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Modeling and Analysis of the Photovoltaic Array feeding a Single Phase SPWM Inverter

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ABSTRACT

In this paper advanced modeling and analysis of the photovoltaic cell in Matlab/ Simulink environment has been discussed. The solar cell model has been developed on the basis of the performance equation of the photovoltaic cell. The effect on the performance due to solar radiation change and the change in temperature has been successfully incorporated in this model. The major contribution made by the paper is development of single phase Sinusoidal Pulse Width Modulated Inverter which being fed by the developed photovoltaic cell. The inverter output performance analysis has been carried in terms THD analysis using FFT in power GUI block. By using the inductive load at the output of the inverter sharp decrease in the output current and voltage waveforms THD is obtained which lead to improved performance of the SPWM inverter.

***Keywords-* Photovoltaic cell; solar radiation; solar Array; SPWM inverter; THD; Matlab-Simulink.**

I. INTRODUCTION

Solar energy which come on the earth in the form of solar irradiance have a great potential to fulfil the electric energy demand of the earth .The energy from the solar irradiation can be harvested by using photovoltaic (PV) power generation technology in which the irradiation is converted into electricity by using solar cell. When photon strikes to solar cell electrons emits and current start to flow, by proper arranging of these solar cell in series and parallel more voltage and current can be produce. Now these days because of advancement in the technology coast of PV system is reducing. As we know that the fissile full are decaying day by many countries preferring the development of PV system to cope the lack of fossil fuel and pollution issue. If large power is generated using PV generation technology than it can be considered as an new alternative solution for the future energy requirement for the coming century's energy arrangement [1].The output voltage obtain from a cell is very small however output voltage can be increased by connecting different cells in the form of panels or modules. An large arrays is obtained by connecting different panels in parallel or/and series . The word *array* is normally used to narrate a photovoltaic panel [2].

The performance of a PV array system depends on the operating conditions as well as the solar cell and array design quality. It is to be observed that the PV array output voltage, current and power changes with the change of solar irradiation, temperature and load current. Therefore the effects of these three quantities must be considered in the design of PV arrays so that any change in temperature and solar irradiation levels should not adversely affect the PV array output to the load/utility, which is either a power company utility grid or any stand-alone electrical type load. Therefore, PV array systems should be designed to operate at their maximum output power levels for any temperature and solar irradiation level at all the time [3,4].

A great deal of research and development for the photovoltaic power generation system has being conducted in order to get renewable and non-polluting sources. Various auxiliary power circuit configurations using photo voltaic arrays have been proposed.Hingaet al propose a novel multi-step PWM inverter for a solar power generation system. The circuit configuration is fabricated by adding a bi-directional switch to the conventional bridge type inverter circuit using the isolated DC power supply for which the solar cell is very suitable. This new type of PWM inverter fabricated offers advantages such as good output waveform, small size of filter, low switching losses, and low acoustic noise [5].

Kinyuaet al propose a novel multi-step PWMinverter for solar power generation system. The presented type of multi-step PWM inverter has special features such that it can be connected conveniently to separate solar cell modules that contribute to an easy implementation of the photovoltaic power generation system [6]. Nonaka, S. suggest a novel three-phase sinusoidal PWM voltage source inverter (VSI). This inverter has an additional arm to the normal PWM three-phase bridge circuit. The additional arm contributes to reduce the ripple in the AC output current [7]. Mekhilef et al proposes a single phase grid connected inverter with the characteristic that when the power supplied by the solar cell is more than the power as required by the load, the excess power is fed to the utility line through a reverse power flow [8] . Dehbonei et al explores the orientation of the space vector modulation (SPM) technique to a photovoltaic assisted single-phase line-interactive inverter. This inverter operates as an uninterruptible power supply (UPS). The performance of this inverter is comparable to a unipolar sinusoidal pulse width modulation (SPWM) operating at higher switching frequencies [9].

The major contribution made by this paper work is development of the mathematical model of the solar cell comprising the effects of the change in operating temperature and solar radiation in the Matlab/Simulink environment and its connection to single phase SPWM for harnessing the solar energy. The research works has been divided into two parts. The first part deals with the effect of change in solar radiation and operating temperature and the second part deals with the development of the SPWM inverter and harmonic analysis for the output voltage of the proposed inverter. The output of the developed inverter shows drastic decrease in the harmonics with inductive load which faithfully maintains the power quality issues.

II. MATHEMATICAL MODELING OF THE SOLAR CELL

This section deals with the detailed mathematical modeling of the solar cell. The equivalent circuit of the solar cell available in the literature is shown in figure below. From the circuit diagram it is clear that the single unit of the solar cell has been replaced by an equivalent current source bypassed by a diode circuit. Therefore the current flowing through the load is given by equation (1)

$$I = I_{ph} - I_s(e^{\frac{q(V+IR_s)}{NkT}} - 1) - \frac{(V+IR_s)}{R_{sh}} \tag{1}$$

In this equation, $I_{ph}$is the photocurrent,

$I_s$is the reverse saturation current of the diode,

*q*is the electron charge, *V* is the voltage across the diode,

K is the Boltzmann's constant,

T is the junction temperature,

N is the ideality factor of the diode, and

R_s and R_{sh} are the series and shunt resistors of the cell, respectively.

The above equation takes into account the effect of the solar radiation and the effect of change in temperature due to the change in temperature.

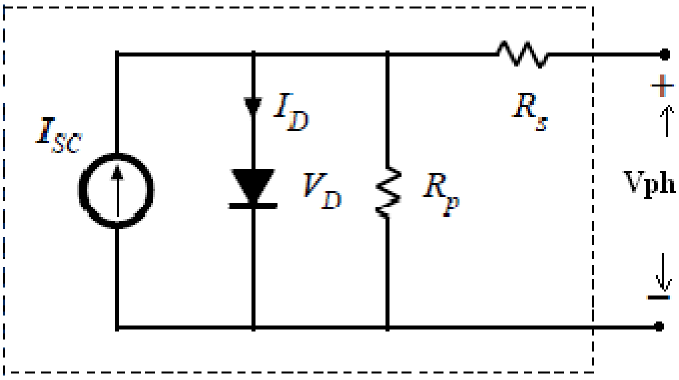


Figure1: Equivalent circuit of the PV cell

Nomenclature:

Exponential equations for circuit diagram of the PV model: k – Boltzmann's gas constant; $1.38x10^{-23}$ J/K;TR – Reference temperature of the cell; 300 ºK; TP – Photovoltaic panel temperature; e – Electronic charge; $1.602x10^{-19}$ J/V; V – Voltage imposed across the cell (V); ISCR – Short circuit current; under STC; I-V – Panel outputcurrent and voltage; I_{OS} – Panel dark saturation current, which depends strongly on temperature (A); IOR – Panelsaturation current, which depends on TR; K – Short circuit temperature coefficient; 0.0017 (A/ºC); C – Solar irradiance (W/m²); ILG – Generating current by solar radiation; EGO – Band gap voltage; 1.1eV for Si; A – Diode quality factor; 1.92; R_S – Series resistance of cell (in ohms); R_{SH} – Shunt resistance of cell (in ohms).

2.1 Effect of Change of Solar Radiation on the Solar Cell Current:

There is a direct effect of the solar radiation or solar energy on the output solar cell current. The solar energy consists of photons of energy which when strike with the surface of the crystalline silicon material of the solar cell, emit energy which is given by the following mathematical relation:

$$I = [I_{sc} - K_i(T - 298)]\frac{\beta}{100} \tag{2}$$

In equation (2)

K_i is the cell's short circuit current temperature coefficient (0.0017 A/◦C) and

β is the solar radiation (W/m^2).

2.2 Effect of Change in Operating Temperature on Solar Cell:

There is a drastic change in the value of the reverse saturation of the solar cell when the operating temperature changes abruptly. The following mathematical equation explores the effect of the change in the value of the current I_s due to the change in operating temperature. The following mathematical equation explores the relation between I_s and temperature T

$$I_s(T) = I_s \left(\frac{T}{T_{nom}} \right)^3 (e^{\frac{qE_g}{NkT}(\frac{T}{T_{nom}} - 1)} - 1)$$

where

I_s is the diode reverse saturation current,

T_{nom} is the nominal temperature,

E_g is the band gap energy of the semiconductor and

V_t is the thermal voltage.

2.3 Derivation for the output voltage of the Solar Cell:

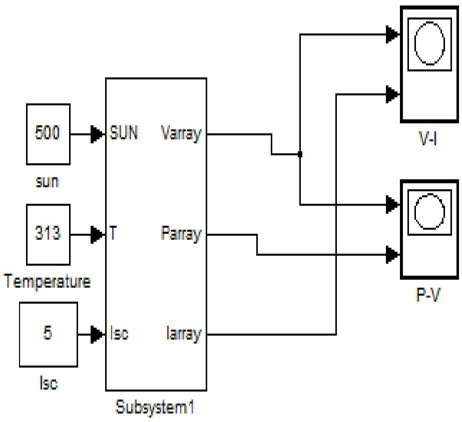
Now from the equivalent circuit of the solar cell shown in figure (1), the voltage across the load connected to the output terminal of the inverter can be given by the below mathematical expression

(3)

$$V_c = \frac{AkT}{q} \ln(\frac{I_{ph} + I_s - I}{I_s}) - R_s I$$

III. MODELING OF THE SOLAR CELL WITH SIMULINK:

For carrying out the mathematical modeling of the solar cell consider the performance equation of the solar cells which are given by the equations (1), (2), (3) and (4). These three equations are combined together and the output of the solar cell appears in the form of the output voltage dc in nature and having stable magnitude. The modeling of the solar cell has been carried in Simulink environment. The Simulink diagram is shown in figure (2). The figure (3) shows the subsystem1 part of the figure (2) which is the model of the solar cell in Matlab/Simulink environment. The figure 4 shows the subsystem2 of the figure 3 which is the sub model of the solar cell in Matlab/Simulink environment.



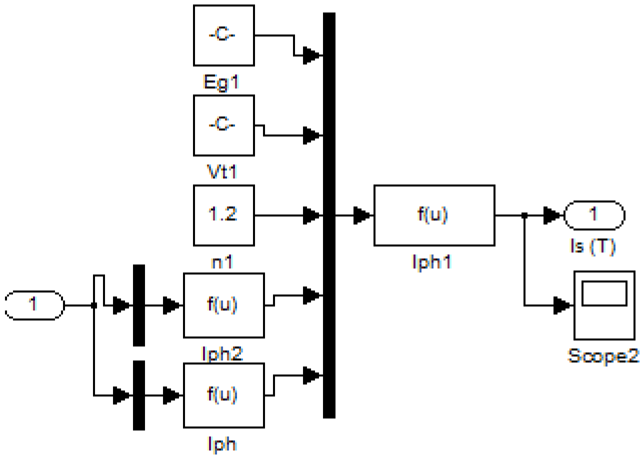


Figure 2.The Simulink model of the solar cell

Figure 4. Simulink model of the Subsystem 2

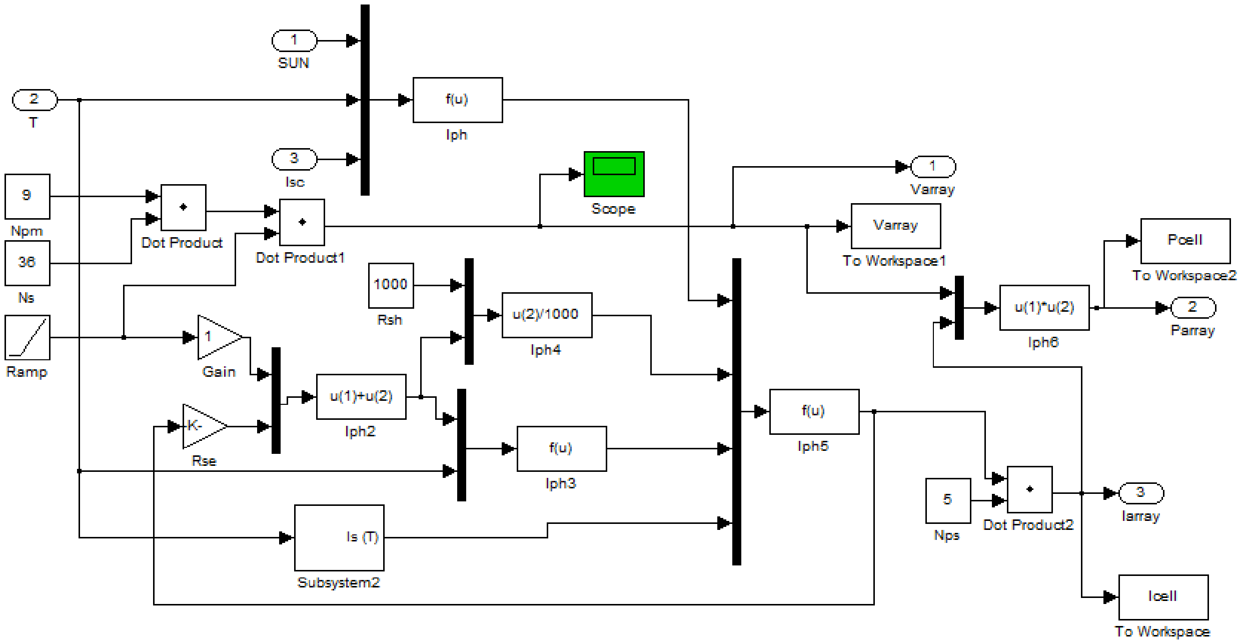


Figure 3.The Simulink model of the subsystem 1 (Single Solar Cell Unit).

3.1 Simulation Results of Solar Cell:

Effect of Change in Operating Temperature and Solar Radiation:

From the discussion carried so far it is clear that the value of V_{ph}, I_{ph} and output power P of the solar cell is totally dependent on operating temperature and corresponding solar radiation present on any particular day. Therefore the performance analysis of the solar cell has been carried for the four operating temperature ranges of 40, 50, 60 and 70 ^{0}C. The values of the solar radiations are assumed to be 500, 700, 900 and 1100W/m^2.

Figure 5 shows the I-V and P-V output characteristics of PV module with varying irradiance at the constant temperatures and varying temperature and constant irradiance. Figure 5 (a) shows the I-V characteristics at constant temperature and different insolation levels. It is describe that the PV output current increases rapidly with increase in insulation level and the curve reach to its maximum value .This point is call maximum operating point, at this point maximum power can be draw by the load from PV system.

The optimum operating points changes with the solar insulation, temperature and load conditions. Figure 5(b) shows the P-V characteristics of the PV module at different irradiance and at the constant temperature. From the graphs, it can be illustrated that the output current and voltage increases with the increases in irradiance,. This lead to the net increase in power output with an increase in irradiance at the constant temperature.

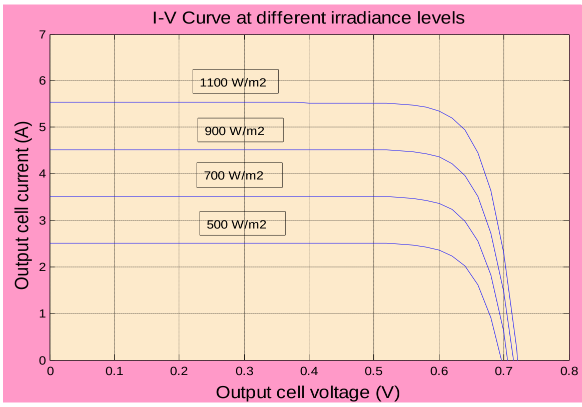


Figure 5(a)

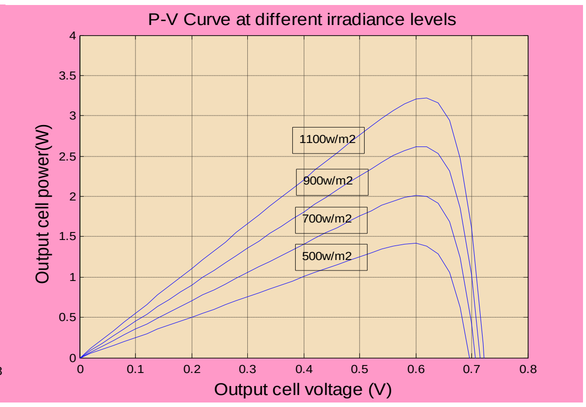


Figure 5(b)

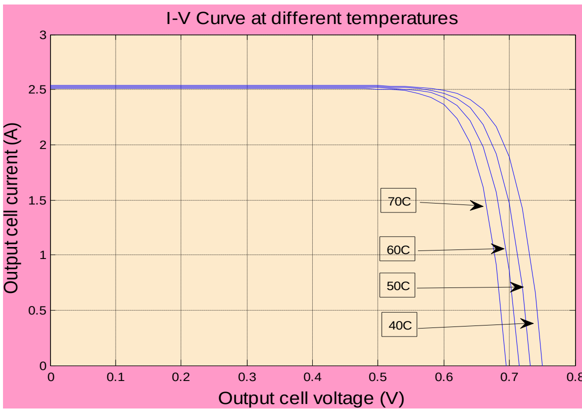


Figure 5(c)

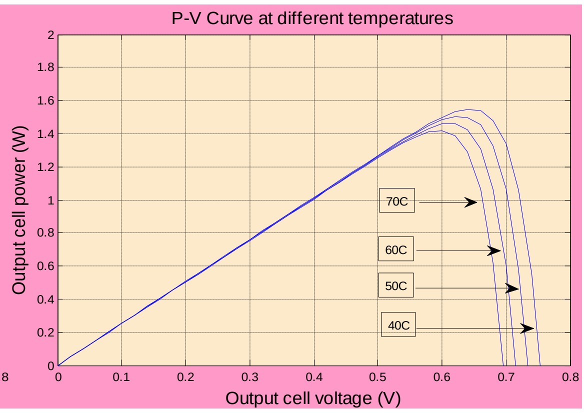


Figure 5(d)

Figure 5: Plots of I vs V and P vs V at different insolation levels and temperatures.

The I-V and P-V characteristics under constant irradiance with varying temperature are presented in figure 5(c) and 5(d) respectively. When the operating temperature increases, the current output increases marginally but the voltage output decreases drastically, which result in net reduction in power output with a rise in temperature.

3.2 Simulation of Solar Array:

The output of the single solar cell is very small and it has no significance for any practical use. Therefore the normal practice is connect a number of tiny solar cell in series to increase its output voltage which give rise to a structure which is called a string of cells. A typical string consists of 36, 54, 60 or 72 cells in series. These cells are connected in parallel to increase the current rating of the panel and this structure is called the solar module.

When different solar modules are connected in series and parallel so to produce appropriate voltage and current the structure so formed is called the solar array. A single solar cell produces an open circuit voltage of 0.7V. In the given circuit 36 cells are connected in a string to produce a typical voltage of 25.2 V and 5 strings are connected in parallel so as to produce a typical output current of 12.5 A in the form of solar module. Ultimately 9 solar modules are connected in series to produce an output voltage of 226.8 V= 230V in the form of solar array. The figure 6(a) and 6(b) shows the I-V curve and P-V curve of the solar array at the temperature of 40^{o}C and solar irradiance of 500W/m^2.

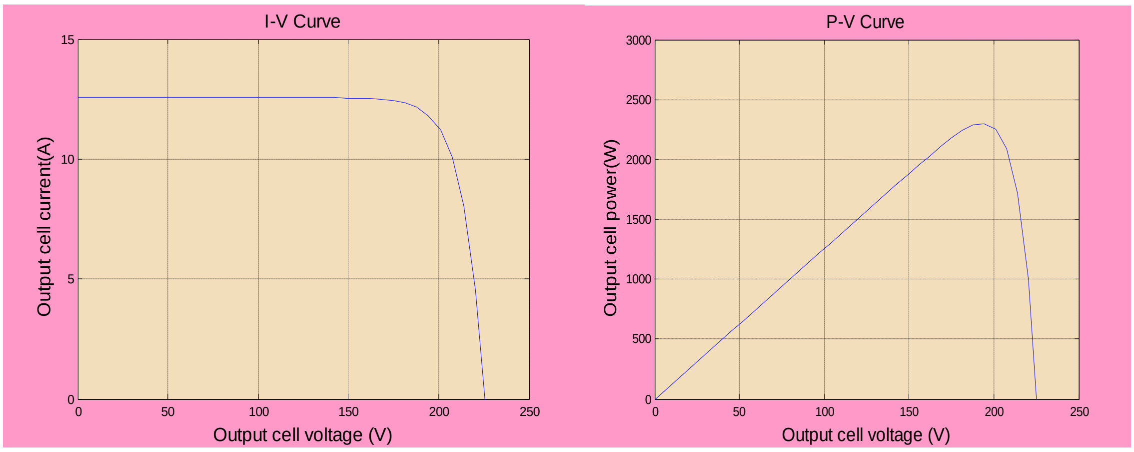


Figure 6(a) **Figure 6(b)**

Figure 6. Plot I-V and P-V characteristics of the typical solar array

3.3. Simulation of Single Phase PWM Based VSI Inverter:

The figure 7 shows the Simulink model of the single phase solar array based sinusoidal pulse width modulated voltage source inverter. The output of solar array is fed to the subsystem3 which is the SPWM inverter. The output of the solar cell consists of the dc voltage and the harmonics . Therefore filter circuits are needed to make the output of the solar cell steady and ripple free. The filter circuit consists of the parallel combination of R and C connected across the subsystem 3. The typical values of the R and C for the filter circuit are chosen as R=10 ohm, and C= 400 MFD. A diode is also connected in series with output of solar cell so as to prevent the reverse flow of the load current.

The subsystem 3 consists of the single phase MOSFET based inverter circuit. The Simulink model of the single phase inverter is shown in figure 7 in the form of subsystem 3. Voltage source pulse width modulated inverter is made up of four MOSFETs switches in H-bridge form and fed by the solar cell. MOSFET switches have been used because of the number of advantages offered by them for switching purpose for low voltage range. For higher power

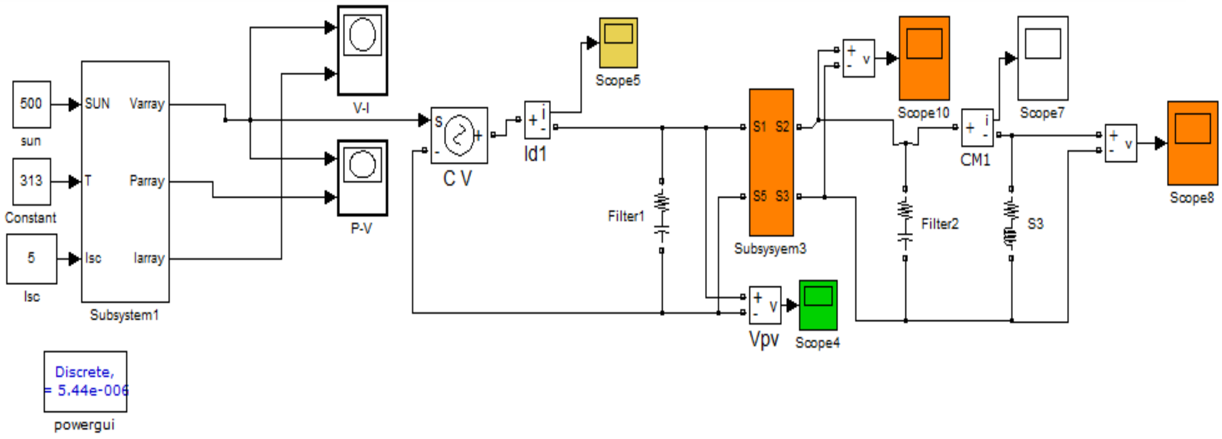


Figure 7. Single phase solar array fed SPWM voltage source inverter

range IGBT based switches are used. The required single phase output is taken from the two arms of H-bridge circuit which is connected to the load on the output side. The harmonics present in the output voltage and the load current has also been measured. The evolution of the harmonic contents has been carried out by its THD and the harmonics spectrum has been extracted using the FFT analysis. Scope7 measure the RMS and THD of the load current. Similarly scope 8 shows the RMS value and THD of the output voltage V_{ab}. The output of the solar cell is fed to the subsystem 3 [10].

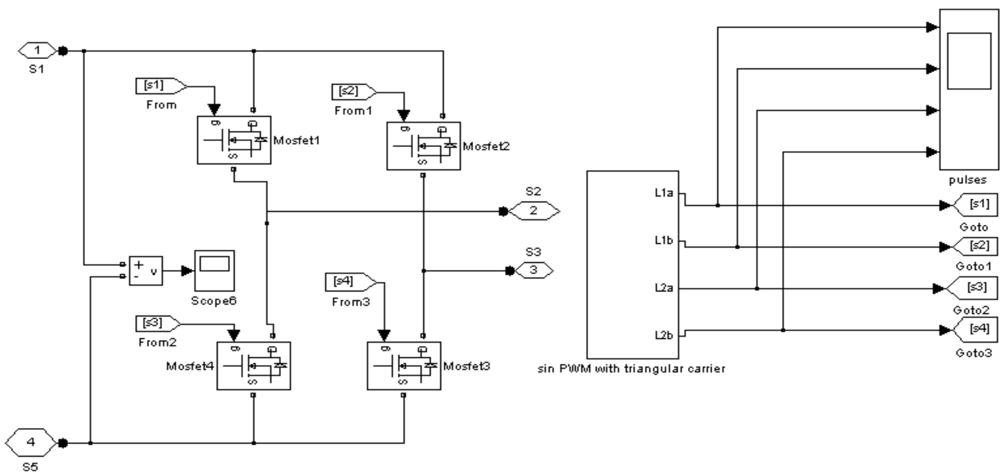


Figure 8: Equivalent circuit of the single phase Sinusoidal pulse Width modulation Inverter (SPWM)

3.4 Generation of Gating Pulses:

The gating pulses for the 4 MOSFETS switch of the voltage source inverter is obtained by using Sinusoidal Pulse Width Modulation (SPWM) technique. Many methods are available for generating PWM voltage i.e. unipolar and bipolar voltage switching.. This work deals with unipolar switching scheme [11] as it offers the number of advantages rather than bipolar scheme.

3.5 Unipolar Switching Scheme:

The unipolar switching is widely used for the implementation of the single phase as well as multiphase inverter. It is because the value of THD is smaller for unipolar switching as compared to bipolar switching. The Simulink model of this switching scheme is shown in figure 9. The waveform of the output pulses are shown by scope 'pulses'. The switching frequency of the inverter switches is taken as 50 kHz.

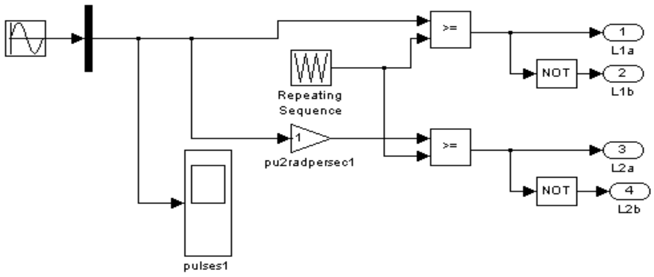


Figure 9: Switching circuit of SPWM Inverter

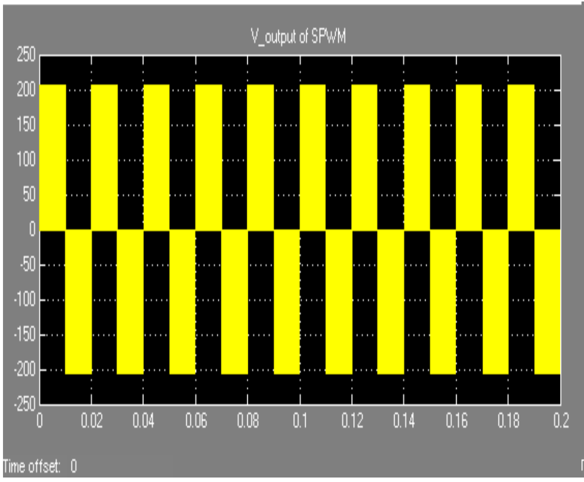
IV. SIMULATION RESULTS OF SINGLE SPWM INVERTER

Simulink results are obtained by modeling the circuit in MATLAB simulink environment. The sinusoidal pulse width modulation technique in under modulation range($m < 1$) is used for the output voltage and load current performance analysis of the inverter and motor . In this case the value of modulation index m=0.8. The load connected at the output of the inverter is considered to be inductive load having the value of R = 10 ohm and L =70 mH. Figure 10(a) and 10(b) gives the graph of the output load voltage and the load currents.

Similarly the figure 10 (c) and 10 (d) shows the harmonic spectrum of the load voltage and the load current. It is clear from the harmonic spectrum analysis that the total harmonic distortion (THD) of the load voltage is 56% and that of the output current is only 1.62% which is very small and can be safely neglected. The waveform of the load current shows the purely sinusoidal waveform. These THD values of the voltage and current have been calculated for an operating temperature of 40 ^{o}C and solar radiation of 500W/m^2. Due to the low harmonic content in the phase voltage , the output current is sinusoidal even if the power factor is near unity.

4.1 Simulation Results at Different Radiation and Temperature:

Since the inverter is fed by solar cell there output of the inverter will be affected by variation in temperature and solar radiation .First of the performance of the inverter is studied at constant temperature and at varying insolation levels. The corresponding values of the output voltage, load current and their harmonic contents are also noted down. From these results, the magnitude of the harmonics remains almost constant but the magnitude of the output voltage and current is affected following the same trend as in show in figure 10 for change in values of insolation level and temperature.



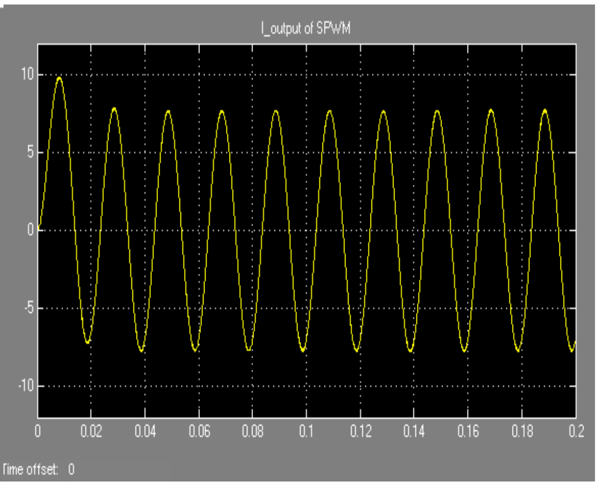
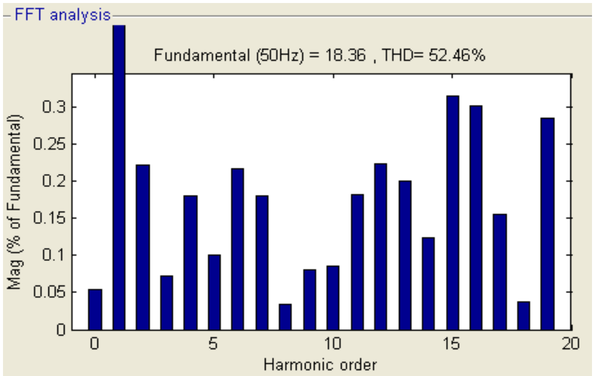


Fig. 10(a): Inverter Output voltage **Fig. 10(b): Inverter Output current**



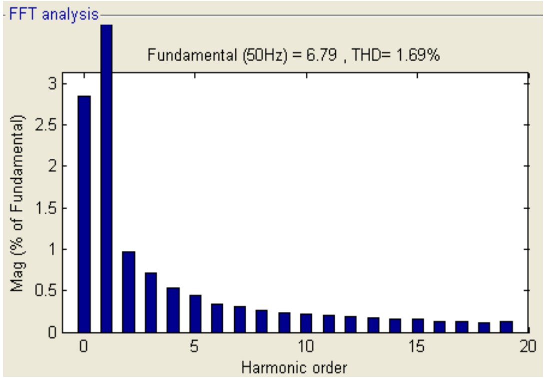


Fig.10(c): Harmonic Spectrum of output load voltage **Fig.10(d): Harmonic Spectrum of output load current**

V. CONCLUSION

This paper deals a solar cell driving a PWM inverter has been proposed which utilizes Sinusoidal pulse width modulation technique for its implementation. The effects of the different operating variables like the solar radiation and the operating temperature of the photovoltaic cell and its impact on the output voltage, current and their harmonic contents has been elaborated . The advantages of the proposed solar cell based inverter are low harmonic contents in the output voltage and almost sinusoidal output load current. Simulation of the complete system for different operating conditions have been made in MATLAB-SIMULINK programming environment.

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