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Solar Powered Single Stage Boost Inverter with ANN Based MPPT Algorithm

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***Abstract*-This paper presents the theoretical analysis, design and simulation of a single phase single stage boost dc-ac converter powered from PV array. The main attribute of the boost inverter topology is the fact that it generates an ac output voltage larger than the dc input one, depending on the instantaneous duty cycle. This paper proposes an accurate solar panel simulation to incorporate the temperature and irradiation dependence of panel voltage and current along with neural network based MPPT algorithm. This paper also analyses the performance of proportional and integral (PI) and sliding mode controllers (SMC) for the closed loop controlling of PV fed boost inverter.**

***Index Terms*—Boost inverter, PV array, PI controller, sliding mode control (SMC) Maximum Power Point Tracking (MPPT), Neural Networks.**

I. INTRODUCTION

Recently, energy generated from clean, efficient and environmentally-friendly sources has become one of the major challenges for engineers and scientist. There are various non-conventional energy resources. Among them, the photovoltaic (PV) generation system has received great attention in research because it appears to be one of the possible solutions to the environmental problems such as global warming, air pollution, acid precipitation, ozone depletion, forest destruction and radioactive substances emission [1]-[4].In general the solar panel voltage and current is affected by the variations in atmospheric condition such as irradiation and temperature. An accurate panel modeling is needed to incorporate the parameter variations in simulation. The panel modeling based on the data sheet values is used in this paper [5]-[6].Voltage Source Inverter (VSI) is probably the most important power converter topology. It is used in many distinct industrial and commercial applications. Among these applications, uninterruptible power supply (UPS) and ac motors drives are the most important.

The conventional VSI, normally referred as buck inverter is having the characteristics that the instantaneous average output voltage is always lower than the input dc voltage. When an output voltage larger than the input is needed, a boost dc-dc converter must be used between the dc source and and inverter. This solution can result in high volume, weight, cost and reduced efficiency depending on the power and voltage levels involved. A new VSI is proposed [7]-[11], referred to as boost inverter, which naturally generates an ac output voltage lower or larger than the input dc voltage depending on the instantaneous duty cycle. In this paper a solar powered boost inverter is proposed. The closed loop regulation of the boost inverter is necessary to achieve good dynamic response under varying plant parameter conditions [12]-[13]. Proportional and integral (PI) and sliding mode controller (SMC) are theoretically analyzed.

II. PV PANEL MODELING

The possibility of predicting a photovoltaic plant's behavior in variance irradiance and temperature is very important for sizing the PV plant and converter. There are numerous methods presented in the literature, for extracting the panel parameters. In this paper a photovoltaic panel model based on the manufacturer's data sheet is presented. The equivalent circuit of the single-diode model for the PV cells is shown in fig 1 [11]. Series resistance (R_S) and shunt resistance (R_{SH}) are parasitic resistances. In this model the effect of R_{SH} is neglected to simplify the model. The output voltage of the PV cell is given by:

$$V_c = \frac{AkT_c}{e}\ln\left[\frac{I_{ph}+I_0-I_c}{I_0}\right]-R_sI_c \qquad (1)$$

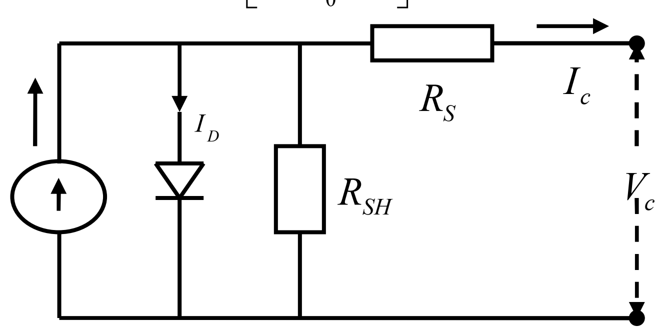


Fig 1 Equivalent Circuit of PV Cell

Active compensation of series resistance, cell output voltage and photo current are taken into account in the modeling of solar PV panel. R_s, V_c, I_{ph} are taken as a function of temperature and irradiance. Thermal voltage for variable temperature T_x

$$V_t = \frac{A_D kTn_c}{e} \qquad (2)$$

Diode ideality factor:

$$A_D = \frac{-\left(I_{mpp}-I_{sc}\right)*V_{mpp}}{V_t * I_{mpp}} \qquad (3)$$

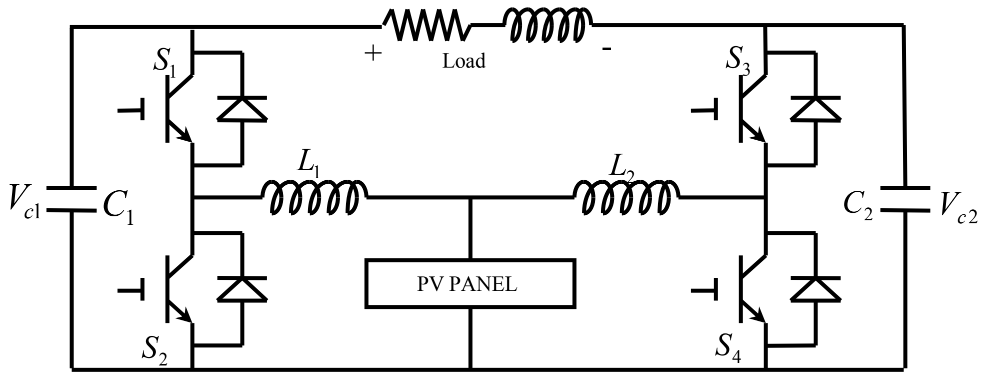


Fig 2 Single Stage Boost Inverter

Series resistance calculation using datasheet values:

$$R_s = -V_{mpp} - \ln\left[\frac{-I_{mpp}+I_{sc}}{I_{sc}}\right]\left[I_{mpp}-I_{sc}\right]\frac{V_{mpp}}{I_{mpp}} + V_{oc} \quad (4)$$

Open circuit voltage:

$$V_{oc} = \ln\left[\frac{I_{sc}}{I_0}\right]V_t \quad (5)$$

Temperature dependence of voltage:

$$V_{ocT} = V_{oc} + K_v\left(T_x - T_c\right) \quad (6)$$

The short circuit current and photo current were considered to be proportional to the value of irradiation:

$$I_{scG} = I_{sc}S_x \quad (7)$$

$$I_{phG} = I_{ph}S_x \quad (8)$$

Dark saturation current:

$$I_0 = \frac{-I_{scT}}{-e^{\frac{V_{oc}}{V_t}} + e^{\frac{I_{scT}R_s}{V_t}} - 0.001} \quad (9)$$

The output voltage of the PV panel, compensated for irradiance and temperature:

$$V_x = \frac{-I_xR_s + \ln\left[-I_x e^{\frac{V_{oc}}{V_t}} - I_x e^{\frac{I_{scT}R_s}{V_t}} - I_{sc} e^{\frac{V_{oc}}{V_t}}\right]}{I_{sc}} \quad (10)$$

PV current compensated for irradiance and temperature:

$$I_x = I_{scT}S_x \quad (11)$$

III. THE BOOST INVERTER

The boost inverter achieves DC – AC conversion as follows: the power stage consists of two current bi-directional boost converters and the load is connected differentially across them (Fig. 2). These converters produce a DC - biased sinusoidal waveform (Fig. 3), so that each converter produces a unipolar voltage. The modulation of each converter is 180 degrees out of phase with respect to the other, which maximizes the voltage excursion over the load [7]-[8].

Steady state analysis

The analysis of the boost inverter under steady state is done by considering one converter as a voltage source (Fig. 4). The gain of the converter vs. the duty cycle is obtained by [9].

$$V_o = 2V_a - 2V_{dc1} \quad (12)$$

$$\frac{V_o}{V_{in}} = \frac{2D - G_n\left(1-D\right)}{\left(1-D\right)} \quad (13)$$

Where Gm is the maximum gain (V_{op}/ V_{in}), V_{op} is the peak output voltage, Va is the capacitor voltage V_{dc}, is the dc component of V_a. The inductor current depends on the demanded current and maximum gain; it is determined by [9],

$$I_L = \frac{2D - G_m\left(1-D\right)V_{IN}}{\left(1-D\right)^2 R} \quad (14)$$

The gain characteristic of the boost inverter is shown in fig. 5. With Gm=4. It is interesting to note that the feature of zero output voltage is obtained for D=0.5. If the duty cycle is varied around this point, then there will an ac voltage at the output terminals.

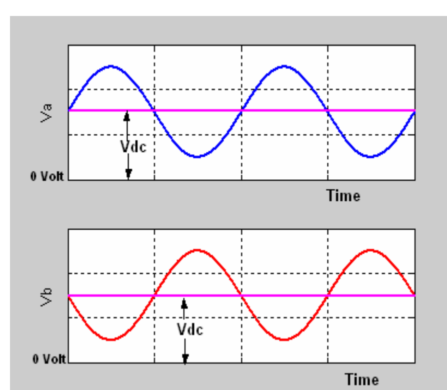


Fig. 3. Output voltage for each DC-DC converter

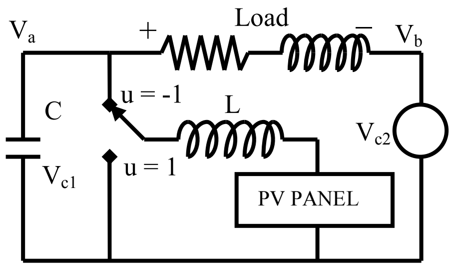


Fig. 4. Simplified circuit of boost inverter

System modeling

The boost inverter is modeled as two dc-dc boost converters, but one of them is considered as an ideal sinusoidal voltage source plus a dc component. The system model is given by [9].

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\end{bmatrix} = \begin{bmatrix}0 & -\frac{W_o}{2}\\ \frac{W_o}{2} & -W_1\end{bmatrix}\begin{bmatrix}X_1\\ X_2\end{bmatrix} + \begin{bmatrix}0 & \frac{W_o}{2}\\ -\frac{W_o}{2} & 0\end{bmatrix}\begin{bmatrix}X_1\\ X_2\end{bmatrix}u + \begin{bmatrix}b\\ c\end{bmatrix} \qquad (15)$$

Where $X_1 = I_L\sqrt{L}, X_2 = V_c\sqrt{C}, W_o = 1/\sqrt{LC}, W_1 = 1/RC, b = V_{in}/\sqrt{L}$

$C = V_b/R, u = \begin{cases}1\\ -1\end{cases}$

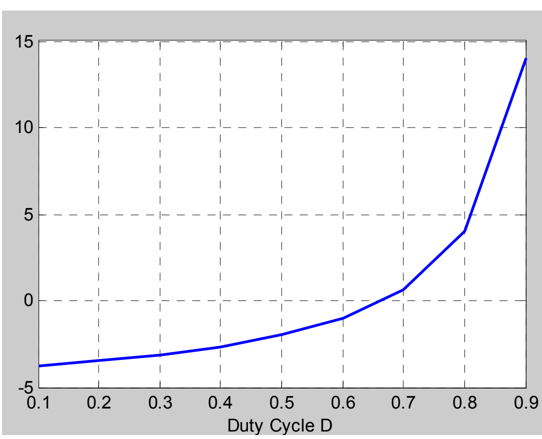


Fig. 5. Gain vs. Duty cycle for the boost inverter (Gm=4)

Design of boost inverter

The inductor and capacitor values are calculated based on the inductor current and capacitor voltage ripple. The switching frequency should be greater than the output voltage frequency. The DC component of the capacitor voltage V_{dc} must be calculated as:

$$V_{dc} \geq \frac{V_{op}}{2} + V_{in} \qquad (16)$$

The maximum capacitor voltage and inductor current is determined by:

$$V_{c\max} = V_{dc} + \frac{V_{op}}{2} \qquad (17)$$

$$I_{L\max} = \frac{2D_{\max} - G_n\left(1 - D_{\max}\right)V_{in}}{\left(1 - D_{\max}\right)^2 R} \qquad (18)$$

$$Where\ \mathrm{D}_{\max} = 1 - \frac{V_{in}}{V_{dc} + \frac{V_{op}}{2}}, G_m{}' = \frac{2\left(V_{dc} - V_{in}\right)}{V_{in}}$$

The inductance and capacitance are calculated with a 20% ad 1.5% of ripple respectively.

$$L = \frac{t_{on}}{0.2I_{L\max}}V_{in} \quad \text{and} \quad C = \frac{t_{on}}{0.015V_{c\max}}I_{op} \qquad (19)$$

Where I_{op} = Peak output current and $t_{on} = \frac{D_{\max}}{f_{\max}}$

IV. TRAINING OF NEURAL NETWORK

The training of a neural network consists of solar irradiance and cell temperature as the input patterns. The target pattern is given by measured I_{mp} for training the neural network. The I_{mp} is calculated for different values of irradiance and cell temperature with respect to above modeled PV module. This calculated I_{mp} values are given as a training data to the neural network. Fig (6) shows the structure of neural network used for training and Fig (7) shows the convergence of error during training process. During the training process, the convergence error is taken as 0.01.

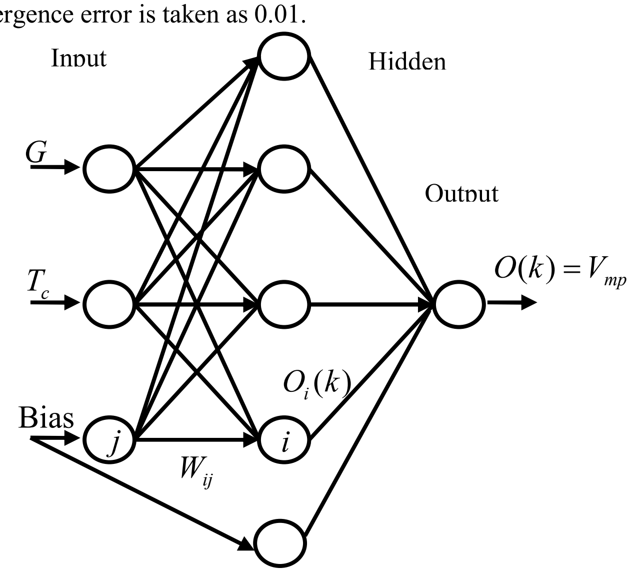
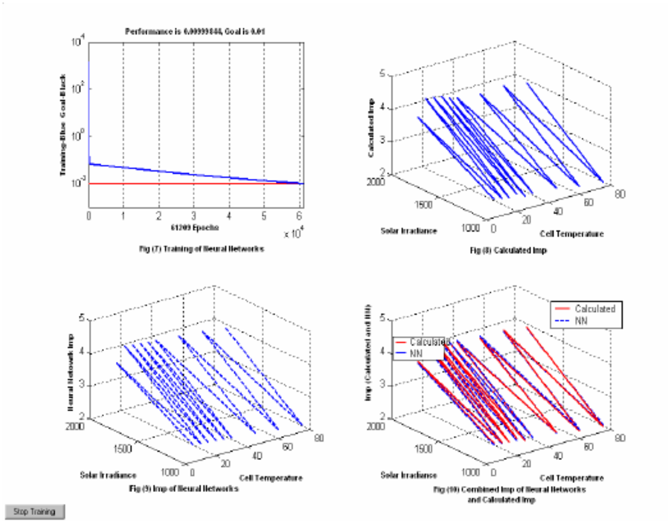


Fig 6 Neural Network Structure

The below graphs represent the I_{mp} of the neural network and the actual value of the PV model. The both graphs are compared as shown in fig (10) we can conclude that the neural network based MPPT gives the best results as close as the actual values of the PV model. Once the value of I_{mp} is calculated the value of maximum voltage point corresponding to the value of I_{mp} can be found out from look up tables.



V. PI CONTROLLER

The proportional and integral (PI) controller is very simple and easy to implement. It improves the system gain and eliminates the steady state error. The output signal from the PI controller is:

$$U(t) = K_p e(t) + K_p / T_i \int e(t)dt \qquad (20)$$

The value of proportional gain (K_p) improves the system gain and thus the steady state tracking accuracy, disturbance signal rejection and the relative stability. The proportional and integral gain (K_i) values are chosen based on the maximum overshoot and system stability.

VI. SLIDING MODE CONTROLLER

For the purpose of optimizing the boost inverter dynamics, while ensuring correct operation in any working condition, a sliding mode controller is a more feasible approach. The main advantage over the classical control schemes is its insusceptibility to plant parameter variations that leads to invariant dynamics and steady-state response in the ideal case. But compared PI controller the control theory involved is rather complex. The sliding surface is a linear combination of the state variables. SMC forces the system to be held in the surface and system is driven to the equilibrium point.

$$\sigma = SX - SX_r = S_e X \qquad (21)$$

Where $S = [S_1 \quad S_2]$, X is the state variable, X_r is the reference variables and $eX = [eX_1 \quad eX_2]^T$ .The condition for the existence of sliding mode is

$$\sigma \dot{\sigma} < 0 \text{ and } S_1 X_2 - S_2 X_1 > 0 \qquad (22)$$

Since X_2 is always positive, X_1 must be positive.

The sliding mode uses two state variables to control the boost inverter, capacitor voltage and the inductor current. For capacitor voltage the reference is a sinusoidal voltage plus a dc component. This reference is independent of voltage. The other state variable is inductor current. The level of this current depends on the load. To avoid the dependence of the current with load, the measured current is filtered using a high pass band filter to obtain the ripple at switching frequency that simulates the error. In the boost inverter, since the current is varying in nature. The cut off frequency of the high pass band filter must be chosen carefully. It must be high enough to eliminate the 50Hz frequency of the current, but not too high that distort the current ripple that simulate the error. (At least 25% higher than 50Hz). Sliding mode controller scheme is shown in fig. 11. The controller parameters are calculated based on the boundary condition.

$$S_1 = \frac{S_2 X_{1p}}{X_{2p}} \qquad (23)$$

Where $X_{1p} = I_{L\max}\sqrt{L}$ and $X_{2p} = V_{c\max}\sqrt{C}$

SIMULATION *PV panel*

The inputs given to the models are current ramp I_c (0 to I_{sc} to simulate the varying current of the panel), T_X the variable ambient temperature and S_X the variable irradiance. The results can be viewed in Figure 12 (a and b) and 13. It may be observed, that with rising temperature, the output voltage of the panel, and implicitly the output power, decreases. The value of the current is not greatly affected by changes of temperature. Irradiance, lower than STC irradiance causes the output voltage, current and power to fall, shown in fig.12.

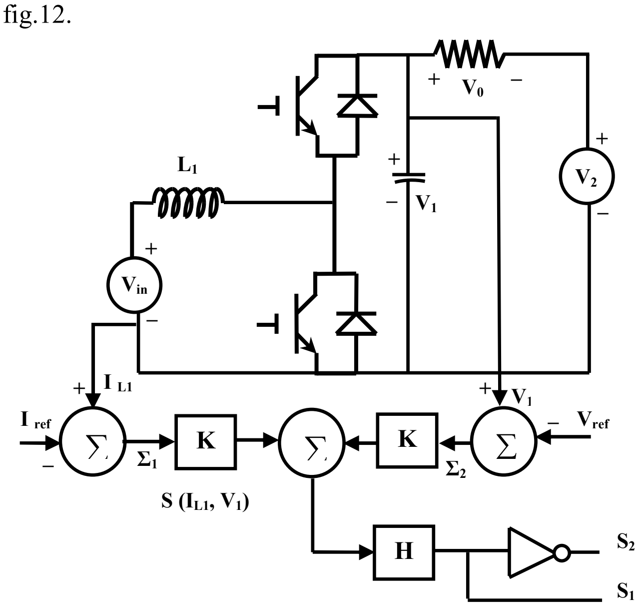


Fig (11) Block Diagram of Sliding Mode Controller.

PV fed open loop boost inverter

The simulation of the boost inverter is done with circuit parameters with Input voltage V_{in}= 42 V, Output voltage V_o=100 Sin(ωt), Output frequency f_0= 50Hz, Switching frequency f_s=30KHz, Load resistance R= 50Ω Inductance L1 and L2=500µH, Capacitance C1 and C2=20µFThe simulation results of a PV fed single stage boost inverter are shown in figure 14. The panel voltage is considered to be varying due to the variation in the irradiance.

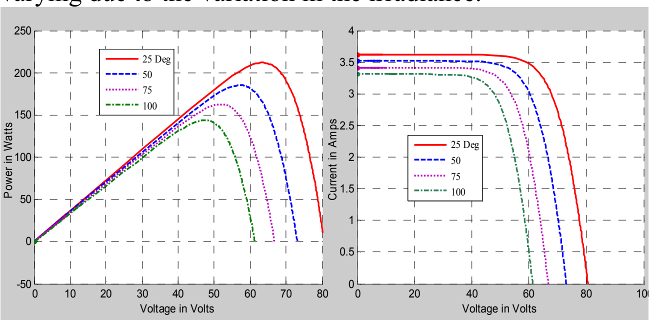


Fig 12 PV and VI Characteristics with Constant Irradiance of 1400 W/Sq.M

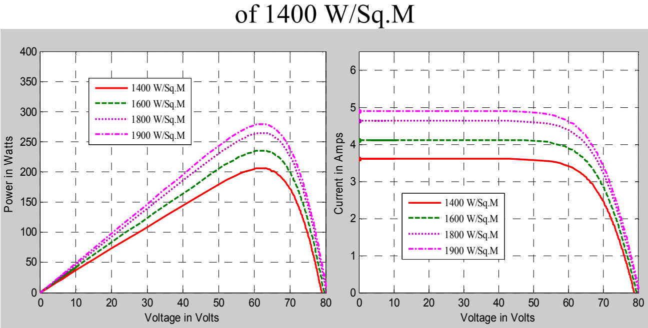


Fig 13 PV and VI Characteristics with Constant Cell Temperature of 25^0C

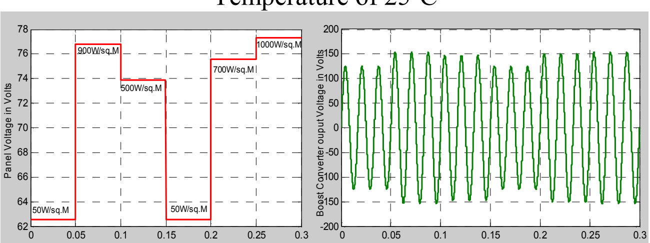


Fig.14. Simulation results of open loop PV fed boost inverter

PV fed boost inverter with PI controller

The simulation results of a PV fed single stage boost inverter are shown in figure 15. The panel voltage is considered to be varying due to the variation in the irradiance. From figure 15 it is clear that the dynamic response of the PI Controlled PV fed boost inverter is poor.

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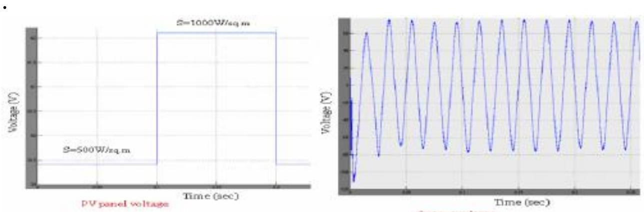

Fig.15. Simulation results of PI Controlled PV fed boost inverter

PV fed boost inverter with SMC controller

The simulation results of a PV fed single stage boost inverter are shown in figure 16. The panel voltage is considered to be varying due to the variation in the irradiance

CONCLUSION

A solar powered boost inverter has been proposed and simulated. The accurate solar panel has been designed to change the panel voltage and current with the changing atmospheric condition. Due to the parameter variations closed loop controlling has been employed to improve the system performance. A simple PI controller has been employed and found from the simulation that system is not completely robust. To improve the dynamic stability and robustness sliding mode controller has been proposed and simulated. It has been observed that the system is robust and insensitive to parameter variation when it is controlled by sliding mode controller. A PV fed boost inverter is useful for applications in which the instantaneous output ac voltage should be larger than the input dc voltage. The total harmonic distortion of the open loop boost inverter is below 5. And also the proposed inverter is very environmental friendly as it is powered by solar panel. Reference Points for the controllers are fed from neural networks.

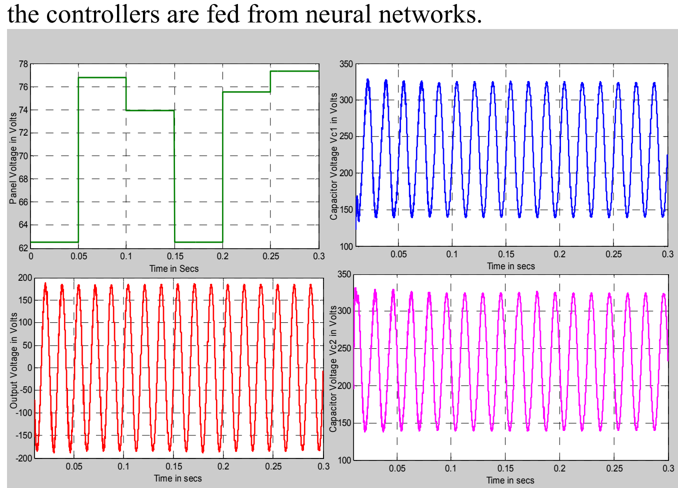

Fig.16. Simulation results for sliding mode controlled PV fed boost inverter

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