Solar PV cell based Multilevel Inverter fed Induction Motor

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***Abstract*—** Due to the increased Electricity consumption Renewable energy sources such as sun, wind etc., are widely adopted for Electric Power generation. Integration of Renewable energy sources to the grid plays a major role in utilization of energy. Renewable energy sources cannot be directly connected to the grid. Power Electronic converters play a major role in interfacing renewable energy sources to grid or load. The poor quality of voltage and current of a conventional inverter fed induction machine is due to the presence of harmonics and hence there is significant level of energy losses. The Multilevel inverter is used to reduce the harmonics. The inverters with a large number of steps can generate high quality voltage waveforms. The higher levels can follow a voltage reference with accuracy and with the advantage that the generated voltage can be modulated in amplitude instead of pulse-width modulation. This paper discusses photovoltaic (PV) based Multilevel inverter fed Induction Motor topology with involves Pseudo carrier modulation technique as control scheme. The topology offers much less total harmonic distortion. The PV system is verified through simulation in MATLAB/SIMULINK and the FFT spectrums for the outputs are analyzed to study the reduction in the harmonics.

Index Terms— Induction Motor, Multilevel three phase inverter, THD, Renewable energy sources

I. INTRODUCTION

Nowadays the power obtained from solar and wind energy are connected to the grid for better utilization of renewable energy sources. The power extraction from renewable energy sources cannot be directly utilized by the loads or the grid. The power electronic interface such as DC-DC converters and DC-AC inverters especially MLIs are used as an interface between them. Adjustable Speed Drives (ASDs) are the essential and endless demand of the industries and researchers. They are widely used in the industries to control the speed of conveyor systems, blower speeds, machine tool speeds and other applications that require adjustable speeds. In many industrial applications, traditionally, DC motors were the work horses for the Adjustable Speed Drives (ASDs) due to their excellent speed and torque response. But, they have the inherent disadvantage of commutator and mechanical brushes, which undergo wear and tear with the passage of time. In most cases, AC motors are preferred to DC motors, in particular, an induction motor due to its low cost, low maintenance, lower weight, higher efficiency, improved ruggedness and reliability. All these features make the use of induction motors a mandatory in many areas of industrial applications. The advancement in Power Electronics and semiconductor technology has triggered the development of high power and high speed semiconductor devices in order to achieve a smooth, continuous and step less variation in motor speed. Applications of solid state converters/inverters for adjustable speed induction motor drive are wide spread in electromechanical systems for a large spectrum of industrial systems.[3],[6],[10].

Voltage or current converters, as they generate discrete output waveforms, force the use of machines with special isolation, and in some applications large inductances connected in series with the respective load. Also, it is well known that distorted voltages and currents waveforms produce harmonic contamination,

Additional power losses, and high frequency noise that can affect not only the power load but also the associated controllers. All these unwanted operating characteristics associated with PWM converters could be overcome with multilevel converters, in addition to the fact that higher voltage levels can be achieved.

The poor quality of output current and voltage of an induction motor fed by a classical two-level inverter is due to the presence of harmonics. The presence of significant amount of harmonics makes the motor to suffer from severe torque pulsations, especially at low speed, which manifest themselves in cogging of the shaft. It will also causes undesired motor heating and Electromagnetic interference [12]. The reduction in harmonics calls for large sized filters, resulting in increased size and the cost of the system. Nowadays multilevel inverters are the promising alternative and cost effective solution for high voltage and high power applications including power quality and motor drive problems. Multilevel structure allows raising the power handling capability of the system in a powerful and systematic way. The advancements in the field of power electronics and microelectronics made it possible to reduce the magnitude of harmonics with multilevel inverters, in which the number of levels of the inverters.

There are several PV system configurations. These configurations are the centralized technology, string technology, multi-string technology and AC-module technology. The number and type of power converters that is used to interconnect the PV system to the grid is dependent of the technology that is used. The multi-string technology has several different groups of PV arrays. Each group is connected in series with a DC/DC converter. This allows using this technology with some multilevel topologies, such as, the cascaded multicell inverters [7-9]. This topology is based on the series connection of single-phase inverters with separated DC sources

In this paper solar PV cell interfaced Nine Level inverter fed induction motor drive is designed and implemented. The simulation of solar PV cell interfaced Nine Leve level inverter fed induction motor model is done using Matlab/Simulink. The FFT spectrums for the outputs are analyzed to study the reduction in the harmonics.

II MULTILEVEL INVERTERS

Multilevel inverters have drawn tremendous interest in the power industry. They present a new set of feature that are well suited for use in reactive power compensation. Multilevel inverters will significantly reduce the magnitude of harmonics and increases the output voltage and power without the use of step-up transformer. A multilevel inverter consists of a series of H-bridge inverter units connected to three phase induction motor. The general function of this multilevel inverter is to synthesize a desired voltage from several DC sources. The AC terminal voltages of each bridge are connected in series. Unlike the diode clamp or flying-capacitors inverter, the cascaded inverter does not require any voltage clamping diodes or voltage balancing capacitors.[1-2],[13]. This configuration is useful for constant frequency applications such as active front-end rectifiers, active power filters, and reactive power compensation. Choosing appropriate conducting angles for the H bridges can eliminate a specific harmonic in the output waveform. The required conduction angles can be calculated by analyzing the output phase voltage of cascade inverter assuming that four H-bridges have been used, the output voltage Vao can be given as:

Vao = Va1 +Va2 +Va3 +Va4 +Va5…

Since the wave is symmetrical along the x-axis, both
Fourier coefficient A0 and An are zero. Just the analysis of Bn is required. It is given as:

$$B_n = \{[4V_{dc}]/n\pi\}\left[\sum_{j=1}^{\infty}\cos(n \propto_1)\right]$$

where
j = Number of dc sources
n = odd harmonic order

Therefore, to choose the conducting angle of each H bridge precisely, it is necessary to select the harmonics with certain amplitude and order, which needs to be eliminated. [3],[4],[5] To eliminate 5th, 7th, and 11th harmonics and to provide the peak fundamental of the phase voltage equal to 80% of its maximum value, it needs to solve the following equation with modulation index M = 0.8:

$\mathrm{Cos}(5_{\alpha1}) + \mathrm{Cos}(5_{\alpha2}) + \mathrm{Cos}(5_{\alpha3}) + \mathrm{Cos}(5_{\alpha4}) = 0$
$\mathrm{Cos}(7_{\alpha1}) + \mathrm{Cos}(7_{\alpha2}) + \mathrm{Cos}(7_{\alpha3}) + \mathrm{Cos}(7_{\alpha4}) = 0$
$\mathrm{Cos}(11_{\alpha1}) + \mathrm{Cos}(11_{\alpha2}) + \mathrm{Cos}(11_{\alpha3}) + \mathrm{Cos}(11_{\alpha4}) = 0$
$\mathrm{Cos}(\alpha_1) + \mathrm{Cos}(\alpha_2) + \mathrm{Cos}(\alpha_3) + \mathrm{Cos}(\alpha_4) =0.8*4$

A. Single phase structure of a five level Cascaded Multilevel inverter

A single-phase structure of an m-level cascaded inverter is illustrated in Fig 1. Each separate dc source (SDCS) is connected to a single-phase full-bridge, or H-bridge, inverter. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0, and $–V_{dc}$ by connecting the dc source to the ac output by different combinations of the four switches, S11, S12, S13, and S14. To obtain $+V_{dc}$, switches S11 and S14 are turned on, whereas $–V_{dc}$ can be obtained by turning on switches S12 and S13. By turning on S11 and S12 or S13 and S14, the output voltage is 0. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs.

The structure shown in Fig.3 is used to produce Five Level Inverter output voltage by giving same DC source value. Here for nine levels output 205V from solar PV cell is given for four H-bridges to get 800 V output.

III SOLAR PV SYSTEM

First stage PV array or module is connected with the system which connects the input to the inverter. The nine level MLI (Multilevel Inverter) is used to convert DC voltage to AC voltage and feeds the energy to the Induction Motor. The inverter has to be controlled in order to obtain harmonic less voltage to achieve good power quality. Pseudo carrier modulation technique is used.

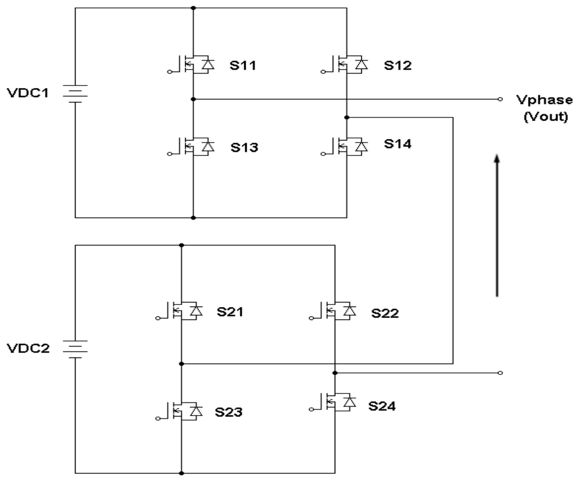

Fig. 3 Single Phase Structure of Cascaded Multilevel inverter

3.1 Modeling of Solar PV

The Solar-PV cells are used to produce electricity by directly converting solar energy to electrical energy. Each solar cell is basically a p-n diode. As sunlight strikes a solar cell, the incident energy is converted directly into electrical energy without any mechanical effort. The voltage and current levels are produced from PV cells are very less, thus these PV cells are connected in series and parallel called modules and arrays to produce required voltage and current levels. The solar PV array is modeled by considering the output characteristics of PV panel which directly have relation with power converters which exists in the system. The solar PV cell is a non linear device which can be represented by a current source connected parallel with diode as shown in Fig.3.1 The model does not take into account the internal losses of the current. A diode is connected in anti-parallel with the light generated current source.

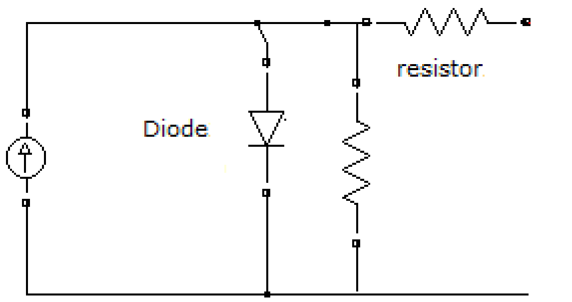

Figure 3.1: Equivalent circuit of solar cell and PV device

The output current I is obtained by Kirchhoff law:

$$I = I^{ph} - I^{d} \qquad (1)$$

Iph is the photocurrent, Id is the diode current which is proportionalto the saturation current and is given by the equation

$$I^{d} = I0\left[\exp\left(\frac{V}{A.N_s V_T}\right) - 1\right] \qquad (2)$$

V is the voltage imposed on the diode.

$$V^{T} = K.T^{C}/q \qquad (3)$$

I0 is the reverse saturation or leakage current of the diode(A), VTc = 26 mV at 300 K for silisium cell, Tc is the actual cell temperature (K), k Boltzmann constant 1.381 · 10_23 J/K, q is electron charge (1.602 · 10_19 C).

VT is called the thermal voltage because of its exclusive dependence of temperature.

Ns: is the number of PV cells connected in series. A is theideality factor. It depends on PV cell technology. It is necessary to underline that A is a constant which depends on PV cell technology. All the terms by which, V is divided in equation (2) under exponential function are inversely proportional to cell temperature and so, vary with varying conditions. In this work, this term is designed by ‘a’ and called the thermal voltage(V), the ideality factor, is considered constant, according to technology of the PV cell. The thermal voltage ‘‘a’’ is presented by equation (4)

$$a = \frac{N_S AKT_C}{q} = N_S \cdot A \cdot V_T \qquad (4)$$

‘a’ is called ‘‘the modified ideality factor’’ and is considered as a parameter to determine, while A is the diode ideality

From figure 4.1 (b)

In reality, it is impossible to neglect the series resistance Rs and the parallel resistance RP because of their impact on the efficiency of the PV cell and the PV module. When RS is taken into consideration, equation (2) should take the next form:

$$I_d = I0\left[\exp\left(\frac{V + IR_S}{a}\right) - 1\right] \quad (5)$$

By applying Kirchhoff law, current will be obtained by the equation:

$$I = I_{ph} - I_d - I_P \quad (6)$$

Ip, is the current leak in parallel resistor.

According to the equation (7), the output current of a module containing Ns cells in series will be:

$$I = I_{ph} - I0\left[\exp\left(\frac{V + IR_S}{a}\right) - 1\right] - \frac{V + IR_S}{R_P} \quad (7)$$

It is not easy to determine the parameters of this transcendental equation. But this model offers the best match with experimental values.

Determination of Iph

The output current at the standard test conditions (STC) is:

$$I = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V}{a_{ref}}\right) - 1\right] \quad (8)$$

This equation allows quantifying Iph,ref which cannot be determined otherwise. When the PV cell is short-circuited

$$I_{SC,ref} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{0}{a_{ref}}\right) - 1\right] = I_{ph,ref} \quad (9)$$

This equation allows quantifying Iph,ref which cannot be determined otherwise. When the PV cell is short-circuited

$$I_{ph,ref} \approx I_{sc,ref} \quad (10)$$

The photocurrent depends on both irradiance and temperature:

$$I_{ph} = \frac{G}{G_{ref}}\left(I_{ph,ref} + \mu_{sc}.\Delta T\right) \quad (11)$$

G: Irradiance (W/m2), Gref : Irradiance at STC= 1000 W/m2, DT =Tc - Tc, ref (Kelvin), Tc,ref : Cell temperature at STC = 25+ 273 =298 K, lSC : Coefficient temperature of short circuit current (A/K), provided by the manufacturer, Iph, ref : Photocurrent (A) at STC.

The shunt resistance Rp is generally regarded as great, so the last term of the relationship (8) should be eliminated for the next approximation. By applying equation (8) at the three most remarkable points at standard test condition: the voltage at open circuit (I =0, V= Voc,ref), the current at short circuit (V =0, I= Isc,ref), and the voltage (Vmp,ref) and current (Imp,ref) at maximum power, the following equations can be written:

$$I_{SC,ref} = I_{ph,ref} - I_{o,ref}\left[\exp\left(\frac{I_{sc,ref}.R_s}{a_{ref}}\right) - 1\right] \quad (12)$$

$$0 = I_{ph,ref} - I_{o,ref}\left[\exp\left(\frac{V_{oc}}{a_{ref}}\right) - 1\right] \quad (13)$$

$$I_{pm,ref} = I_{ph,ref} - I_{0,ref} * \left[\exp\left(\frac{V_{pm,ref} + I_{pm,ref} R_S}{a_{ref}}\right) - 1\right] \quad (14)$$

The (-1) term has to be neglected because it is very smaller than the exponential term. According to equation (11), and by substituting (Iph,ref) in equation (14):

$$0 \approx I_{sc,ref} \exp\left(\frac{V_{oc,ref}}{a_{ref}}\right) \tag{15}$$

$$I_{0,ref} = I_{sc,ref} \exp\left(\frac{-V_{oc,ref}}{a}\right) \tag{16}$$

The reverse saturation current is defined by:

$$I_0 = DT_c^3 \exp\left(\frac{-q\varepsilon_G}{A.K}\right) \tag{17}$$

In order to eliminate the diode diffusion factor, equation(18) is computed twice; at Tc and at Tc,ref. Then, the ratio of the two equations is written in the next expression:

$$I0= I_{o,ref} \left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left[\left(\frac{q\varepsilon_G}{A.K}\right)\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \tag{18}$$

$$I0= I_{sc,ref} \exp\left(\frac{-V_{oc,ref}}{a}\right)\left(\frac{T_c}{T_{c,ref}}\right)^3 \times \exp\left[\left(\frac{q\varepsilon_G}{A.K}\right)\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \tag{19}$$

Equation (20) presents I0 with some parameters provided by the manufacturers as (Voc, ref, Tc,ref), others, related to the technology of the PV cell, as (A, eG) and some constants. But ''a'' and Tc are dependents of actual temperature. That is why; I0 has to be determined at real time.

Determination of Rp and Rs

In order to make the proposed model more credible, RP and RS are chosen so that the computed max power Pmp is equal to the experimental one Pmp,ex at STC conditions. So it is possible to write the next equation:

$$I_{mp,ref} = P_{mp,ref}/V_{mp,ref} = P_{mp,ref}/V_{mp,ref}$$

$$I_{ph,ref} - I_{o,ref}\left[\exp\left(\frac{(V_{mp,ref} + I_{mp,ref}.R_s)}{a}\right) - 1\right] - \frac{V_{mp,ref} + R_s I_{mp,ref}}{R_p} \tag{20}$$

The iteration starts at RS= 0 which must increase in order to move the modeled Maximum Power Point until it matches with the experimental Maximum Power Point. The corresponding RP is then computed. There is only one pair (RP, RS) that satisfies this condition.

$$R_p = \frac{V_{mp,ref} + I_{mp,ref} R_s}{I_{sc,ref} - I_{sc,ref}\left\{\exp\left[\frac{V_{mp,ref} + R_s I_{mp,ref} - V_{oc,ref}}{a}\right]\right\} + I_{sc,ref}\left\{\exp\left(-V_{oc,ref}/a\right)\right\} - \left(P_{max,ex}/V_{mp,ref}\right)}$$

IV. INDUCTION MOTOR DRIVE

[1] Synchronous speed of Induction Motor is directly proportional to the supply frequency. Hence, by changing the frequency, the synchronous speed and the motor speed can be controlled below and above the normal full load speed. The voltage induced in the stator, E is proportional to the product of slip frequency and air gap flux. The motor terminal voltage can be considered proportional to the product of the frequency and flux, if the stator voltage is neglected. Any reduction in the supply frequency without a change in the terminal voltage causes an increase in the air gap flux. Induction motors are designed to operate at the knee point of the magnetization characteristic to make full use of the magnetic material. Therefore the increase in flux will saturate the motor. This will increase the magnetizing current, distort the line current and voltage, increase the core loss and the stator copper loss, and produce a high pitch acoustic noise. While any increase in flux beyond rated value is undesirable from the consideration of saturation effects, a decrease in flux is also avoided to retain the torque capability of the motor. Therefore, the variable frequency control below the rated frequency is generally carried out by reducing the machine phase voltage, V, along with the frequency in such a manner that the flux is maintained constant. Above the rated frequency, the motor is operated at a constant voltage because of the limitation imposed by stator insulation or by supply voltage limitations.

V MATLAB/SIMULINK RESULTS

5.1 IMPLEMENTATION OF PHOTOVOLTAIC CELL MATLAB SIMULINK

Photovoltaic (PV) cell is modeled using the equations mentioned in Section II of the paper. The MATLAB SIMULINK model of a single PV is shown in fig 5.1

The parameters given are shown below

Table 5: PV module of 200W with 36 cells connected in series at irradiation of 1000W/m^2

Parameters	Values
Voltage at maximum power Vmp (V)	26.1
Current at maximum power Imp (A)	7.66
Power maximum Pmp (W)	200W
Isc (A)	8.42
Voc (V)	32.5
Rs in ohms	0.55

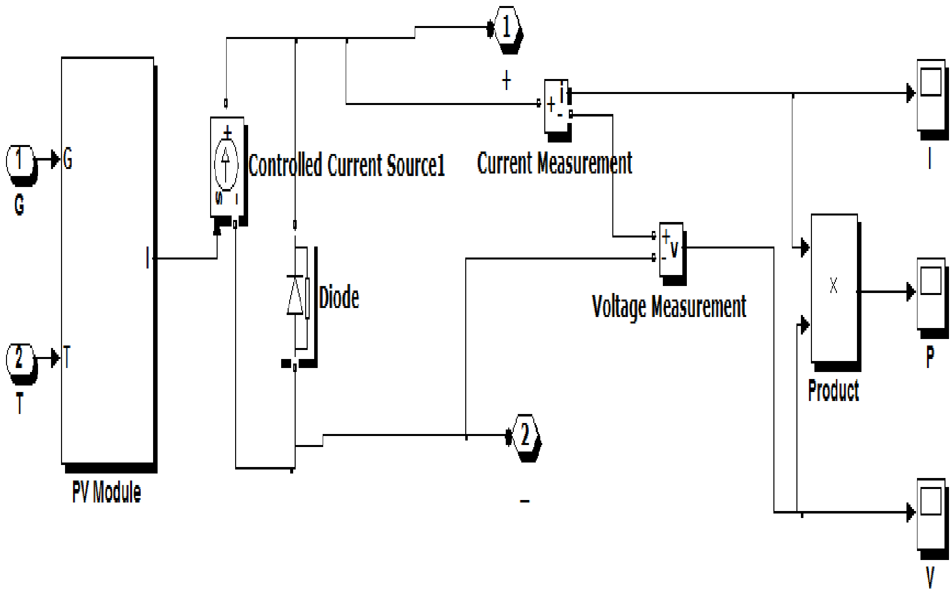

Figure: 5.1 PV module

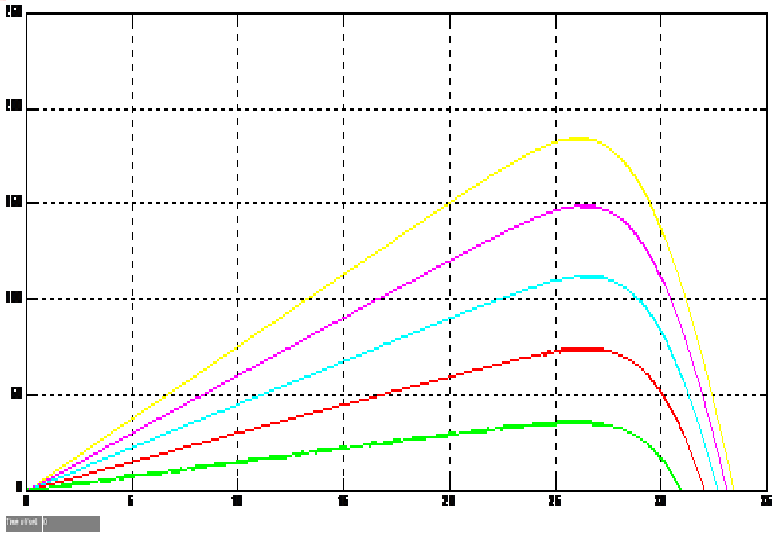

Figure 5.2 PV characteristics at different insolation levels

Fig 5.2 shows the PV characteristics at insolation levels of 1000W/m^2,800W/m2, 600W/m^2,400W/m^2,and 200W/m^2.The MATLAB SIMULINK models of PV array of is shown in fig 5.3

5.2 ARRAY CALCULATION

For 10KW array

Number of Modules = Total Power/ Rated Power of 1 PV module=10KW/208=48
Number of series PV modules in string = voltage required/Vmp=400/26.1=15.32=16
Number of parallel PV strings = Current required/Imp=25/7.66=3.2=3
Therefore only 3 strings are connected in parallel in which 16 modules connected in series in string.

The MATLAB SIMULINK model of PV Array of 10KW with Three level Multilevel inverter is shown in Fig 5.3. Here the output of three phase three level Multilevel Inverter is taken through the three winding transformer and then it is interfaced with grid.

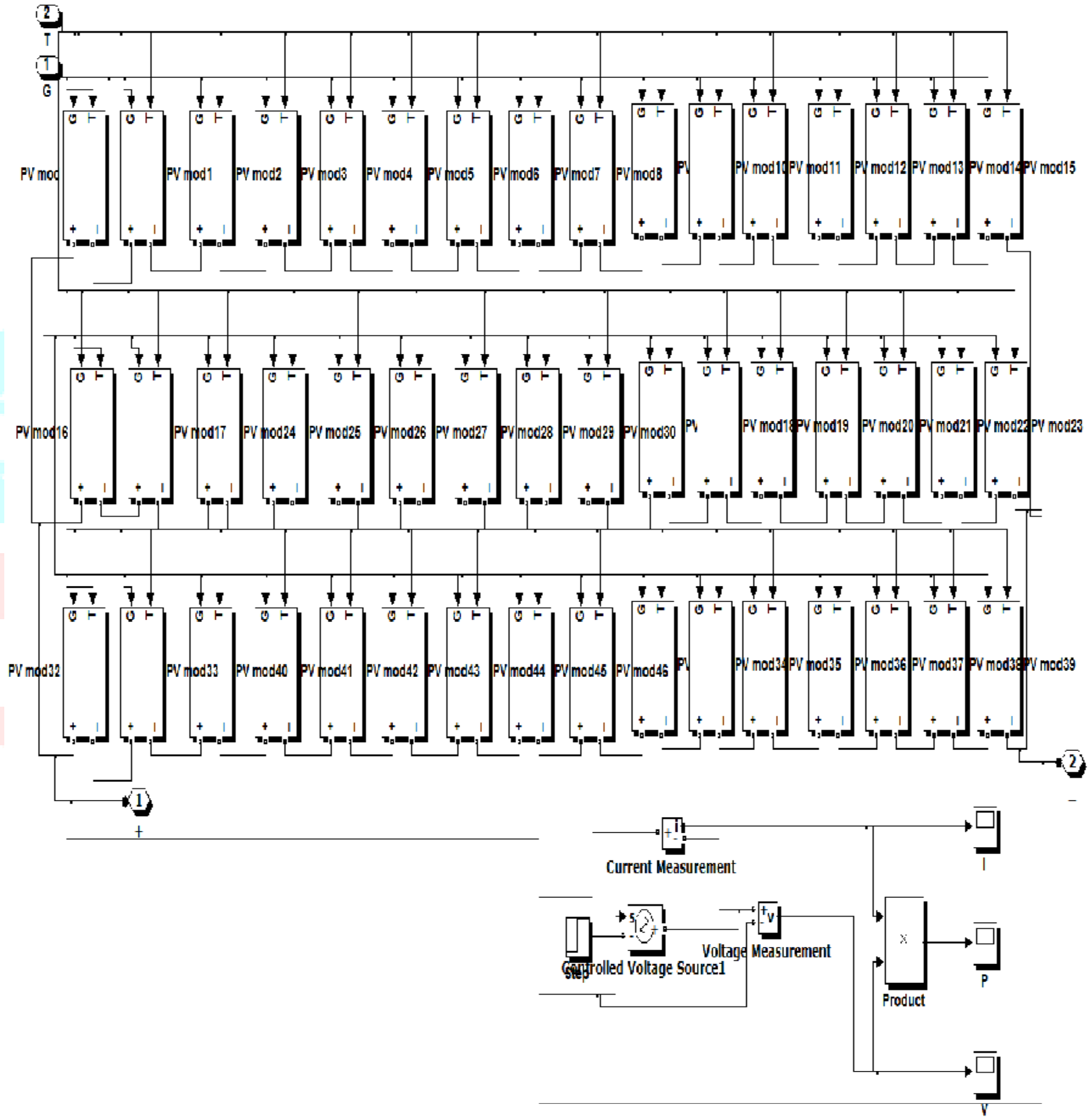

Figure: 5.3 PV array of 10 KW

Solar PV based nine level multilevel inverter fed induction motor drive is implemented in MATLAB SIMULINK which is shown in Fig.5.4. The single phase nine level inverter output is shown in Fig.5.5. In fig 5.6 we can observe that main winding current is initially high and then reduces, the auxiliary current is zero after 1 cycle. It also gives the details of Electromagnetic torque and the speed of the motor running at 1470. FFT analysis is done for the MLI output voltage and the corresponding spectrum is shown in Fig.5.7 It can be seen that the magnitude of fundamental voltage for nine level inverter fed induction motor drive is 819.2 Volts. The total harmonic distortion is 1.75 percent

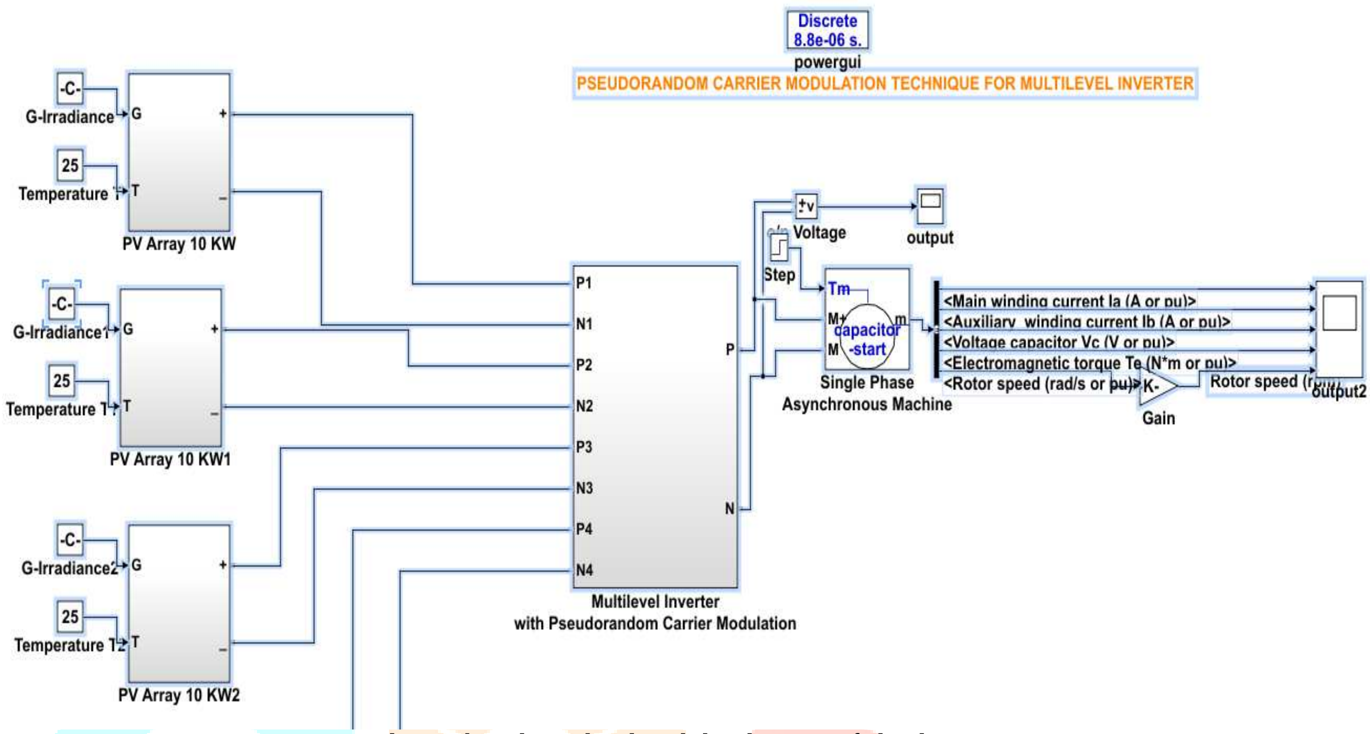

Fig. 5.4 Solar PV based nine level Multilevel inverter fed induction motor

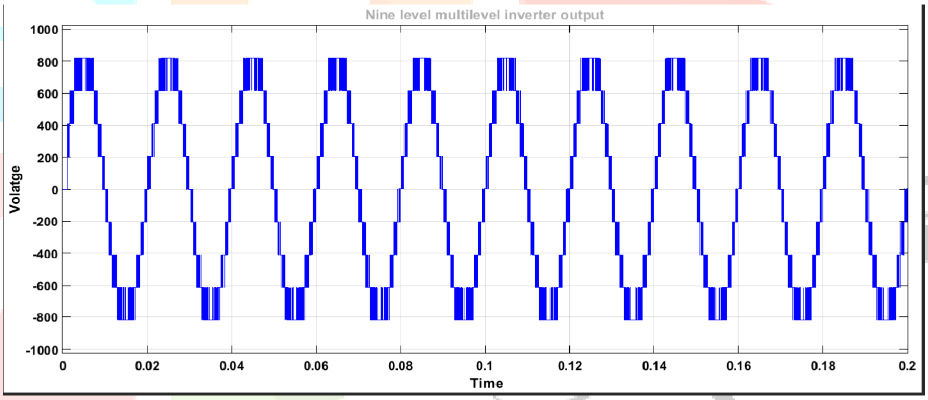

Fig 5.5 Single phase nine level inverter output

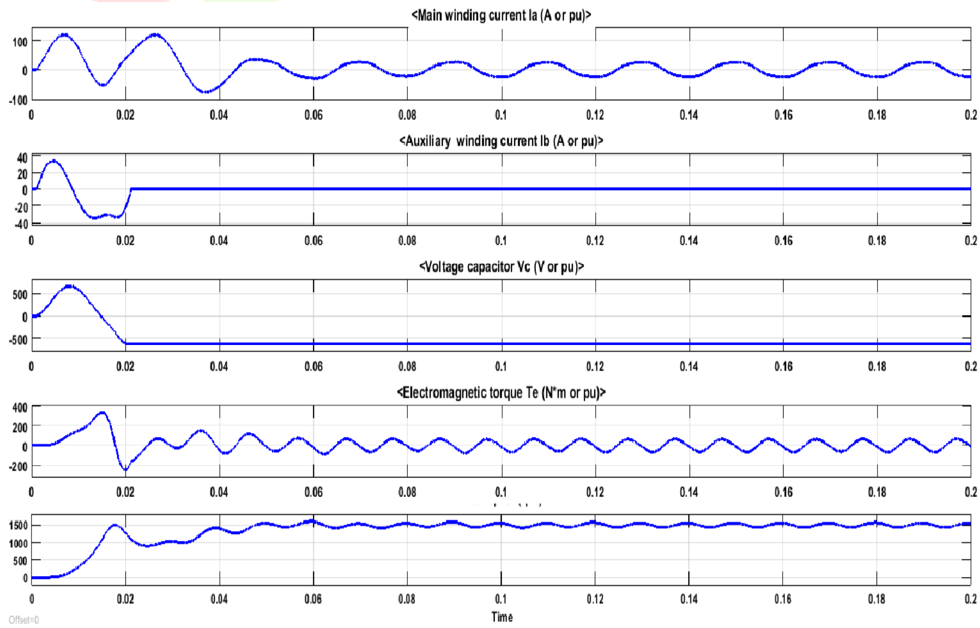

Fig 5.6 Main winding current, the auxiliary current, Electromagnetic torque and the speed of the Induction Motor

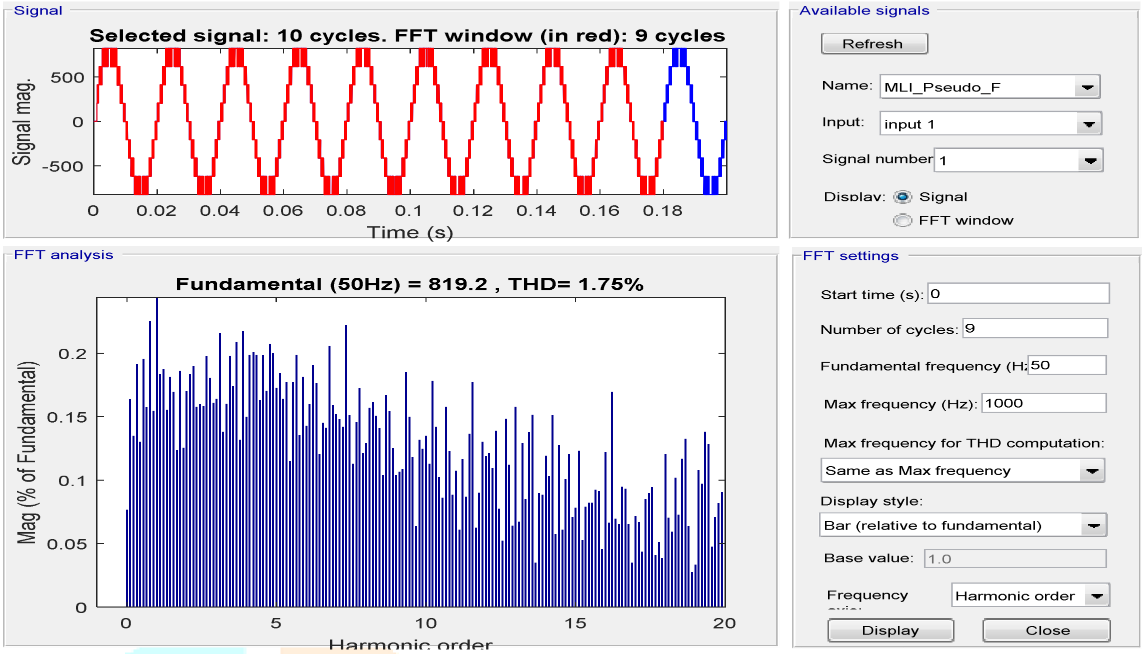

Fig 5.7 FFT analysis of Voltage

VI CONCLUSION

Increasing demand on energy efficiency and power quality issues, grid connected solar PV systems is taking a good place. In this paper solar PV cell interfaces nine level multi level inverter fed induction motor drive is simulated using the blocks of Matlab/Simulink. The simulation results of voltage, current, speed and spectrum are presented. This drive system can be used in industries where adjustable speed drives are required to produce output with reduced harmonic content.

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