International Conference on Control, Engineering & Information Technology (CEIT'13)
Proceedings Engineering & Technology - Vol.4, pp. 49-54, 2013

Modelling and performance analysis of multilevel inverter for single-phase grid connected photovoltaic modules

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***Abstract*— Power electronic converters always have been circuits of difficult modeling because differential equations that describe them have discontinuities. Although this situation has been improved since the appearance of the bond graph approach, able to jointly describe both continuous and discrete behaviors exhibited by some physical systems, nowadays it is possible to obtain very precise models which help us in the study and design of such circuits. This work gives an overview on single-phase grid converter based on seven level diode clamped multilevel inverter for photovoltaic system with maximum power tracking. In the first part, we develop a bond graph model of the inverter. A bond graph MPPT strategy is developed, the performance of the algorithm is studied. Then, we present the bond graph model of solar cell. Thus, we study a cascade constituted by tow photovoltaic cell panels - five-level NPC VSI - permanent magnet synchronous machine (PMSM) fed by photovoltaic PV energy systems at different illuminations. At the full solar intensity, the maximum power point of current/voltage I/V characteristic of the PV modules is designed to be at the rated conditions of the machines. The steady-state output characteristics, the torque-speed characteristics, of the three DC motors with the two inputs are presented and compared.**

***Keywords*—Bond Graph; Multilevel Inverter; Photovoltaic; Modelling; Permanent Magnet Synchronous Machine.**

I. Introduction

The interest and importance in renewable energy has been aroused due to the Kyoto agreement on the global reduction of greenhouse emissions. Photovoltaic is one of the important renewable energy sources [1], [2], [3] and the cost of the photovoltaic is on falling trend and is expected to fall further as demand and production increases [4], [5]. The benefits of power generation from these sources are widely accepted. They are essentially inexhaustible and environmentally friendly.

Among the different renewable-energy sources possible to obtain electricity, solar energy has been one of the most active research are as in the past decades, both for grid-connected and standalone applications [6], [7]. The installed PV power has been increasing in the past, and a more significant increase is expected in the near future, owing to the potential advances in the PV conversion technology and the reduction in cost-per-watt that a large-scale production will bring about [8].

Photovoltaic power supplied to the utility grid is gaining more and more visibility while the world's power demand is increases. Growing demand, advancements in semiconductor technology and magnetic materials such as high frequency inductor cores, has a significant impact on PV inverter topologies and their efficiencies, on the improvement of the control circuits on the potential of costs reduction. The user naturally wants to operate the Photovoltaic (PV) array at its highest energy conversion output by continuously utilizing the maximum available solar power of the array. The electrical system PV modules are powered by solar arrays requires special design considerations due to varying nature of the solar power generated resulting from unpredictable and sudden changes in weather conditions which change the solar irradiation level as well as the cell operating temperature. This work gives an overview on single-phase grid converter based on seven level diode clamped multilevel inverter for photovoltaic system with maximum power tracking. Multilevel voltage source inverters offer several advantages compared to their conventional counterparts. By synthesizing the AC output terminal voltage from several levels of voltages, staircase waveforms can be produced, which approach the sinusoidal waveform with low harmonic distortion, thus reducing filter requirement. The need of several sources on the DC side of the converter makes multilevel technology attractive for photovoltaic applications.

II. Bond graph approach

Bond graph, a graphical modeling language, provides a model formalism that decomposes the system into subsystems that map to the physical connections [9]. Bond graph provides a systematic way to model dynamic systems with different energy domains, such as electrical, hydraulic, mechanical, etc., in unified frame work. In bond graph modeling, a physical system can be described by bond graph components which include source elements Se and Sf, dissipative element R, storage elements C and I, four junctions 0, 1, TF and GY. These generalized BG components are connected by bonds, which represent energy exchange between two physical components. For each bond, there are two energy variables, effort and flow, to describe the states of the physical components. BG modeling utilizes these BG components and their bond connections to describe the behavior of a physical system [10].

III. SYSTEM CONFIGURATION

The system configuration for the topic is as shown figure 1. Here the PV array is a combination of series and parallel solar cells. This array develops the power from the solar energy directly and it will be changes by depending up on the temperature and solar irradiances. So we are controlling this to maintain maximum power at output side we are boosting the voltage by controlling the current of array with the use of PI controller. By depending upon the boost converter output voltage this AC voltage may be changes and finally it connects to the utility grid that is which feeds a PMSM. Here we are using seven-level diode clamped multilevel inverter to obtain AC output voltage from the DC boost output voltage.

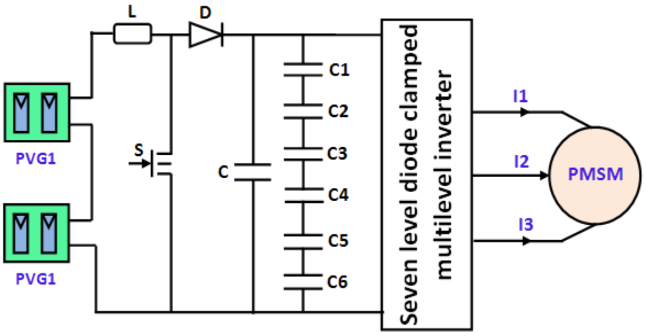


Fig. 1 Two photovoltaic generator single-phase grid converter seven level diode clamped multilevel inverter

IV. MODELLING OF PHOTOVOLTAIC SYSTEM

A. *Bond graph modelling of PV array*

Several models of solar cell exist to calculate their electric characteristics [11, 12, 13, 14, 15, 16]. To improve the accuracy, model parameters such as irradiance correction factor and Temperature coefficient of a series resistance are discussed in [17].

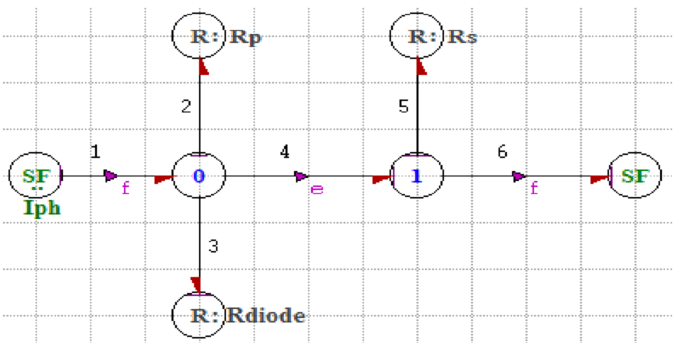


Fig. 2 Bond graph model of PV

All these models have the disadvantage that required parameters are not published in standard data sheets. Thus it is of interest to have a simpler model to calculate the electrical properties of photovoltaic modules with only those data that are available from data sheets. For the bond graph representation, the PV generator is then modelled by a flow source Sf = I_{ph} in parallel with the resistors R_p, the whole followed by a serial resistance Rs. The PV diode bond graph representation is a non-linear resistor R_{diode}.

B. *Boost Converter*

The boost converter which has boosting the voltage to maintain the maximum output voltage constant for all the conditions of temperature and solar irradiance variations. A simple boost converter is as shown in figure (3). The boost converter contains an IGBT and a diode which are represented as a dual ideal switch U in order to simplify the circuit analysis. If U is a state of 0, the diode is on and the IGBT is off and vice versa if U is a state of 1.

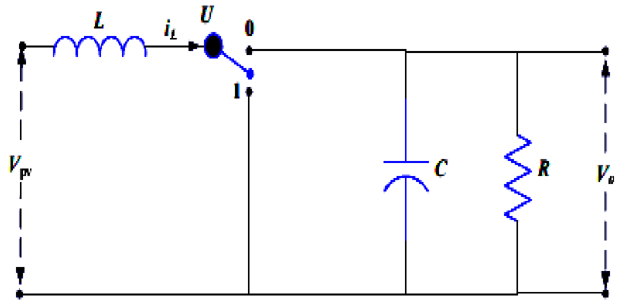


Fig. 3 Boost converter circuit diagram.

The boost converter contains also passive components: an inductor L, an capacitor C and a resistance R. The operation principle of the boost converter can be demonstrated for each switching period under the continuous conduction mode (CCM) into two modes [18]: the first mode is an ON mode in the duration the period $0 \le t \le t_{on}$ and its state equations can be represented as follows:

$$\begin{cases} L\dfrac{di_L}{dt} = V_{pV} \\ C\dfrac{dV_0}{dt} + \dfrac{V_0}{R} = 0 \end{cases} \quad (1)$$

Where ton is the ON mode time and i_L the continues inductor current. The second mode is an OFF mode in the duration $t_{on} \le t \le T_s$ and its state equations can be represented as the following:

$$\begin{cases} L\dfrac{di_L}{dt} + V_0 = V_{pV} \\ i_L - C\dfrac{dV_0}{dt} - \dfrac{V_0}{R} = 0 \end{cases} \quad (2)$$

Where T_s is the switching period. The design of a boost converter for a PV system is a complex task which involves many factors. In general, the input and output voltages of the boost converter are varied with the solar irradiances and load variations. The output voltage is also varied MPPT controller. Thus the selection of boost converter components (the input inductor and the output capacitor) is a compromise between dynamic responses and the MPPT algorithm trigger time. The maximum value of the state variables should be calculated to estimate the value of the boost converter [18].

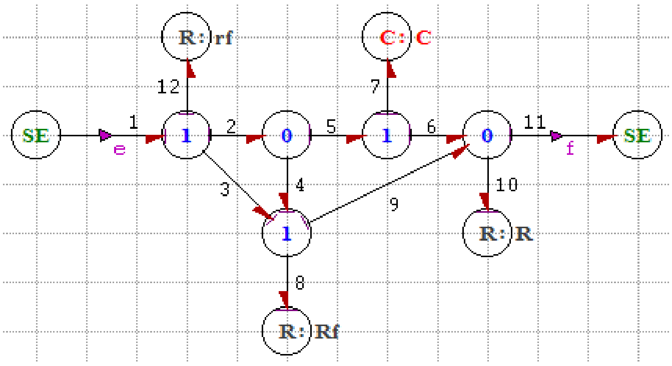


Fig. 4 Bond graph model of boost converter.

C. Maximum power point tracking

The proposed integrated Maximum Power Point Tracker (MPPT) has been used to force the PV array to work around the maximum power point. For this reason, the MPPT is required to track the maximum power available in the PV array. The MPPT operates by periodically incrementing the terminal voltage of the PV array and continuously seek. The radiation and temperature are used to calculate the maximum PV array output power and PV array terminal voltages. The MPPT operates by periodically incrementing the terminal voltage of the PV array and continuously seek the peak power point. The control system adjusts the boost converter to seek maximum power point of PV array. Changing the duty ratio according to the error signal between the maximum and actual power will pass the maximum power available from PV system to the electric utility. The bond graph control scheme (BG-MPPT) for the three-phase grid-connected photovoltaic energy conversion system is depicted in figure (5).

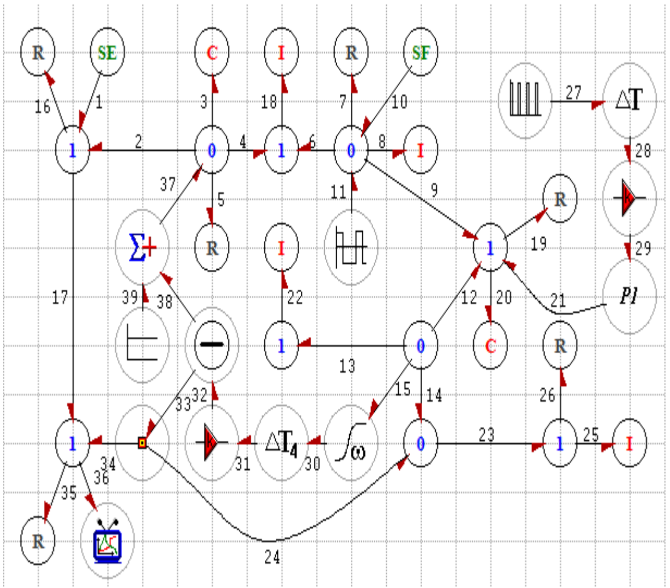


Fig. 5 The bond graph MPPT control of the global system

D. Multilevel Inverter topology

Multilevel converters have many advantages for medium and high power systems as they synthesize a higher output voltage than the voltage rating of each switching device. Stepped output voltage allows a reduction in harmonic content of voltage and current waveforms, switching frequency, and semiconductors voltage level. The presented merits make multilevel converters appropriate for medium and high voltage renewable energy applications. The best known multilevel topologies [19] are diode-clamped, flying capacitor, and cascade inverter, the latter being normally considered for PV application. However, the diode-clamped converter is the most popular converter in renewable energy system due to is structure. Different current [20], [21] and voltage control [22] techniques have been proposed for multilevel converters to have an optimum efficiency. Although each type of multilevel converters share the advantages of multilevel voltage source inverters, they may be suitable for specific application due to their structures and drawbacks. This work is interested on seven level diode clamped multilevel inverter. Concept of the diode clamped topology was proposed by Nabae [23]. This topology has found wide acceptance for its capability of high voltage, and high efficiency operation. A phase leg of a three level diode-clamped inverter is shown in figure (7) it consists of two pairs of switches and two diodes.

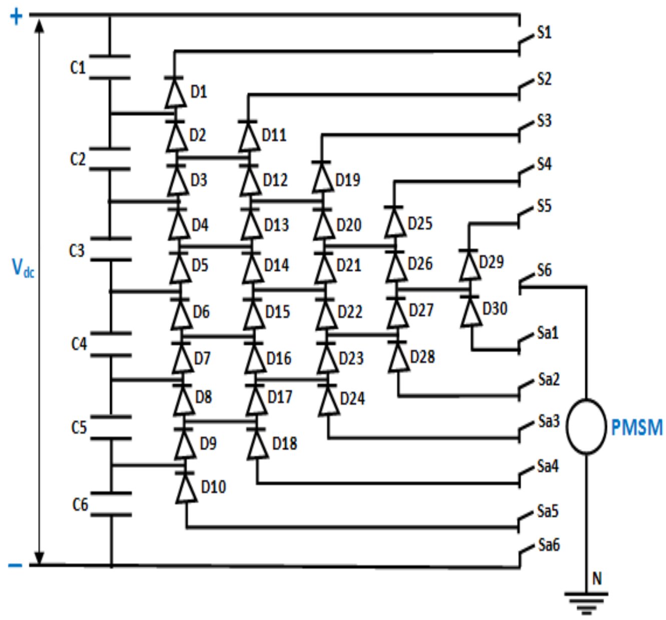


Fig. 6 Simple single-phase bridge inverter circuit

In this paper seven- level diode clamped multilevel inverter. A diode clamped multilevel inverter for m-level consists of m-1 capacitors, 2(m-1) switching devices on the DC bus and produces m levels operation on the phase voltage. So the seven-level diode clamped multilevel inverter consisting of twelve switching devices (S1-S6, Sa1-Sa6), ten clamping diodes (D1-D10), six capacitors (C1-C6), provides seven voltage levels. Assuming the DC source voltage Vdc is evenly split by the capacitors can be produced by turning on simultaneously the switch combinations of (S1 S2 S3 S4 S5

S6), (S2 S3 S4 S5 S6 Sa1), (S3 S4 S5 S6 Sa1 Sa2), (S4 S5 S6 Sa1 Sa2 Sa3), (S5 S6 Sa1 Sa2 Sa3 Sa4), (S6 Sa1 Sa2 Sa3 Sa4 Sa5) and (Sa1 Sa2 Sa3 Sa4 Sa5 Sa6) respectively. Seven switch combinations where always six switches are switched simultaneously generate seven different voltage levels at the AC output of the inverter. By adding more levels on the DC bus the numbers of levels of the voltage at the inverter output terminals are also increased. This allows for reduced distortion of the output waveform. Tables must be numbered using uppercase Roman numerals. Table captions must be centred and in 8 pt Regular font with Small Caps. Every word in a table caption must be capitalized except for short minor words as listed in Section III-B. Captions with table numbers must be placed before their associated tables, as shown in Table 1.

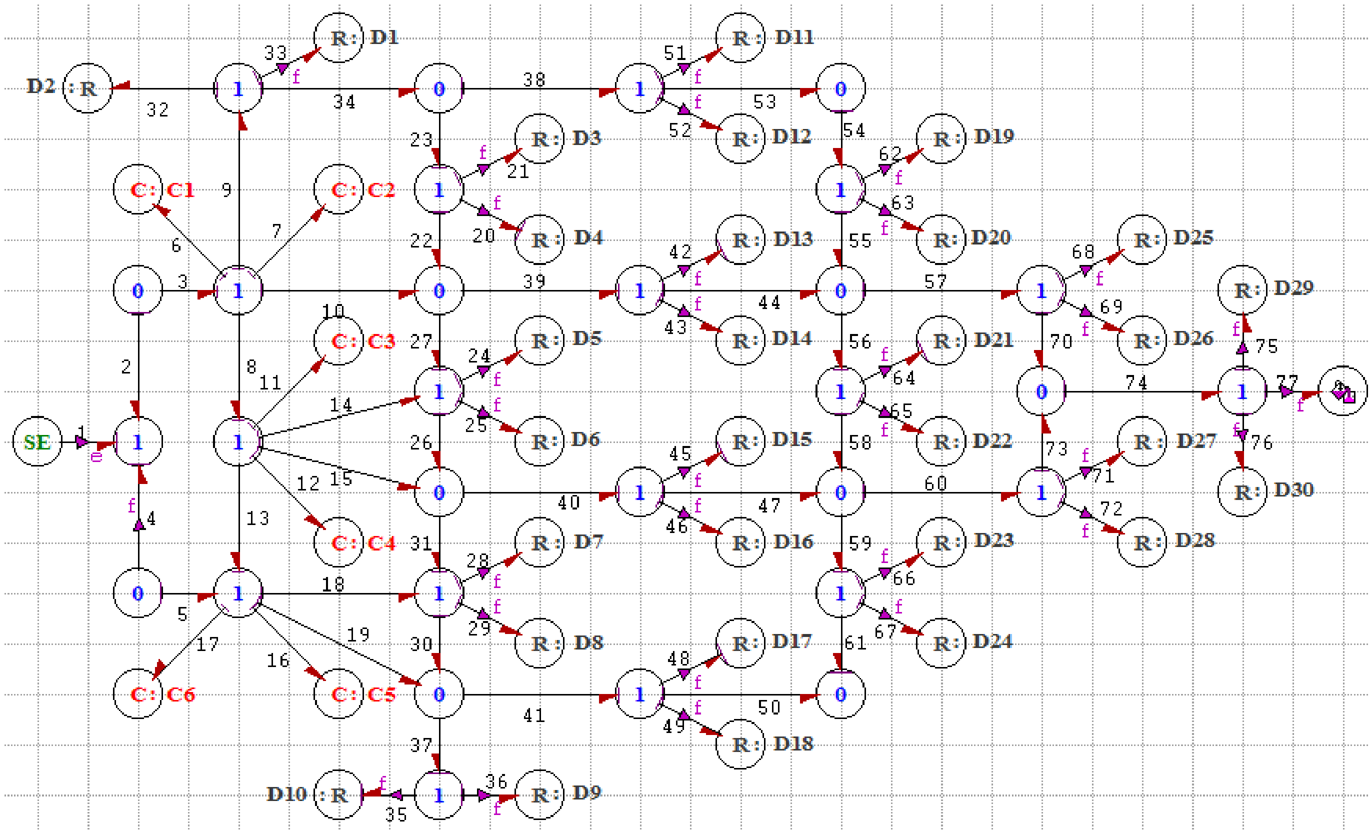


Fig. 7 Bond graph of simple single-phase bridge inverter circuit

E. Permanent magnet synchronous motor

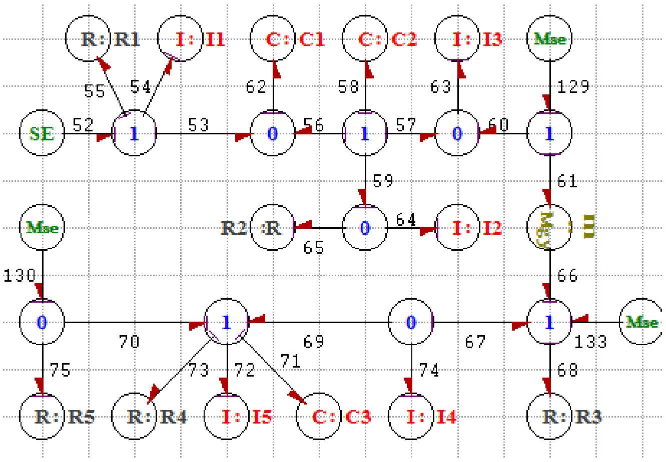


Fig. 8 Bond graph model of PMSM

The diagram below represents bond graph model of a permanent magnet synchronous motor (PMSM) by presenting some parameters held in account. Rotor speed and the moment of inertia is modelled by I, resistance stator, rotor, frictions are modelled by R, the condensers, the mechanical structures are modelled by C, electromechanical transformation modelled by a gyrator GY and the electric source by SE. The figure (8) gives the bond graph model of a PMSM.

V. SIMULATION RESULTS

The converter circuit topology is designed to be compatible with a given load to achieve maximum power transfer from the solar arrays. The power will be maximum for along the variations of temperature and solar irradiance in the PV array which is giving to input to seven-level diode clamped multilevel inverter.

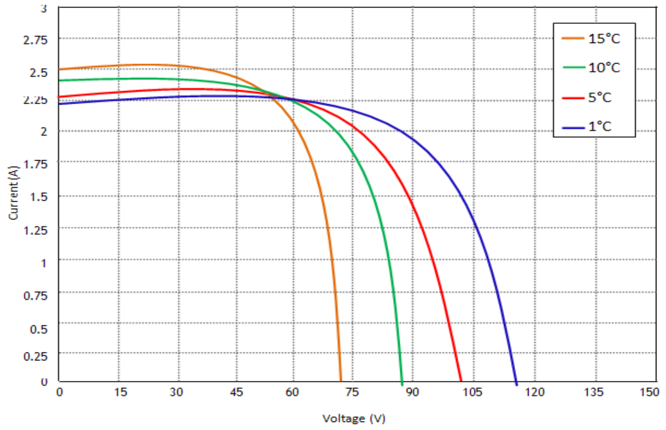


Fig. 9 I-V characteristics of PV module for various temperatures at rated solar intensity

We observed that the designed seven-level diode clamped multilevel inverter successfully followed the variations of solar irradiation. The maximum power point tracking controls their respective voltage, current waves. Here the power is maintaining maximum value and similarly the boost converter boosting the voltage under the control of the MPPT. By this, PV array, boost converter output voltages are converted to AC voltages which are supplied to the grid by using seven-level diode clamped multilevel inverter and its characteristics also mentioned here.

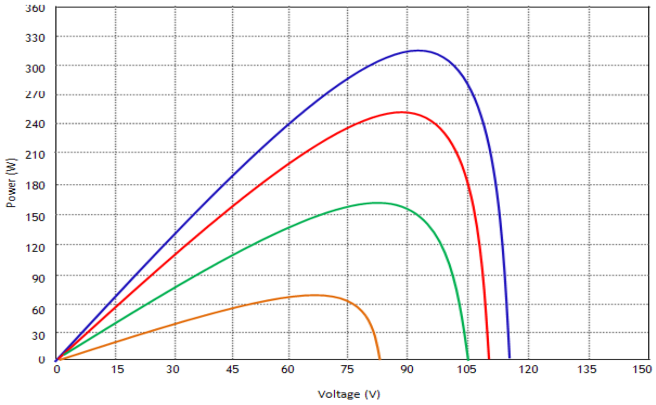


Fig. 10 P-V characteristic of PV module

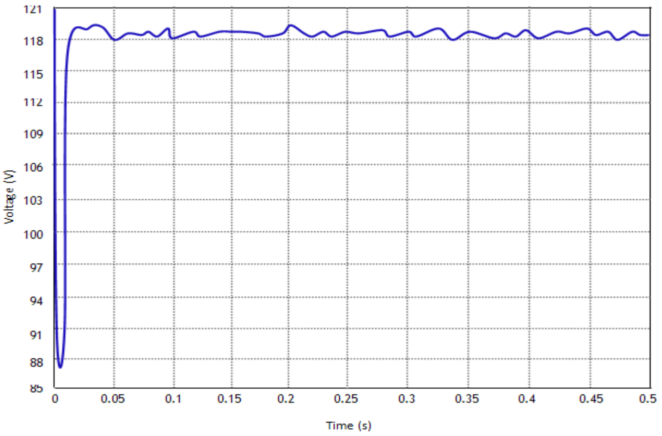


Fig. 11 Input voltage of boost converter

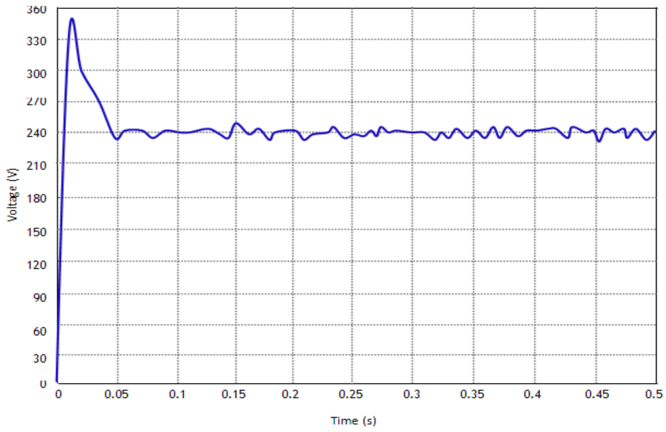
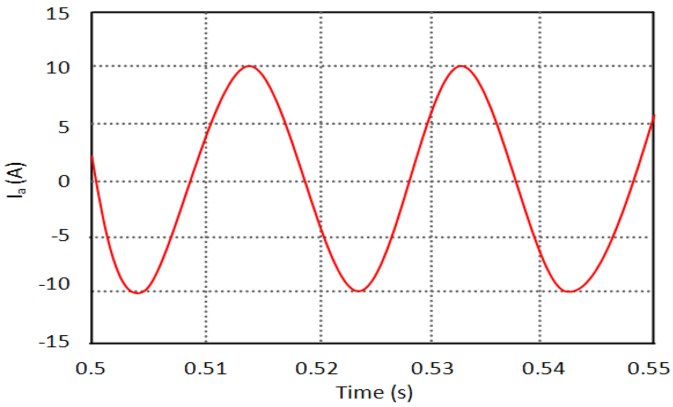
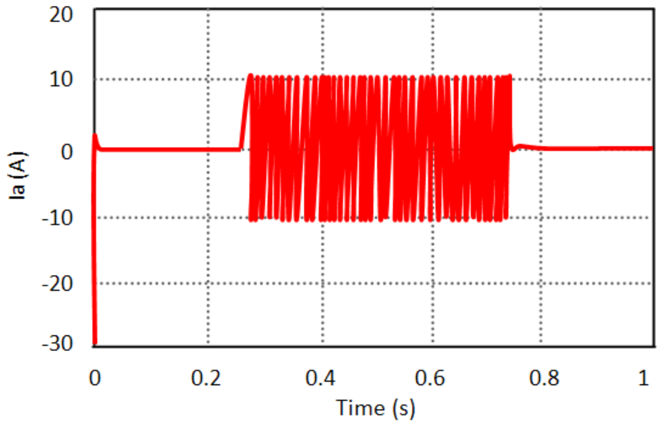
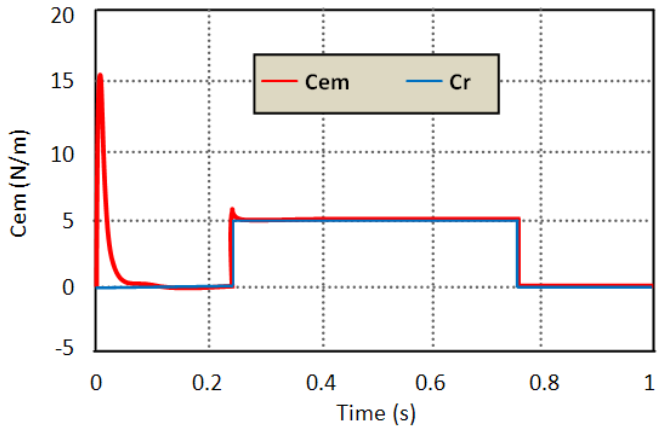


Fig. 12 Output voltage of boost converter







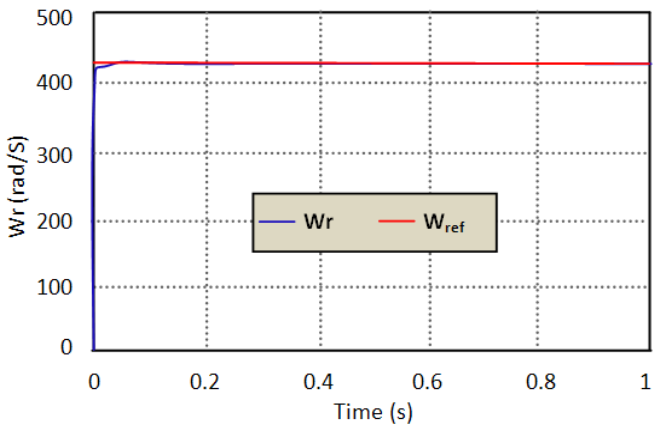


Fig. 13 Performance of PMSM

The performance of the speed control algorithm of the PMSM shows that the current of the machine nearly is sinusoidal. The speed and the torque effect for the charge variation between two instants t=1.5s and t=2.5s (Figure13).

VI. CONCLUSIONS

The present work proposes a general bond graph structure for linear and nonlinear modeling of photovoltaic layers with polarization through their thickness, which can handle the most important physical phenomena in their behavior. In order to consider the power transformation between the irradiation and temperature and its effect on the photovoltaic material, the model has an intermediate domain where the dipole and electric field in the material are defined. This paper, we have studied the performances of multilevel inverter for single-phase grid connected photovoltaic modules. Multilevel voltage source inverters offer several advantages compared to their conventional counterparts. By synthesizing the AC output terminal voltage from several levels of DC voltages, staircase wave forms can be produced, which approach the sinusoidal waveform with low harmonic distortion, thus reducing filter requirements. The need of several sources on the DC side of the converter makes multilevel technology attractive for photovoltaic applications.

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