SEPIC Converter with Closed Loop PI Controller for Grid Utilized PV System

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Abstract

The solar PV energy generation system has been scrutinized as a most prominent energy system by power producers across the world as it uses renewable energy source for harnessing electricity. However, to the increase overall production, the grid connected PV system with SEPIC converter has been employed as it boost up the low level DC voltage from the PV panel up to the level it matches the grid voltage. By assigning closed loop control strategy along with PI controller ensures the control performance and helps in extricating maximum possible power from the PV panel. The attained voltage is fed in to the grid through a 1φ VSI by assigning PI controller that eliminates the steady state error and helps in achieving the target grid voltage by analogizing actual power with the reference power. The entire control output of the proposed scheme is simulated by means of MATLAB and it is clearly observed from the result that the source current THD of the proposed system is significantly less and it is noted as 4.57%.

Keywords: SEPIC converter, PI controller, Grid synchronization, PV system.

I. Introduction

Power generation as well as distribution systems are experiencing considerable modifications, due to advanced technologies like amalgamation of extensive renewable energy production, improved transmission as well as control schemes, and increased storage capacity. Among various renewable energy resources, solar PV (Photovoltaic) based energy generation system is widely used because of its static structure, minimal size as well as low maintenance cost [1]. But, the output voltage bring about by the PV system is generally minimum and it affects the efficiency and reliability of the system [2]. Hence, there is a need for a high switching frequency device to uplift the minimal PV voltage. This is obtained by incorporating the PV panel with a DC/DC converter which boosts the PV voltage and improves the energy extraction [3].

Among the DC/DC converters, boost converters are employed to improve the voltage of the PV panel, and it also suppresses the ripple current brings out from the PV panel further improving the reliability as well as extrication efficiency of the panel [4].In spite of these advantages, the boost converters possess discontinuous input and output current, which leads to variations in the gain of the circuit affecting the circuit dynamics [5]. To overcome this, buck-boost converter is introduced which accomplishes broad input as well as output voltage range offering increased efficiency. It has an additional input feature that it increases the dc input voltage range, allowing the PV panel to be more versatile yet, its operation is centralized [6]. In contrast, CUK converters utilized by the PV panel exhibited minimal switching losses along with improved voltage moderation and increased efficiency providing flexible operation. But, these converters lagged in resulting sharp speed up/down voltage affecting the specific utilization [7]. Moreover, the utilization of CUK converters is restricted to medium-low power range and when operated in high-power range requires large input as well as output inductors and the converter gets adversely damaged when connected to a utility grid due to its grid voltage fluctuations [8]. To overcome these limitations, an efficient SEPIC converter is proposed which tracks the maximum output power providing potent grid synchronization.

In general, the optimum power has been extracted from the PV panel with the utilization of Proportional- Integral (PI) controllers. Numerous MPPT algorithms are applied to the PI controllers for modulating the duty ratio of the PV panel. Perturb & Observe (P&O) is a widely utilized MPPT algorithm in industry as it is simple and cost-effective. More accurate results are obtained by adopting Incremental Conductance (INC) instead of P&O which is free from oscillations regarding the tracking of maximum power point. In contrast to these advantages, this method is restricted by environmental situations [9]. These demerits can be solved by utilizing closed loop control algorithms which balance the dc-link voltages resulting in minimal distortions maintaining the power quality of the grid system efficiently [10]. The closed loop algorithms generate optimal results tackling the external disturbances which in turn support the real-time functioning of the grids [11].

Moreover, the output DC voltage from the converter has to be converted to AC form and this is achieved by a 1ϕ voltage source inverter (VSI) which is further linked to a grid. Due to the issues like voltage distortions caused by local nonlinear loads and disturbances in the grid, grid synchronization is considered to be a significant task. To attain an effective grid synchronization, the basic components of the point of common coupling voltage has to be evaluated considering the fluctuations in power quality [12]. These grid synchronization concepts upgrade the control efficiency and interpolate improved quality power in the grid thereby obtaining accurate results [13]. Subsequently, they regulate the grid functioning to avoid anomalies of parameters within the PV system and grid. They also provide appropriate as well as stabilized approach to recognize the parameters that support the grid without any limitations [14]. Due to the variations between the input signals and the controller resulting in frequency transients of the system. Hence there is a need to develop effective grid synchronization which is simpler and easier to implement [15].

This paper proposes a SEPIC converter that ensures non-pulsating input current while providing an output with the similar voltage polarity of the input. A PI controller is utilized which adopts a closed loop algorithm providing an accurate and responsive correction to the control function. A 1ϕ grid is interlinked to the PV system which offers high voltage gain with improved control analysis.

II. Proposed Control System

The diagrammatic representation of the proposed control system is depicted in Fig. 1. It consists of a PV panel linked with SEPIC converter through a closed loop PI controller. A VSI along with a synchronized single phase grid is connected at the output.

The PV panel is of high demand due to its static property, minimal size and decreased maintenance cost. But the output voltage is usually low and this requires a DC-DC converter to uplift the voltage to the desired level. Hence a SEPIC converter is utilized to uplift the voltage, thus improving the voltage gain with minimal switching losses. The converter outcome is given to a single phase VSI which inverts the input DC voltage to output AC voltage. A PI controller is deployed for the appropriate evaluation of signals considering the reference input and the obtained signal which minimizes the steady-state error thus prevents fluctuations. The output from the inverter is fed to the synchronized grid which provides the power of improved quality.

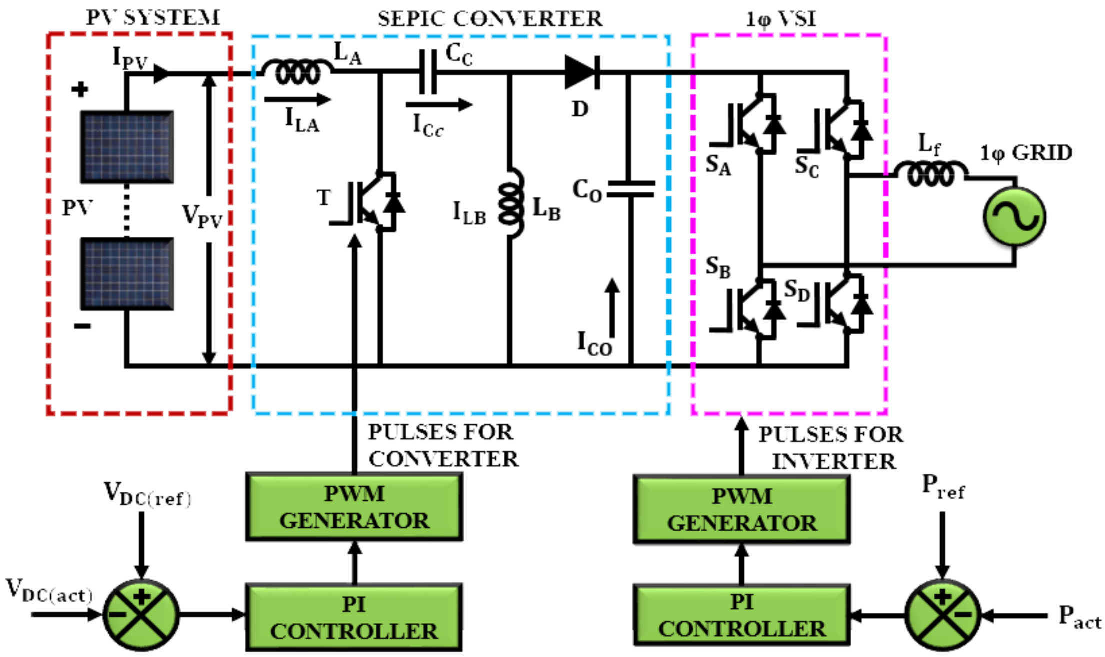


Fig.1. Proposed control block diagram

III. Modeling of Proposed System

A. Modeling of PV system

PV system is an effective as well as promising renewable energy source and plays an important role in power generation. The major component of the PV system is the solar system which is generally a semiconductor diode disposed to solar irradiance. The solar irradiance comprises of photons having various levels of energy, of which few are absorbed in the p-n junction. The photons which possess greater energy compared to band gap generate energy which is utilized at a level equal to the band gap and the remaining energy is exhausted as heat. The model diagram of the PV system is shown in Fig. 2.

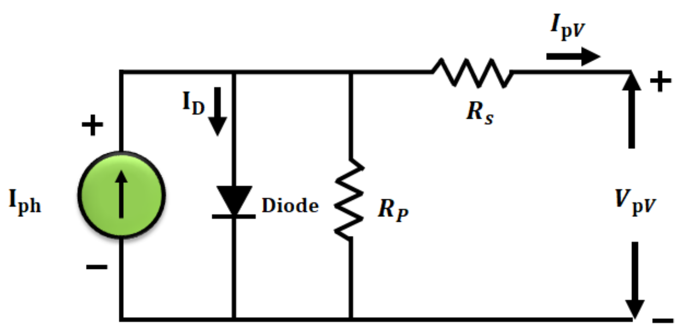


Fig.2. Equivalent circuit of the PV system

Where, R_s and R_p denotes the series and parallel resistances if the of the PV system respectively. Since the value of R_p is too large and R_s is too small, they are eliminated to make the evaluation simple.

The V-I characteristic equation of the PV solar system is estimated as follows: The photo-current of the PV system is given by,

$$I_{pc} = [I_{si} + K_i (T - T_o)] * \frac{G}{1000} \tag{1}$$

Where I_{pc} - Photo current

K_i - Short circuit temperature coefficient

T - Operating temperature in Kelvin

T_o - Reference temperature

G - Solar irradiation (W/m^2)

PV cells are usually connected in groups called PV modules and linked in series or parallel to form PV arrays in a PV system. The module reverse saturation current is given by,

$$I_r = \frac{I_{si}}{\left[exp\left(\frac{qV_0}{N_S KnT}\right) - 1\right]} \tag{2}$$

Where, I_r - Reverse saturation current (A)

I_{si} - Short circuit current (A)

q - Charge of electron (1.6*10^{-19}C)

V_0 - Open circuit voltage

N_s - Total count of PV cell connected in series

K - Boltzmann constant (1.3805*10^{-23}J/K)

n - Ideality factor of the diode

T - Operating temperature (K)

The current output of the PV module is given by

$$I_{PV} = N_p * I_{pc} - N_p * I_s * \left[exp\left(\frac{\frac{V_{PV}}{N_S} + I_{PV} * \frac{R_S}{N_P}}{n * V_{th}}\right) - 1\right] - I_p \tag{3}$$

Where N_p= number of cells connected in parallel

I_s = saturation current

V = output voltage

R_s= series resistance

V_{th}= diode thermal voltage

I_p = parallel current

The diode thermal voltage V_{th} is calculated from the values of Boltzmann constant, operating temperature and the electron charge and the parallel current I_p is determined from the count of cells connected in series as well as in parallel and the corresponding series and parallel resistance. The output voltage obtained from the PV system is fed to the SEPIC converter.

B. Modelling of SEPIC converter

A SEPIC converter is a conventional DC-DC converter which has the output voltage with the similar polarity of the input voltage. The output voltage generated can be greater than, less than or equal to the input voltage. It comprises of an active power switch which is normally an IGBT T, with a diode D, two inductors L_A and L_B and two capacitors C_c and C_0 as shown in Fig. 3.

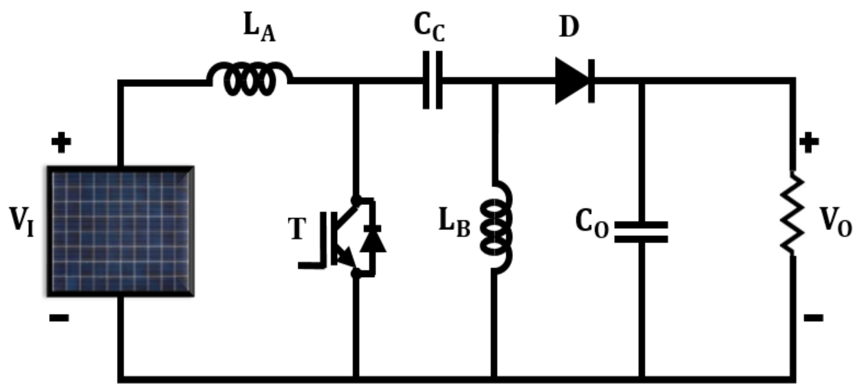


Fig. 3. SEPIC converter

i). T-ON condition

Here, the switch T is turned ON, L_A and L_B are charged by the V_i and V_c. The coupling capacitor C_c has the negative polarity and hence the diode D operates in reverse biased condition. When the coupling capacitor discharges, both L_A and L_B gets charged. The circuit diagram during the turn ON condition is depicted in Fig. 4.

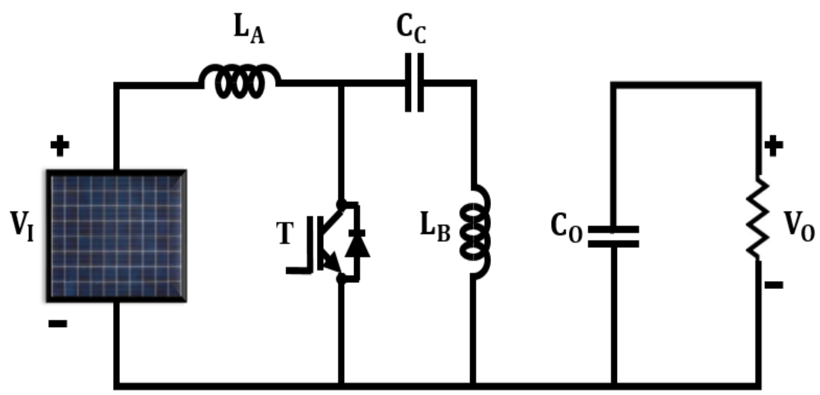


Fig. 4. T-ON condition

ii). T-OFF condition

Here, the diode D operates in forward biased condition. The inductor L_A charges the coupling capacitor C_C and the inductor L_B transfers its energy to the output. The circuit diagram during the turn OFF condition is depicted in Fig. 5.

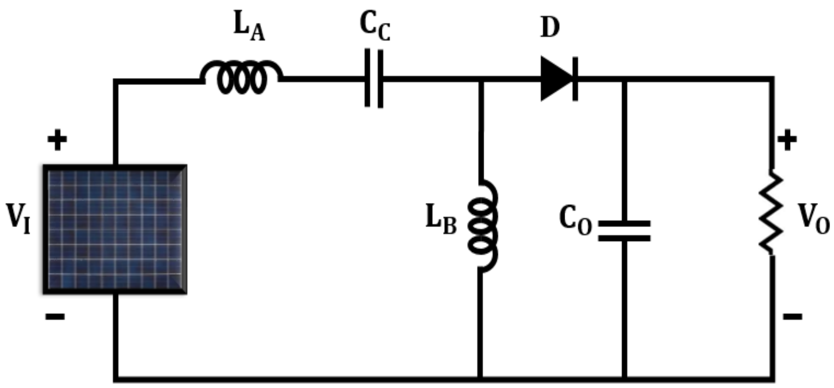


Fig.5. T-OFF condition

The SEPIC converter's duty cycle has been given as,

$$D = \frac{V_o+V_D}{V_i+V_o+V_D} \tag{4}$$

Where V_i= input voltage

V_o= output voltage

V_D= diode voltage

The inductance values are given by,

$$L_A = L_B = \frac{V_{i(min)}}{\Delta I_L * f_{SW}} \tag{5}$$

Where $V_{i(min)}$= minimum input voltage

ΔI_L = ripple current of inductors = $I_{o*} \frac{V_0}{V_{i(min)}} * 40\%$

f_{SW} = switching frequency

The peak voltage of the MOSFET is given by, $V_P= V_i +V_o$ (6)

The peak current of the MOSFET is given by, $I_P= I_{LAP}+I_{LBP}$ (7)

Where I_{LAP} = peak current across L_A

I_{LBP} = peak current across L_B

The minimum peak reverse voltage of the diode is given by,

$V_{PRD} = V_{i\,(max)} + V_{o\,(max)}$ (8)

The rms current across the coupling capacitor is given by,

$$Ic_c(rms) = Io * \sqrt{\frac{V_o+V_D}{V_{i(min)}}} \quad (9)$$

The rms current across the output capacitor is given by,

$$I_{o(rms)} = Io * \sqrt{\frac{V_o+V_D}{V_{i(min)}}} \quad (10)$$

And the output capacitor $C_o \geq \frac{I_o*D}{V_{rip}*0.5*f_{sw}}$ (11)

The proposed SEPIC converter obtains improved voltage gain and output power when compared to other conventional converters. As the duty ratio increases, the voltage gain also increases. Due to the presence of a single switch, the circuit remains simple with reduced switching losses.

C. Modelling of closed loop PI controller

A closed loop PI Controller determines an error signal by finding the difference between the output and the set point of the system. The controller calculates an error value by subtracting the received process variable from the preferred reference input. The error is further reduced by adding or subtracting the inputs, bringing the process variable closer to the set point. This method is generally applicable when the mathematical model of the process is tedious. The block diagram of the PI controller is illustrated in Fig. 6.

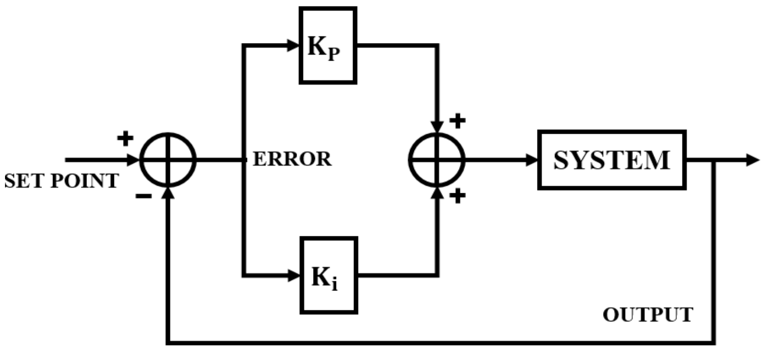


Fig.6. Block diagram of closed loop PI controller

The feedback error is used to measure the output of a PI controller in the time domain is given as,

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (12)$$

The tracking error denoted by the variable e is the difference between the expected and the actual performance.

Applying Laplace transform on both sides in equation (12),

$$U(S) = \left(K_p + \frac{K_i}{S}\right) E(S)$$

$$\frac{U(S)}{E(S)} = K_p + \frac{K_i}{S} \quad (13)$$

Hence the transfer function of the proportional controller is given by $K_p + \frac{K_i}{S}$.

The PI controller is connected to the SEPIC converter which reduces the steady-state error making the system stable and stops the system from fluctuations. These controllers provide better transient response with improved gain margin and phase margin.

D. Modelling of Single phase VSI and Grid

The single phase VSI receives the SEPIC converter's output. A VSI converts a fixed voltage from a system, such as a DC power supply to a variable frequency AC supply. The circuit diagram for the voltage source inverter connected to the grid is shown in Fig.7.

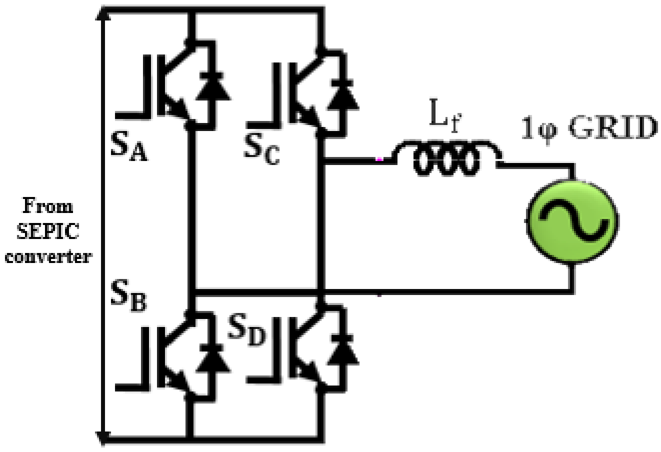


Fig.7. Single phase VSI and Grid

The inverter consists of switches S_A, S_B, S_C and S_D and the pulses for the VSI are generated from the PWM generator. A PI controller is utilized for grid synchronization, in which the actual and reference powers are being analogized. Due to the synchronization, the inverter injects better quality power into the grid at reasonable variations in terms of voltage, frequency and phase angle. As a result, a high quality integrated voltage is obtained as the output in the single phase grid.

IV. Results and Discussions

This paper explores the experimental study of grid-tied PV system with a SEPIC converter and a closed loop PI controller. Table 1 lists the parameters of PV panels and their respective ranking.

Table.1. Parameter of PV panel and SEPIC Converter and their Ratings

Panel Parameters	Ratings
Temperature Range	$-40\ to + 85^{\circ}C$
Operating current	$5.8A$
Operating voltage	$16.8V$

Maximum voltage	$1000V\ DC$
No. of panels	10
Total No. of series cells	36
Cell area	$125mm \times 31.25mm$
Converter Ratings	
Switching Frequency	$10KHz$
Capacitors C_1, C_2	$47\mu F$, $100\mu F$
Inductors L_1, L_2	$60mH$
Diode	$MUR1560$

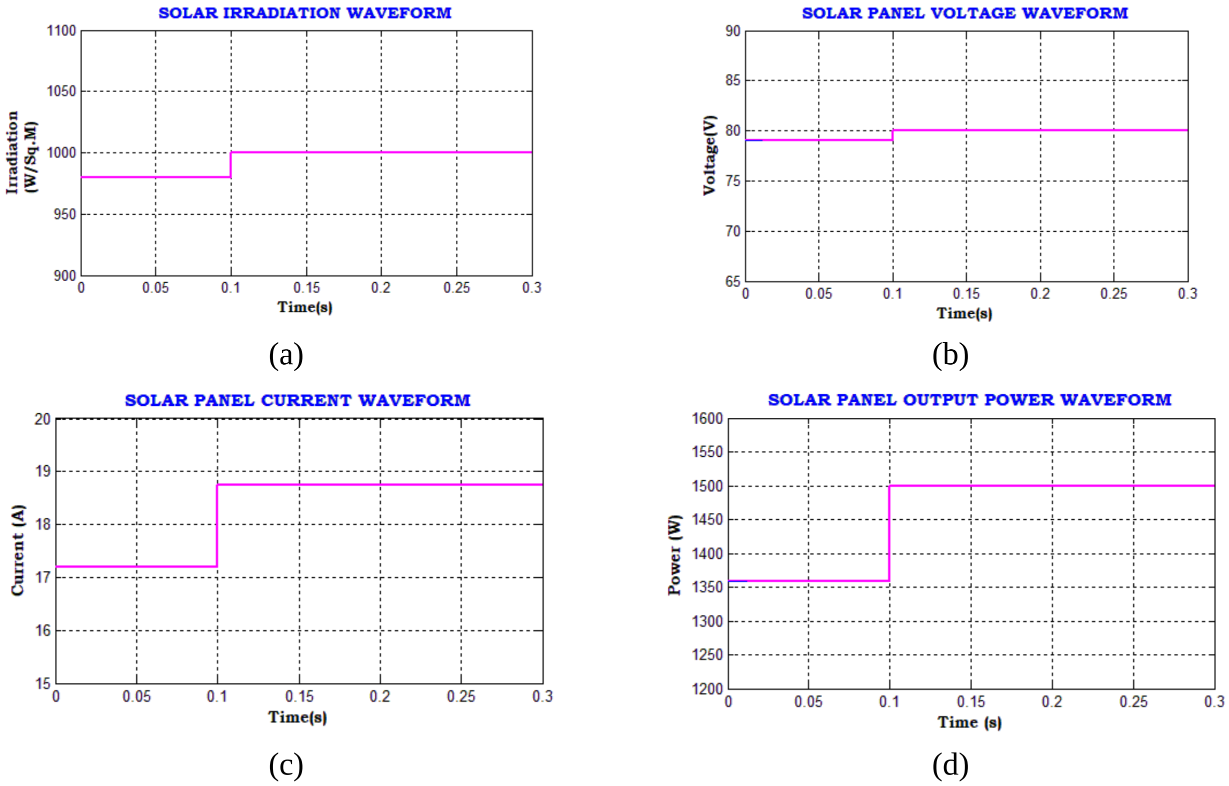


Fig.8. Parameters of solar panel (a).solar irradiation waveform (b).solar panel voltage waveform (c).solar panel current waveform (d).solar panel output waveform

Fig.8 shows the parameters of a solar panel, demonstrating that the solar irradiation reaches $1000\,W/m^2$ after 0.1s, at the same time the panel output voltage reaches 80V and the output current provided by the PV panel is 18.8A with 1500W output power. To achieve the target voltage from the panel, a PI controller with closed loop control strategy has been employed. Fig.9 depicts the SEPIC converter's output waveform. The pulse generated by the PWM generator is fed in to the converter.

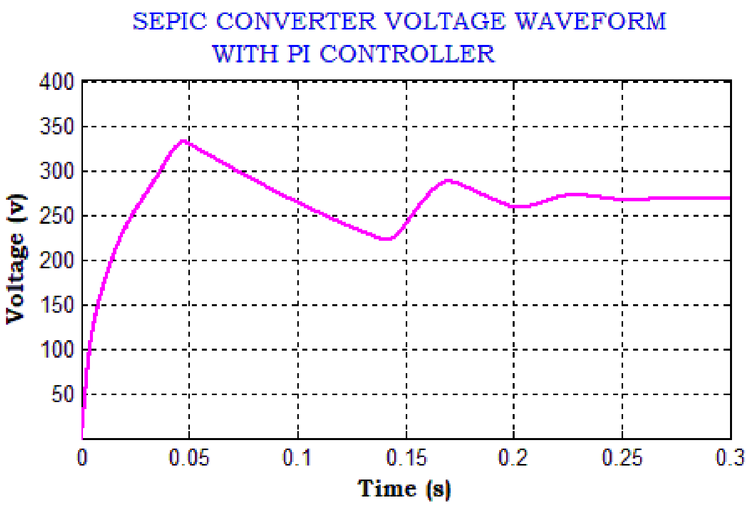
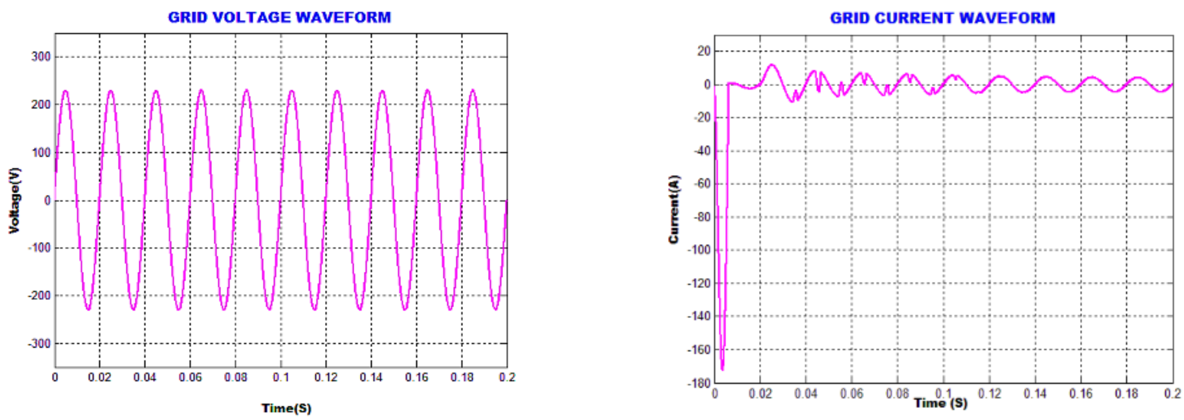


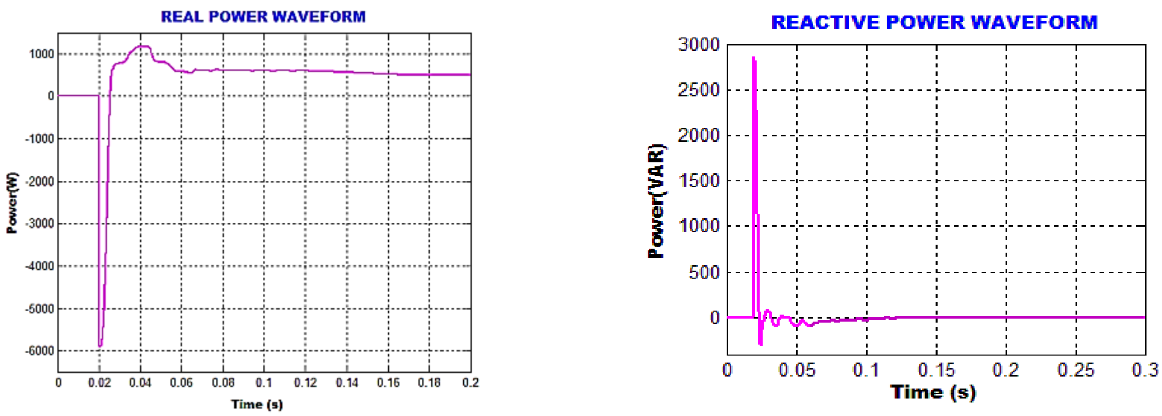
Fig.9. Output Voltage of SEPIC Converter

The SEPIC converter's output is injected in to the grid by means of VSI. The inverter's output is regulated by a PI controller that helps in eliminating the distortions by producing the control signal. Fig.10 represents the voltage and current waveform generated by grid.



(a) (b)

Fig.10. Grid waveform (a). voltage (b) .current



(a) (b)

Fig.11. Power consumption (a).real power (b). reactive power

PI controller analogizes the actual and reference power and the pulse generated by the PWM generator is given to the inverter. Fig.11. depicts the waveform of real and reactive power. The waveform clearly shows that the real power initially rises and falls before stabilizing at a constant value of 500W, on the other hand, the reactive power is zero. The proposed work's total harmonic distortion (THD) has been greatly reduced and its value is expressed as 4.57% and Fig.12 reflects the THD representation.

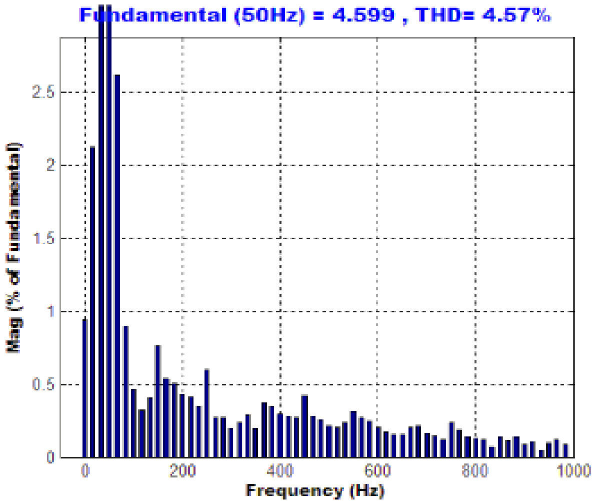


Fig.12. Source current THD

Finally, various converters' voltage gains have been analogized, so the SEPIC converter's voltage gain ratio is 1:8, the CUK converter's voltage gain ratio is 1:2 and the boost converter's voltage gain ratio can be noted as 1:1.5. As a consequence of the above contrast, the voltage transfer gain of the SEPIC converter is significantly higher than that of other traditional converters.

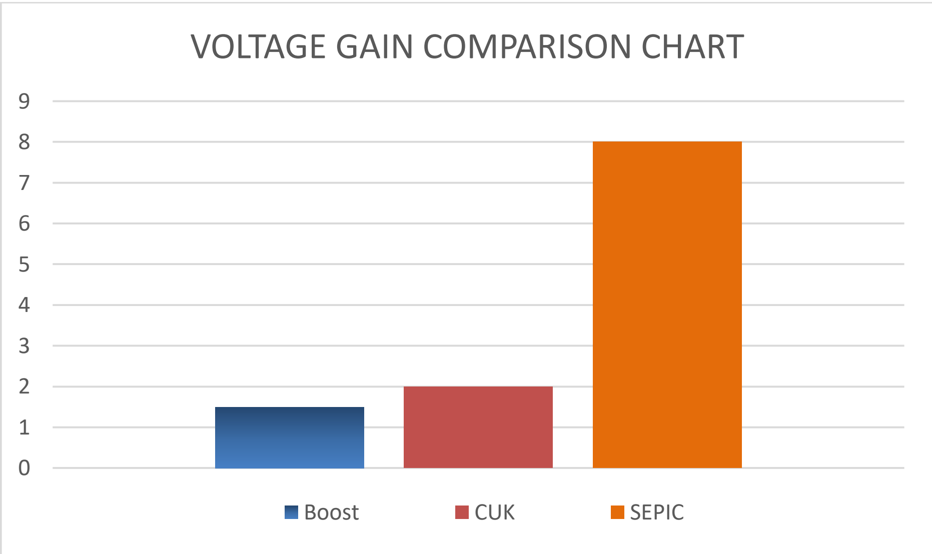


Fig.13. Voltage transfer gain comparison

As a result, the PV system with SEPIC converter and closed loop PI controller offers an excellent tracking efficiency. Also the source current THD has been registered as 4.57%, which is significantly low.

V. Conclusion

This paper presents an efficient SEPIC converter with closed loop PI controller for a grid utilized PV system. The output voltage harnessed by the PV system is not efficient hence it is fed to a SEPIC converter which provides a boosted output of similar polarity of the input voltage. It offers improved voltage gain with minimized switching losses. A VSI is employed which converts the fixed DC voltage to variable frequency AC voltage. A closed loop PI controller is utilized for evaluating the error signal and maintains the steady state error. Thus, the proposed system provides improved power quality with grid synchronization along with minimized distortion.

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