high efficiency.

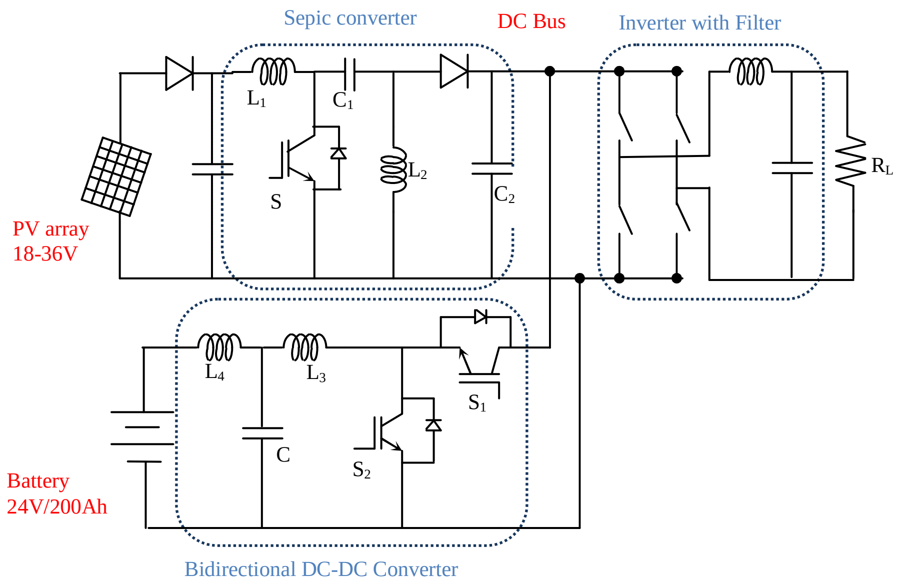

Figure 1. Block diagram of Proposed system Configuration

The output Power of the SEPIC converter is varied due to temperature and irradiations. Hence, the Maximum power is tracked and extracted from the PV array and transferred to the stand-alone load through single phase Inverter. The controller generates the gating pulses for the SEPIC converter, BDC and Inverter to extract maximum power, Energy management and to maintain desired ac output voltage and frequency across load terminals.

4.1 Sepic Converter

The buck–boost feature of the SEPIC widens the applicable PV voltage and thus increases the adopted PV module flexibility. Among all the available converters, SEPIC has the merits of noninverting polarity, easy-to drive switch, and low input-current pulsating for high-precise MPPT that makes its integral characteristics suitable for the low-power PV charger system.

SEPIC Converter can raise the output voltage to a suitable range, and can supply an isolation route to isolate the input and output terminal after terminate charging. But this circuit has two disadvantages; one is low efficiency and the other needs two inductors. The efficiency is not the major factor when charger is designed and use of coupling inductor solves the other disadvantage. Therefore the SEPIC is a good choice for constant current converter design.

The operation principle of SEPIC is: when S turns ON, the input source stores energy in the inductor L_1. The inductor current I_{L1} increases linearly. The energy stores in capacitor C_1 will transfer into inductor L_2. The energy for the load is supplied by capacitor C_2.When S turns OFF, the energy stored in inductor L_1 transfer to C_1. The energy stored in L_2 will transfer to C_2 through Diode and supplying the energy to loading.

4.2 MPPT Algorithm

The ‘‘P&O’’ method is that which is most commonly used in practice by the majority of authors. It is an iterative method of obtaining MPP. It measures the PV array characteristics, and then perturbs the operating point of PV generator to encounter the change direction. The maximum point is reached when $(dP_{pv}/dV_{pv})=0$. An example algorithm flow chart of the most basic form is shown in Fig. 2.

The operating voltage of the PV generator is perturbed, by a small increment ΔV_{pv}, and the resulting change, ΔP_{pv}, in power, is measured. If ΔP_{pv} is positive, the perturbation of the operating voltage should be in the same direction of the increment. However, if it is negative, the system operating point obtained moves away from the MPPT and the operating voltage should be in the opposite direction of the increment.

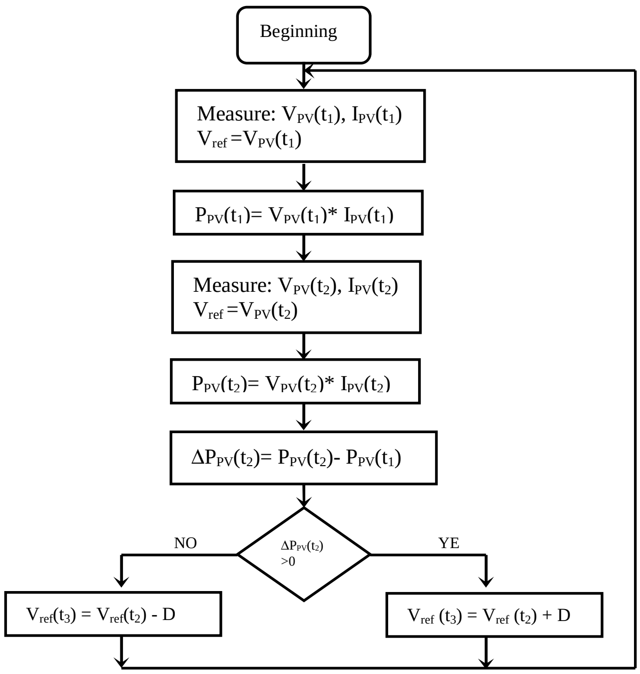

Figure 2. P&O algorithm

4.3 Bidirectional DC-DC Converter

A bidirectional DC-DC converter which allows transfer power between two DC sources becomes an important topic of power electronics. when power flows to one direction the converter works in buck mode, on the other hand, when the power flows to the other direction the converter works in boost mode. When there is excess energy in PV array, BDC works in buck mode and the Battery will be in charging mode but when there is cloudy or at nights, BDC works in boost mode and then battery supplies power to load. This can be achieved by controlling the duty cycle. LCL configuration is used to effectively damp out the ripples in the Battery current. Possible modes of operation of BDC are; Buck mode, Boost mode, Bidirectional mode.

4.4 PWM Converter

The block diagram of closed loop operation of single phase inverter is shown in Fig.3. Output voltage of inverter is controlled by using PI controller. Sine wave pulse width modulation (SPWM) is used to control the four switches of inverter.

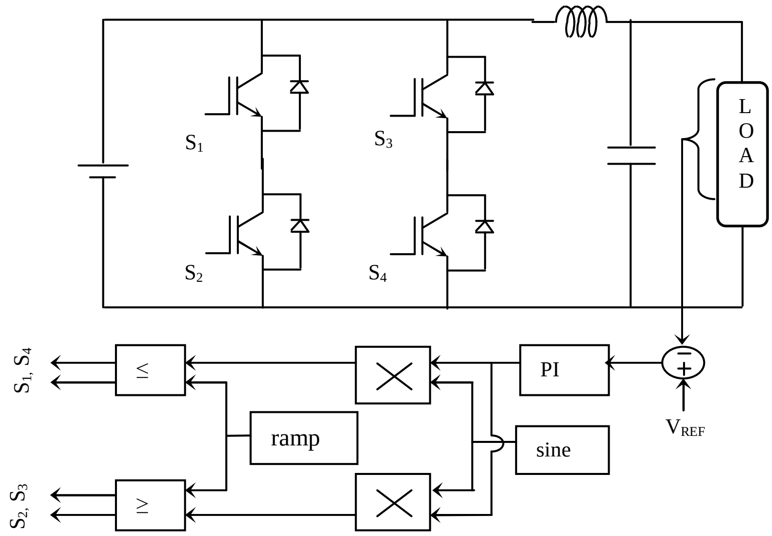

Figure 3. Closed loop operation of PWM inverter

3. MODES OF OPERATION

The working situation of the system can be divided into four operation modes based on the value of the voltage of the solar cell array (V_{PV}), the voltage of the battery (V_{Bat}), and the charging or discharging current of the battery (I_{Bat}), which are illustrated in Table 1.

Table 1. Conditions for modes of operation

Mode-I	Mode-II	Mode-III	Mode-IV
$V_{bat\_min} < V_{bat} < V_{bat\_max}$	$V_{pv} > V_{pv\_min}$	$V_{bat\_min} < V_{bat} < V_{bat\_max}$	$V_{bat} \le V_{bat\_max}$
$V_{pv} > V_{pv\_min}$	$I_{bat} \ge I_{bat\_max}$	$V_{pv} \le V_{pv\_min}$	$V_{pv} \le V_{pv\_min}$
$I_{bat} < I_{bat\_max}$	$V_{bat} \ge V_{bat\_max}$	$I_{bat} < 0$	$V_{pv} > V_{pv\_min}$
		$V_{bat} \ge V_{bat\_max}$	$I_{bat} \ge I_{bat\_max}$

3.1. Mode-I

The SEPIC converter works in Maximum Power Point Tracking (MPPT) mode and the BDC in Boost mode in mode I, where the DC Bus voltage and reverse inductor current of the BDC is controlled to get a stable voltage (54VDC) for DC Bus. When solar cell cannot provide enough energy to power load (Ppv<Po), the shortage will be complemented by battery via the BDC; and when solar cell can provide more power than load needed (Ppv>Po), solar cell powers load and residual power charges battery synchronously.

So battery can work between charging and discharging state freely, and the difference between charging and discharging state is the reverse power flow direction.

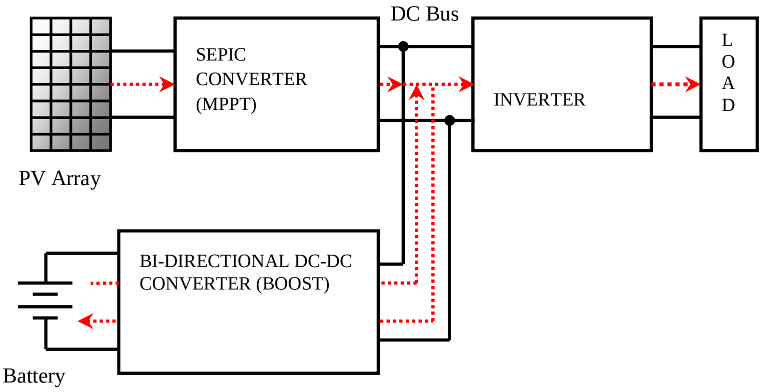

Figure 4. Power management in Mode -1

3.2. Mode-II

Mode II starts when V_{Bat} reaches over-charged-point voltage or I_{Bat} reaches the maximum charge current during mode I, then the operation mode of BDC must change from Boost to Buck mode, which control V_{Bat} and inductor current of BDC to charge the battery, meanwhile the operation mode of SEPIC Converter must also change from MPPT to CV mode immediately, which control the DC Bus voltage to be 54VDC.

3.3. Mode-III

When V_{PV_min} in the case of overcast sky or at night, the output power of solar cell is zero (Ppv=0), then the SEPIC Converter stops working and only the BDC works in Boost mode to regulate the DC Bus voltage to be stable to power the load.

3.4. Mode-IV

Due to continuous raining days during operation mode III, the battery may come into over-discharge state for continuously supplying power to load. When V_{Bat_min} reaches over-discharged-point voltage, the BDC immediately stop working to protect the battery, and the whole system stops.

4. RESULTS AND DISSCUSIONS

The simulation results of the proposed scheme such as active power fed to load, load voltage and load current, DC link voltage and current are shown in figures. Three similar solar panel with open circuit voltage V_{oc} = 21.2V and I_{sc} 5.17A are connected in series which triples the Voltage keeping current same. The change in climatic conditions effects the inverter voltage and current. The maximum power rating of each panel is 80W, as the panels are connected in series maximum power will be 160W. The main objective is to extract the maximum power. SEPIC converter specifications are given below; Input voltage = 10V to 36V DC; Maximum Duty cycle = 0.855; Minimum Duty cycle = 0.5; Switching Frequency = 10Khz.For above specifications the inductor and capacitor values are calculated by using standard design equations.L_1=2.5e-6H, L_2 =2.5e-6H, C_1 =4e-6F, C_o = 100e-6 F

Due to change in the temperature and irradiance the respective maximum power changes. The maximum power is tracked at 70% duty cycle.

4.1 System waveforms of Mode – I

The SEPIC Converter works in Maximum Power Point Tracking (MPPT) mode and the BDC in Boost mode in mode I, where the DC Bus voltage and reverse inductor current of the BDC is controlled to get a stable voltage ($56V_{DC}$) for DC Bus. The entire wave forms corresponding to MODE-I are shown as Figure 5-8.

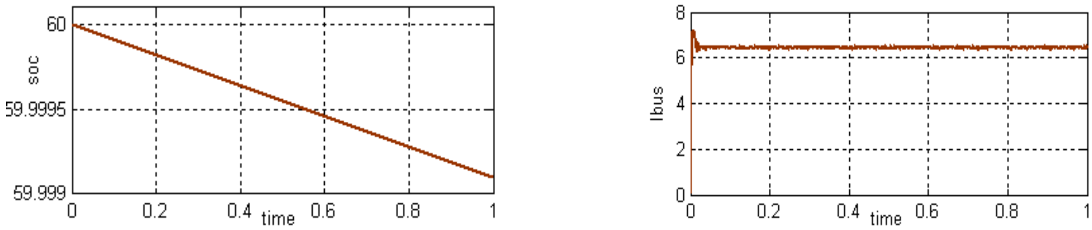

Figure 5. SOC of Battery (Discharging) and Output current of DC bus

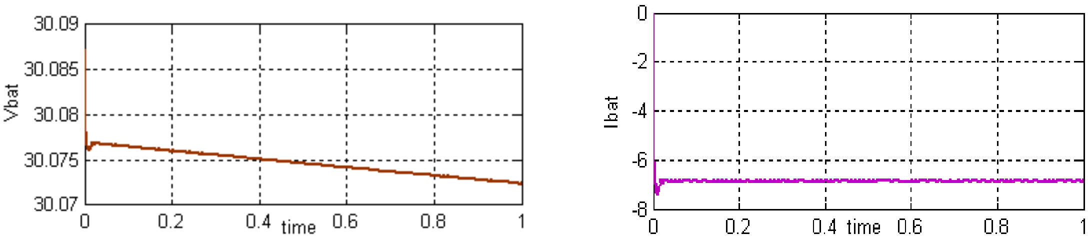

Figure 6. Output Voltage (V_{bat}) and Output current (I_{bat}) of Battery

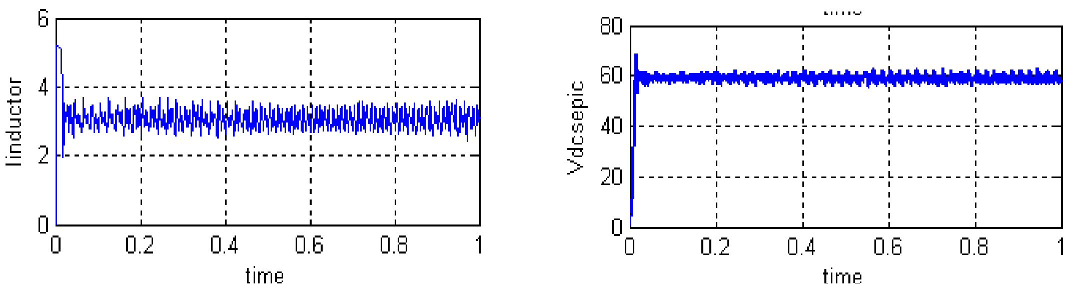

Figure 7. Inductor Current (I_{l1}) and Output Voltage of SEPIC Converter

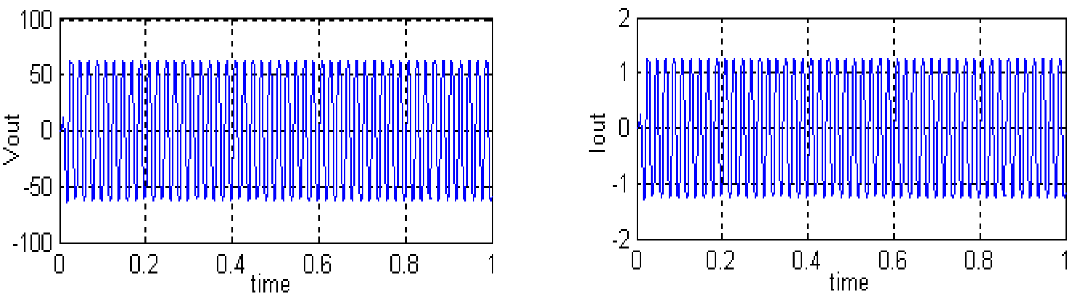

Figure 8. Output Voltage and Output Current of 1-ø Inverter

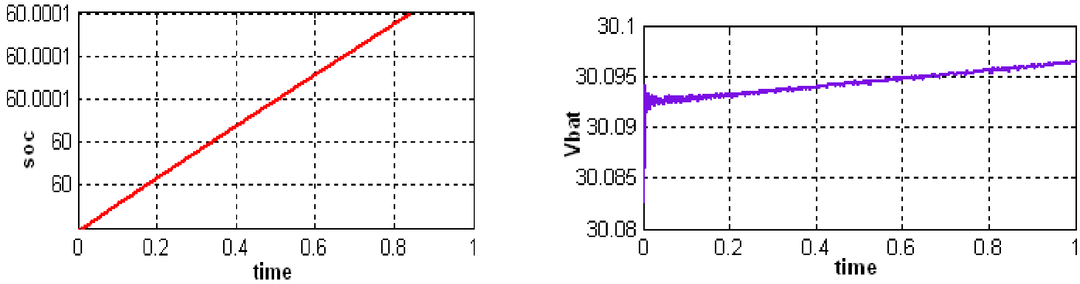

Figure 9. SOC of Battery (Charging) and Output voltage (V_{bat})

4.2 System waveforms of Mode – II

V_{Bat} reaches over-charged-point voltage (32.22V) or I_{Bat} reaches the maximum charge current during mode I, then the operation mode of BDC must change from Boost to Buck mode, which control V_{Bat} and inductor current of BDC to charge the battery. The entire wave forms corresponding to MODE-II is shown as Figure 9-11.

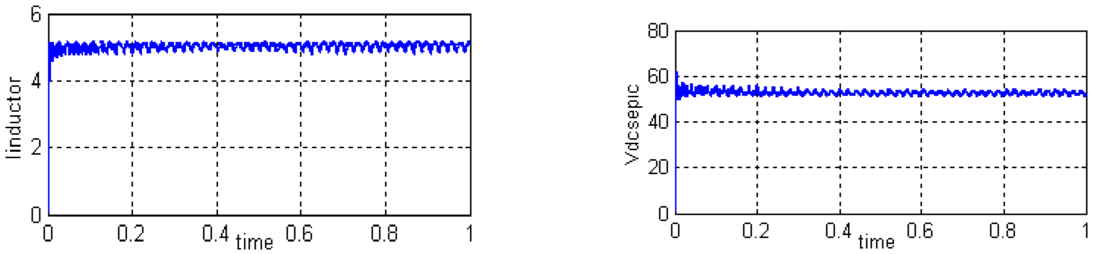

Figure 10. Inductor Current (I_{l1}) and Output Voltage of SEPIC Converter

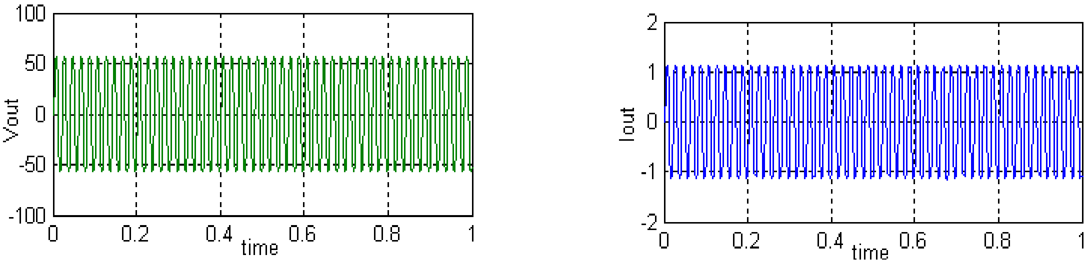

Figure 11. Output Voltage and Output Current of 1-Ø Inverter

4.3 Output waveforms of change in Buck to Boost Mode

Fig.12 to Fig.15 shows the waveforms corresponding to change from MODE-II to MODE-I i.e. Buck to Boost mode. In case of MODE-III, power is supplied by battery alone and wave forms are shown in Fig. 16 to Fig 21.

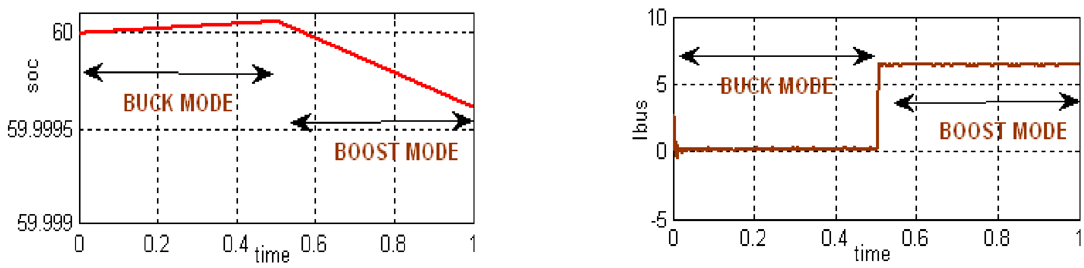

Figure 12. Change in SOC and Bus current (I_{bus}) from Buck to Boost Mode

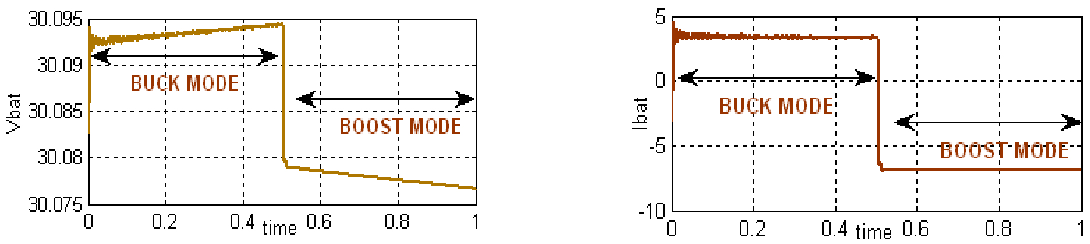

Figure 13. Change in Battery voltage (V_{bat}) and I_{bat} from Buck to Boost Mode

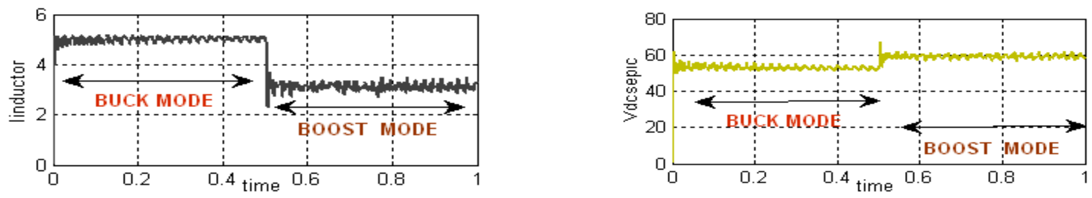

Figure 14. Change in I_{L1} and DC bus voltage (V_{dc}) from Buck to boost Mode

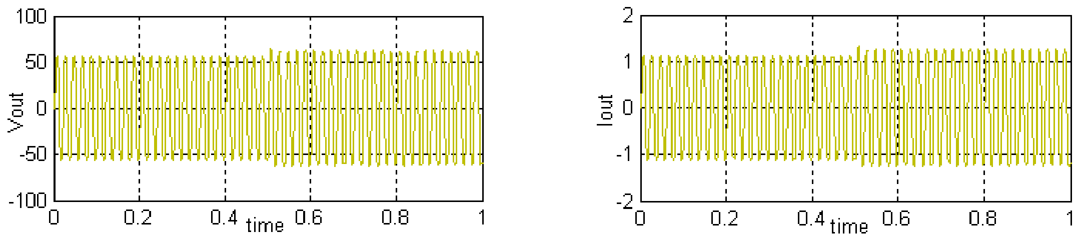

Figure 15. Output Voltage and Output Current of 1-ø Inverter

4.4 Output waveforms of Inverter for Load Disturbance

The output voltage and current waveforms of inverter for changes in the reference voltage is shown as Figure 16-18.

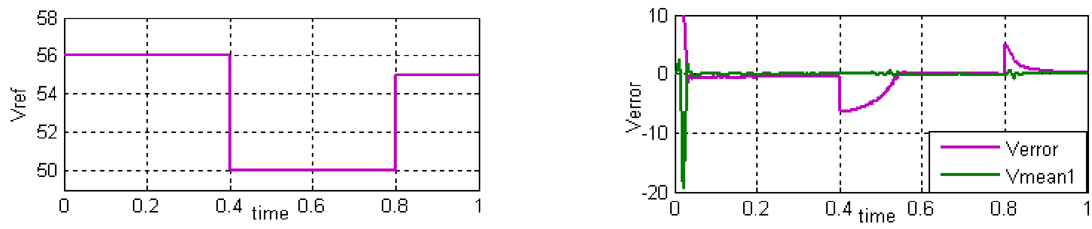

Figure 16. Required output voltage and Error voltage (V_{ref} - V_{out})

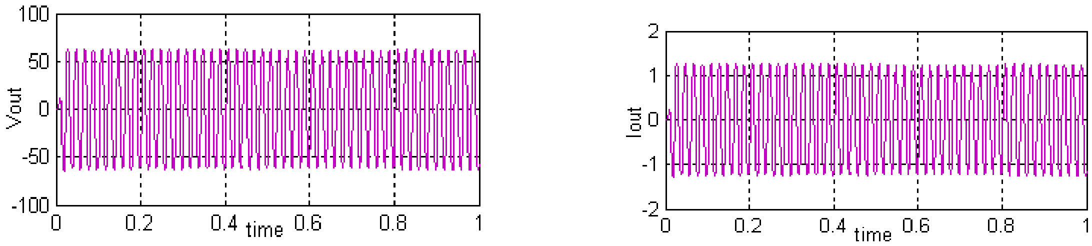

Figure 17. Output Voltage and Output Current of 1-ø Inverter

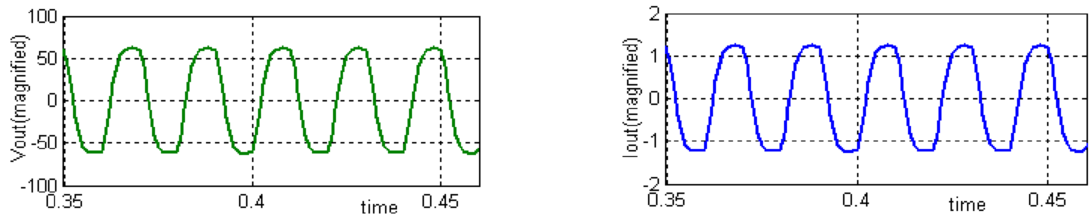

Figure 18. Magnified Output Voltage and Output Current of 1-ø Inverter

4.5 Output waveforms of Inverter for source disturbence

The output voltage and current waveforms of inverter due to change in irradiation levels is shown as Figure 19-21.

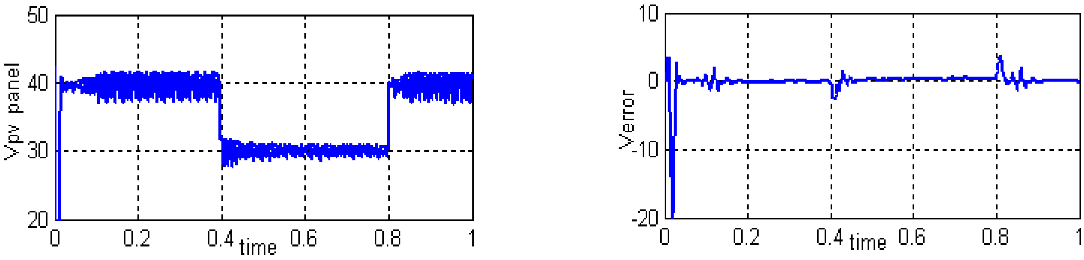

Figure 19. V_{pv} due to change in irradiation levels and Error voltage (V_{ref} - V_{out})

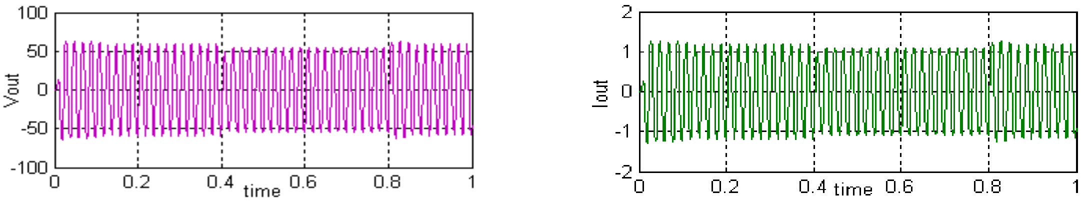

Figure 20. Output Voltage and Output Current of 1-ø Inverter

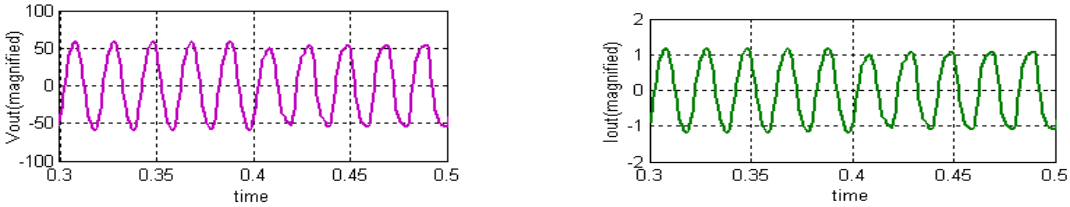

Figure 21. Magnified Output Voltage and Output Current of 1-ø Inverter

5. CONCLUSION

When the PV array is used as a source of power supply to stand alone loads, it is necessary to use the MPPT to get the maximum power point from the PV array and implemented with MATLAB/SIMULINK for simulation. The MPPT is implemented by using a SEPIC-Converter, which is designed to operate under continuous conduction mode. The perturbation and observe Algorithm is used as the control algorithm for the MPPT. From results of simulation, it can be seen that the P&O MPPT algorithm which is able to improve the dynamic and steady state performance of the PV system. BDC is operated in suitable modes according to the conditions of PV panel and battery. The BDC can operate in three modes: buck, boost and shutdown illustrated using simulation results. At the same time, output results of inverter with SPWM control strategy have better voltage control and simulation results of system demonstrate that the PV system has the fast and effective response under changing irradiance levels. So the PV generation system based P&O MPPT method, BDC and SPWM control for single-phase voltage source PWM inverter is feasible and effective.

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