Modeling and Simulation of a Grid Interactive Photovoltaic Power Plant

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This paper presents a simulation model of the electrical part of a grid interactive photovoltaic system. The model contains a detailed representation of the main components of the system that are the solar array, 3 phase inverter and LC filter inverter control circuit and load. A proper control of the DC/AC inverter is developed in order to synchronize the system to the grid. The grid interface inverter transfers the energy drawn from the photovoltaic (PV) array into the grid by keeping common DC coupling voltage constant. This research paper also focuses on the different PV technologies (amorphous silicon, polycrystalline) and their effect to the system in terms of energy output. A simulation model has been developed with the help of mathematical equations and its output has been verified with working solar PV plant. This paper can be useful for the PV power plant designers to analyze the output of the power plant by using the simulation model. This model is a simplified approach of the system's individual modules.

1. INTRODUCTION

The basic device of the PV system is the PV cell. Cells may be grouped to form a module and modules may be used to form a PV array. More sophisticated applications require electronic converter to process the electricity from the PV device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid connected systems and mainly track the maximum power point of the device. PV devices present nonlinear I-V characteristics with several parameters that need to adjust from experimental data of practical devices. The mathematical model of the PV device is used here for analyzing a complete PV system and its component using the Matlab/Simulink simulator. Villalla et al. [1] proposed a mathematical model for photovoltaic module in which they found the parameters of non linear I-V equation by adjusting the curve at three points: open circuit, maximum power, and short circuit. They found the best I–V equation solution by an iterative process for the single-diode photovoltaic (PV) model including the effect of the series and parallel resistances, and warranties that the maximum power of the model matches with the maximum power of the real PV module. In this paper the above fallacies has been removed and a simulink model has been proposed for a real time full scale solar PV power plant and the energy output results have been tested with the data of an operating 14 kW working power plant. Simulation of the mathematical model has been done in Matlab/Simulink software. The proposed design for the grid interactive solar PV system consist of P-V array that simulates the PV voltage and current output, 3-phase inverter which converts the generated DC power into a 3-phase AC filter which is an LC low pass filter reducing the

harmonic distortion by cutting off the high frequency harmonics and control unit in which a PLL synchronizes the output phase of the inverter with the phase of the grid and the PWM synchronizes the insulated gate bipolar transistors (IGBTs).

2. BUILDING MODELING OF PV COMPONENTS

2.1. PV Array

A photovoltaic cell is basically a semiconductor diode whose p–n junction is exposed to light. Photovoltaic cells are made of several types of semiconductors using different manufacturing processes. The monocrystalline and polycrystalline silicon cells are the only found at commercial scale at the present time. The incidence of light on the cell generates charge carriers that originate an electric current if the cell is short circuited. Some authors have proposed more sophisticated models that present better accuracy and serve for different purposes. An extra diode can be used to represent the effect of the recombination of carriers [2,3]. A three-diode model is proposed [4] to include the influence of effects that are not considered by the previous models. For simplicity, the single diode model is studied in this paper. This model offers a good compromise between simplicity and accuracy and has been used by several authors in previous works [5]. This model was used sometimes with simplifications but always with the basic structure composed of a current source and a parallel diode [4,6,7]. The current obtained from a photovoltaic module consisting of a number of cells (N_s) connected in series is represented by eqn (1).

$$I = I_{pv} - I_o [\exp\{\frac{q(V + IR_s)}{akTN_s}\} - 1] - \frac{V + R_s I}{R_p}$$ (1)

Where I_{PV} is the current generated by the incident light (directly proportional to the Sun irradiation); I_d is the Shockley diode equation, I_o is the reverse saturation or leakage current of the diode, $q = 1.60217646 \times 10^{-19}$ C (the electron charge), $k = 1.3806503 \times 10^{-23}$ J/K (the Boltzmann constant), T is the temperature of the p–n junction (in Kelvin), a is the diode ideality constant, R_S is series resistance, R_P is shunt resistance. In the case of a number of modules connected in parallel (N_P), the current obtained from eqn (1) is multiplied by N_P. All PV array datasheets bring basically the following information: the nominal open-circuit voltage ($V_{oc,n}$), the nominal short-circuit current ($I_{sc,n}$), the voltage at the maximum power point (V_{mp}), the current at the maximum power point (I_{mp}), the open-circuit voltage temperature coefficient (K_V), the short circuit current temperature coefficient (K_I), and the maximum experimental peak output power ($P_{max,e}$). This information is always provided with reference to the nominal condition or standard test conditions (STCs) of temperature (25 °C) and solar irradiation (1000 W/m^2). For simplicity, the single diode model will be studied in this paper. The light-generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following eqns [5,8].

$$I_{pv} = [I_{pv,n} + K_1(T - T_n)]\frac{G}{G_n}$$ (2)

$$I_{pv,n} = [I_{sc,n} + K_1(T - T_n)]\frac{G}{G_n}$$ (3)

$$I_{sc} = [I_{sc,n} + K_1(T - T_n)]\frac{G}{G_n}$$ (4)

Where G is irradiance on device surface; G_n = 1000 W/m^2 (nominal solar radiation), T_n = 298.15 K (nominal temperature); K_I = + (0.065±0.015) % °C, $I_{sc,n}$ = 4.8 A [18]. King et.al [9] found that there is typically less than a 5% change in the voltage coefficients over a tenfold change in irradiance from 100 W/m^2 to 1000 W/m^2. The temperature of the PV module can be obtained from the following eqn [10]

$$T - T_a = (219 + 832\bar{K})\frac{NOCT - 20}{800} \qquad (5)$$

Where T_a is the ambient temperature which can be obtained from the Metrological Department; NOCT °C (nominal cell operating temperature, obtained from the BP 380 module datasheet); $\bar{K}$ is the monthly clearness index. The diode saturation current I_o and its dependence on the temperature may be expressed by the following eqn [6].

$$I_c = I_{c,n}[\frac{T_n}{T}]^3 \exp[\frac{qc_g}{ak}(\frac{1}{T_n} - \frac{1}{T})] \qquad (6)$$

Where E_g is the band gap energy of the semiconductor = 1.12 eV. The nominal saturation current $I_{o,n}$ is obtained by evaluating eqn (1) at the nominal open-circuit condition, with V= $V_{oc,n}$.

I= 0, and $I_{PV} \approx I_{sc,n.}$

$$I_{o,n} = \frac{I_{sc,n}}{\exp[\frac{V_{oc,n}}{aV_{t,n}}] - 1} \qquad (7)$$

Where,

$$V_{t,n} = \frac{kT_n}{a}$$

The value of a is stated by Tsai et al. [8] for different types of PV depending on the PV technology. For the calculations in this paper, the value of a will be taken equal to 1.2. The method used here to get R_S and R_P is very simple. The first iterative value of R_S is 0. Then the value of R_P will be calculated from eqn (8) using the values at the nominal conditions which is obtained from the module data sheet. The value of the maximum power is then obtained from the graph ($P_{max.m}$, using a computer code) and compared with the experimental maximum power ($P_{max,e}$). This process is then repeated while increasing the value of R_S by small increment (e.g. 0.01) until the value of the calculated maximum power and the experimental one are equal (or close to each other within a certain tolerance, e.g. 0.001) [1]. It is worth noting that the values of both R_S and R_P obtained are for the nominal conditions. However, the changes in their values due to the temperature changes are small and can be neglected.

$$R_p = \frac{V_{mp}(V_{mp} + I_{mp}R_s)}{\left[V_{mp}I_{pv} - V_{mp}I_o \exp\left(\frac{V_{mp} + I_{mp}R_s}{N_s a}\frac{a}{kT}\right) + V_{mp}I_o - P_{max,e}\right]} \qquad (8)$$

2.2. Inverter

Grid-connected inverters are necessary for dc–ac conversion. To avoid the distortions to the power grid, the generated currents from these inverters are required to have low

harmonics and high power factor. When the output currents are in phase with the grid voltages, the maximum real output power is achieved. For conversion of dc-ac in grid connected PV system, there are several types of topologies and inverter designs are used in existing installations. The main circuit is the part where the DC electric power is converted to AC. This is virtually implemented with the one that is shown in the Figure 1. In this circuit we use a 3 leg inverter for 3-phase conversion which is composed of 6 IGBT. Control unit generates control pulses to drive the IGBTs. The frequency of the IGBTs we use is 15 KHz. A three phase inverter has the basic advantage that generates power in 3-phase and is working without a hitch.

2.3. Control Unit, Filter, Load and Grid Utility

The control unit combines a number of functions. At first, it provides the appropriate pulses to the IGBTs for the PWM technique, Secondly, it synchronizes the inverter generated phases to the grid. The control circuit has been developed in Matlab/Simulink. In order, this simulation gives us realistic and accurate output data for each day, of the simulated days from the PV array, we have to simulate the grid utility and the load. We use a high resistive load for a preliminary house load estimation of about 10kW. The load we use at the simulation can be seen in the Figure 1. Grid utility is simulated using a three phase source from Simpower System Library. Instead of this Grid utility can also be simulated using impedance estimation. Such values have been experimentally measured [11]. The Grid utility is not presented in this contribution. The idea to have a simulation that will work for each day and give us data for such a system has been studied and will be fulfilled in the future. The control unit uses two regulators: an inner current loop controlling the current and an outer DC voltage regulator controlling the DC voltage. LC filters are used to reduce harmonic (harmonic frequencies around multiples of 15 kHz). The LC filter we use can be seen at Figure 1, with L=5mH and C=20µF.
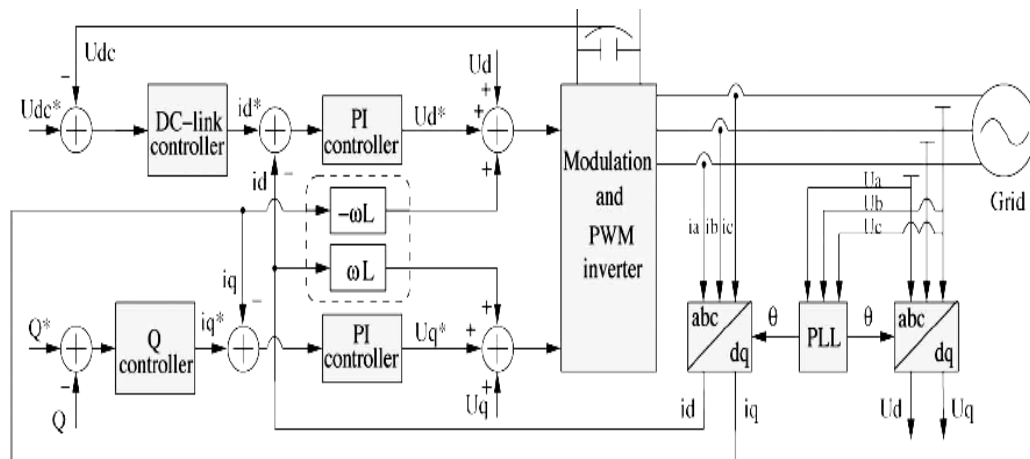

Fig. 1: Matlab/Simulink of grid connected PV system.

3. ENERGY MODELING

The array is characterized by its average efficiency, η_p, which is a function of average module temperature T_c and is given by

$$\eta_p =[1-\beta_p(T_c - T_r)] \tag{9}$$

where η_r is the PV module efficiency at reference temperature Tr (= 25°C), and β_p is the temperature coefficient for module efficiency. Tc is related to the mean monthly ambient temperature Ta through formula as given in eqn (5). η_r, NOCT and β_p depend on the type of PV module considered. The energy delivered by the PV array, E_P, is simply:

$$E_p = \eta_p (A * \bar{H}_t) \tag{10}$$

Whereby given: η_p = array average efficiency, A = area of the array, $\bar{H}_t$ = solar radiation, E_p = energy delivered by the PV array. It has to be reduced by "miscellaneous PV array losses" λ_p and "other power conditioning losses" λ_c

$$E_A = E_p (1 - \lambda_p)(1 - \lambda_c) \tag{11}$$

Whereby given: λ_p = miscellaneous PV array losses, λ_c = other power conditioning losses, E_p = energy delivered by the PV array, E_A = energy available to the load. The energy available to the grid is what is produced by the array, reduced by inverter losses:

$$E_{GRID} = E_A * \eta_{INV} \tag{12}$$

Whereby given: E_A = energy available to the load, η_{INV} = inverter efficiency. Depending on the grid configuration not all this energy may be absorbed by the grid. The energy actually delivered is:

$$E_{DLVD} = E_{GRID} * \eta_{ABS} \tag{13}$$

Whereby given: E_{GRID} = energy delivered to load, η_{ABS} = PV energy absorption rate, E_{DLVD} = energy available to the load

Assumptions: In the energy modeling of the whole of the system it is assumed that the power conditioning losses (λ_c) are 5%, miscellaneous PV array losses (λ_p) are also considered 5%, and grid absorption rate is 95%. The efficiency of the inverter is taken as 95%.

4. SIMULATION RESULTS AND DISCUSSION

In this section, the simulation of single junction PV module will be viewed and verified through the manufacturer's datasheet. The next stage will be simulation of the grid connected PV system and analysis through energy output and also verification through actual case studies. Case study is conducted on 14 kW multicrystalline PV power plant. While energy output yielded from implementing the Case study using MATLAB/SIMULINK were analyzed and later will be verified using the actual monitored data from the PV power plant. The simulation results validate the manufacturer's data

sheet. The irradiance data is measured at every 15 minutes from 10:00 am to 5:00 pm. The simulation is conducted on a week data. Figure 2 and 3 show I-V and P-V curve at different irradiance level. The results are validating the literature theory.
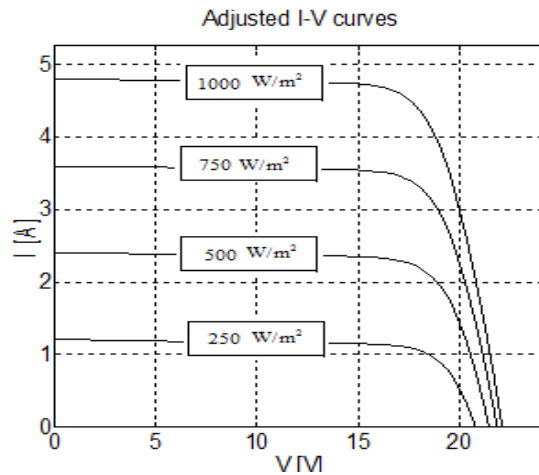

Fig. 2: I-V curve at constant temperature (25°C) and different irradiance.
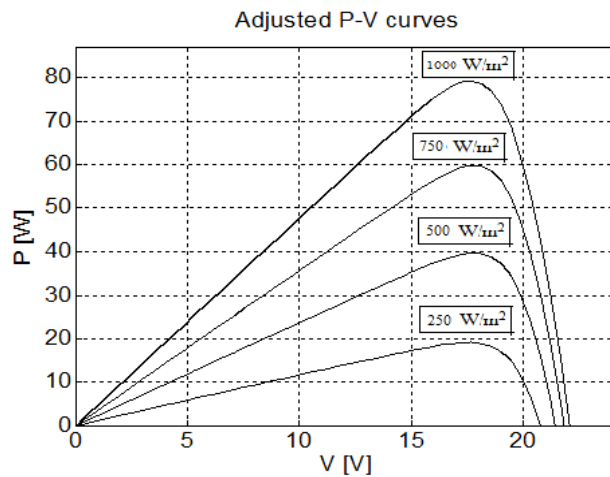

Fig. 3: P-V curve at constant temperature (25°C) and different irradiance.

Figure 4 shows the difference between the actual and simulated energy output. The difference is not so large hence the model can be used for any capacity of power plant by changing the parameters. Beyond this the effect of temperature on efficiency can be observed.
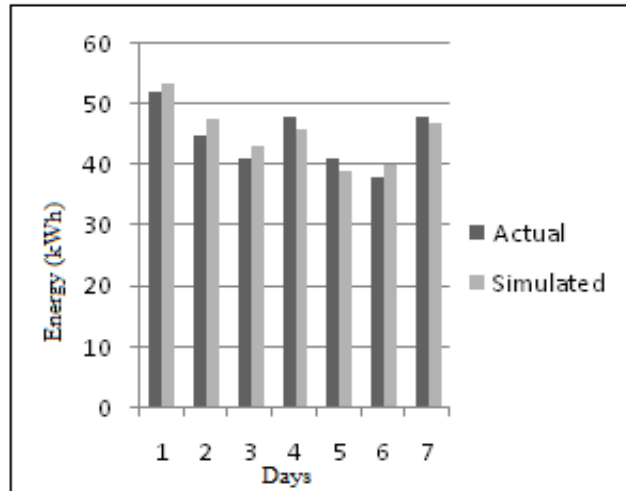
Fig. 4: Comparison between actual energy Vs Simulated energy outputs

Overall findings indicate that this MATLAB modeling can be further used for investigation and make improvement in order to identify which best technologies to be implemented. The simulation results are at Standard Test Condition. These may vary as the environmental condition varies. The current injected in the grid is shown in Figure 5. The total harmonic distortion is 4.78% which is obtained from FFT analysis.
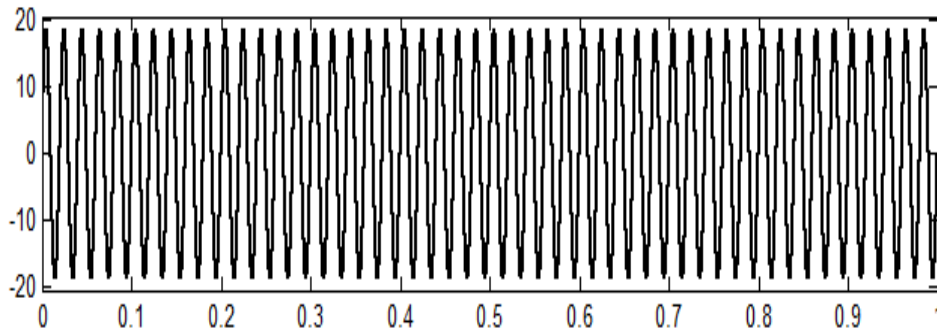
Fig. 5: Current injected in the grid.

5. CONCLUSION

This paper presents the model and simulation of a grid interactive PV plant and analyzes its electrical performance for different operating conditions. Overall system is built by integrating individual models of a PV array, interfaces, and load. Simulation results show that the overall simulink model of the grid interactive PV plant performs well to reflect the system behavior for different operating scenarios. This model does not require storage of the PV module characteristics as data storage but calculates the power generated and energy delivered by the PV module at different solar irradiance. The developed PV model gives properly the I-V and P-V characteristics of a photovoltaic module. This system is able to take into account the variations in the environmental conditions such as

temperature and irradiance. Finally through verification using the real time system, the grid connected model can be used for energy output prediction and it is a user friendly system.

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