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Modelling and Simulation of 1.2 MWpTenaga Suria Brunei Photovoltaic Power Plant

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Abstract

The energy demand in Brunei Darussalam will increase in near future. The renewable energy is one of the alternative energy sources that could satisfy the increasing energy demands. Brunei Darussalam depends heavily on fossil fuel to generate its electricity needs. Fossil fuels are depleted and the main source of pollution. Photovoltaic (PV) systems generate electricity directly from the sunlight without any emission of global warming gases, and the fuel is free. In order to optimize the performance of PV systems their operation should be well understood. In this paper, we present the modelling of a real 1.2 MWp photovoltaic system. The PV power plant is tied to the grid. The PV array, the DC/DC converter and the DC/AC inverter are modelled and implemented in Matlab/Simulink. The controller of the grid-connected inverter is modelled to achieve constant voltage, constant frequency and to be synchronized with the grid. The system is simulated under Brunei weather conditions and the results are acceptable.

Keywords: *Brunei; Grid-connected; Modelling; PV; Simulation*

1. Introduction

The energy demands and the negative environmental effects have promoted the use of renewable energy sources. Producing an electric power from a renewable energy can reduce the number of concerns regarding the inefficient use of electrical energy from fossil fuel. Also, a renewable energy development is one of the methods to cut the consumption of the oil and gas for export, thus reducing the dependency on such resources for electricity generation. Furthermore, these sources are clean, pollution free, and can be found globally with regard to the system size.

The Photovoltaic (PV) system can be grid connected or stand-alone. The PV technology is one of the fastest growing technologies where the yearly increase in the installed PV systems is more than 29% as shown in Figure 1. The PV system has its own uniqueness compared to other systems, as the sunlight is free, it is

sustainable and the solar radiation is directly converted into an electrical energy, the absence of mechanical moving parts, and the long life of the solar panels. Many research papers show that the solar PV technology is economically feasible in many countries. The authors in [2] have discussed the feasibility of the rooftop PV systems in the United Arab Emirates. Ahmad

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Zahedi [3] has investigated the solar PV in Morocco and it is found that it is cost effective. To encourage the customers to install PV systems, Chile implements a net metering [4]. Spain has developed policies for implementing grid-connected PV systems [5]. A techno-economic analysis for PV systems in India is presented in [6]. In [7], the design and the economic feasibility of PV system to power a small village in rural areas in Yemen have been investigated. Two options are considered: on-site PV system and off-site PV system. The off-site PV system is proved to be cost effective. The potential of the grid-connected PV system for different locations in Bangladesh has been investigated in [8]. The feasibility study is carried out for 14 locations across Bangladesh for 1 MWp grid-connected PV system. The authors have showed that it is technically feasible to install a 50.147 GWp in Bangladesh. The performance of 15 MWp solar plant installed in Mouritania is analyzed in [9], where the thin film PV technology is implemented in the plant. A feasibility study for PV system in Cameron is carried out in [10].

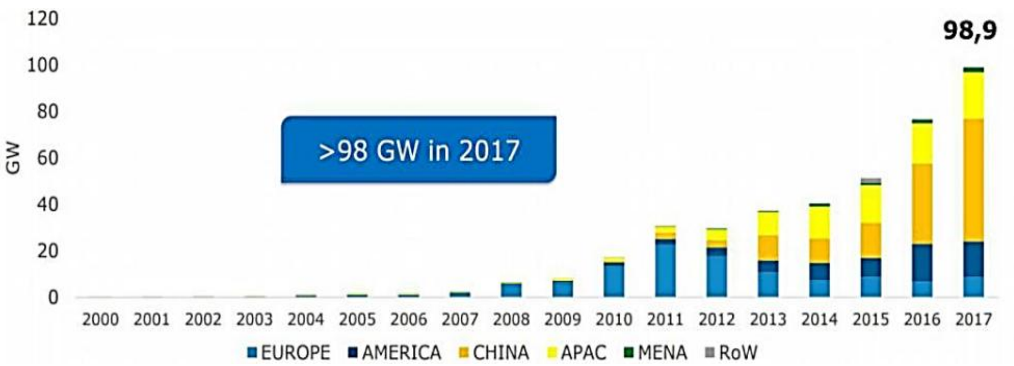

Figure 1: The global annual installed solar PV capacity [1].

In all the contemporary research works, the PV systems have been technically and economically feasible. Brunei Darussalam has a high potential for solar energy harvesting. Matussin in [11] has discussed the renewable energy in Brunei Darussalam for a system consists of 1.2 MWp installed capacity which are generated byTenagaSuria Brunei (TSB) solar PV power plant, and it proves that the implementation of the solar PV power plant in Brunei Darussalam can reduce the use of the natural gas which helps in reducing the overall CO_2 emission from the conventional power plants since the country runs on natural gas for electricity generation.

To optimize the performance of grid-connected PV systems, their modelling is essential. In [12], a model of single-phase grid-connected PV system is presented, the model is implemented in Matlab/Simulink. The modelling of three-phase grid-connected PV system is presented in [13]. The controller of the DC/AC three-phase inverter is designed to achieve constant DC link voltage while synchronizing the frequency and control the power factor. The performance analysis of grid-connected PV system using Matlab is introduced in [14]. A modelling and simulation study for a 45.35 kWp grid-connected PV system in Malaysisa is investigated in [15]. In [16] the model of single-phase grid-connected PV system is implemented in Matlab Simulink. The simulation results are verified through practical implementation. The sizing and the modelling of 1.5 MW grid-connected PV system is presented in [17-18]. The system is then implemented in Matlab/Simulink.

In order to understand the operation of the PV system and to increase their energy yield, their operation under Brunei weather conditions should be investigated. In this paper we present a model of the grid-connected TSB PV power

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plant in Brunei. The model of the TSB PV power plant is implemented in Matlab/Simulink. In the next sections, the model of the grid-connected PV system is described. This includes modelling of the PV array, DC/DC converter, Maximum Power Point Tracker (MPPT), the inverter and its controller. These models are then implemented in Matlab/Simulink. The PV grid connected system is then simulated under different weather conditions.

2. Solar Energy Resource in Brunei

Brunei has high potential of solar energy. The solar radiation in Brunei Darussalam is shown in Figure 2. As it clearly shown from Figure 2, the solar radiation is in the range between 4.7 to 5.8 kWh/m^2 per day which is considered as high range level globally. The irradiation is obtained using different sources which are NASA, by estimation, and the measured data. The estimated values are higher than the measured and the data from NASA, whereas both the measured and the data from NASA are close to each one. In this paper, the NASA data of irradiation was used to design the PV system due to its reliability and its regular updates as well as the flexibility to access the irradiation history from previous years up to date.

The tilt angle of the PV array is one of the most important parameters in PV system design,Pacudan [19] has explained the significance of the tilt angle. In order to achieve a maximum solar radiation the tilt angle should be optimized. Based on the measured data from TenagaSuria Brunei (TSB) project in Brunei Darussalam, the 5° tilt angle gives a better overall electricity output compared with 15° tilt angle [19]. Figure 3 shows the aerial view of the TSB PV power plant (PVPP). The configuration of the PVPP is shown in Figure 4. The PVPP consists of six PV arrays each one is rated 200 kWp. Each array is connected to a DC/DC converter to harvest maximum power and the output of each two DC/DC converter is connected to a DC/AC inverter. The three inverters are connected to isolation transformer. Then the three transformers are connected to 415-V/11-kV transformer. Saloman et al [20] have discussed another important factors such as the power quality, protection coordination and grid synchronization. These factors could lead to power system instability if the PV penetration level is high.

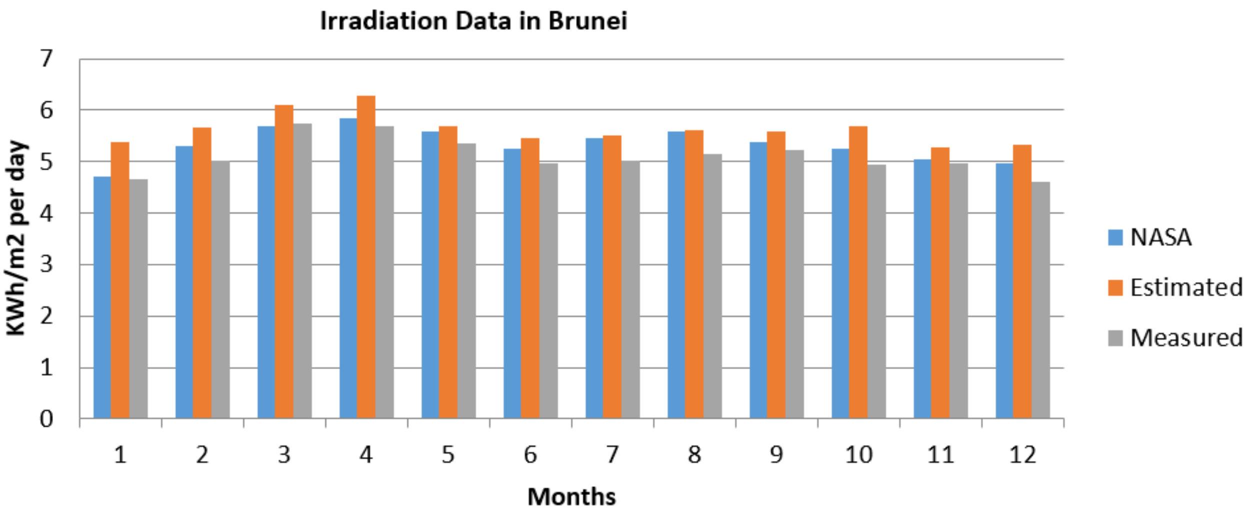

Figure 2: The Solar Radiation in Brunei

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Figure 3: The aerial view of TSB PV power plant

3. The Mathematical ModleOf The TsbPv Power Plant

The grid-connected PV system used in the modelling is shown in Figure 5. The PV array is composed of series and parallel connection of Sharp Monocrystalline Photovoltaic Module (NUS0E3E). The PV array is rated 200 kWp. The PV array is connected to a DC/DC Buck converter equipped with MPPT. The output of the DC/DC converter is connected to a three-phase DC/AC inverter with 400 V output voltage. The controller of the inverter has to achieve: 1) constant amplitude voltage, 2) constant frequency, and 3) synchronize the output voltage with the grid voltage. The output of the inverter is then fed to step-up transformer to connect the system to the 11 kV grid. In the following sections the mathematical model of each component in the system is presented.

3.1 The PV Array

There are many methods in the literature for modelling PV modules [21-23]. The model used in this paper is based on the single-diode model and extracting some of the parameters from the manufacturer data sheet. The electrical circuit model of the PV module is shown in Fig 6. The model is with middle complexity where the temperature dependence of I_0, I_{ph}, and V_{oc} is included. Also the parasitic resistances R_s and R_{sh} and their temperature dependence are taken into account. The ideality factor is used as a variable to match the simulated data with the manufacturing data. The mathematical model of a solar cell based on the single diode model is given as [24-25]:

$$I(T,G,V) = I_{ph} - I_0(e^{(V+IR_s)/nV_{th}} - 1) - (V + I \cdot R_s)/R_{sh} = I_{ph} - I_D - I_{sh} \quad \textbf{(1)}$$

where the variables in (1) are given by [22];

$$I_{ph} = I_{ph0} \cdot G / G_{nom} \quad \textbf{(2)}$$

$$I_{ph}(T) = I_{ph} + K_0(T - T_{meas}) \quad \textbf{(3)}$$

$$K_0 = (I_{ph}(T_2) - I_{ph}(T_1))/(T_2 - T) \quad \textbf{(4)}$$

$$I_0 = I_{SC(T_1)} \cdot (T/T_1)^{3/n} \cdot \exp[-E_g / V_s(1/T - 1/T_1)] \quad \textbf{(5)}$$

$$I_0(T_1) = I_{SC(T_1)} / (e^{qV_{OC(T_1)}/nkT_1} - 1) \quad \textbf{(6)}$$

$$R_s(T) = -dV/dI_{V_{OC}} - 1/(I_{0(T_1)} \cdot q/nkT_1 \cdot e^{qV_{OC(T_1)}/nkT_1}) \quad \textbf{(7)}$$

$$R_{sh} = V_{OC} / [I_{ph} - I_0(\exp(qV_{OC}/nkT_{meas}) - 1)] \quad \textbf{(8)}$$

$$R_{sh}(T) = R_{sh} \cdot (T/T_{meas})^{\alpha} \quad \textbf{(9)}$$

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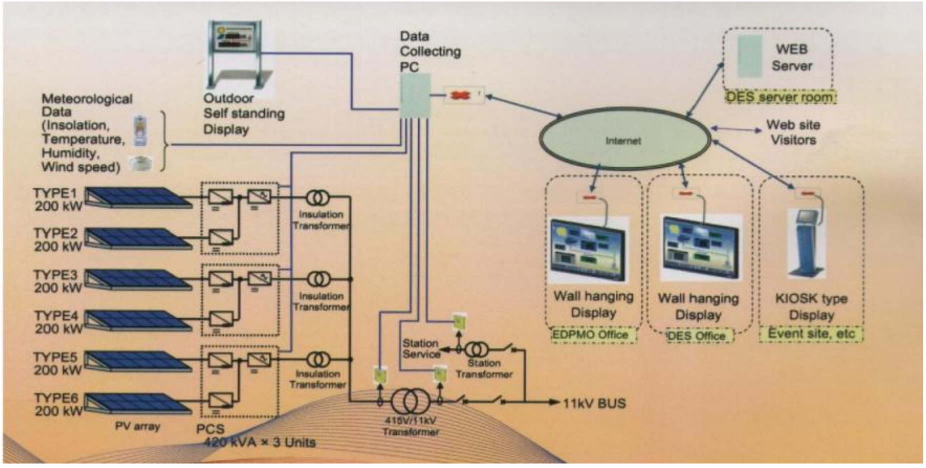

Figure 4: The configuration of the 1.2 MWP PV system

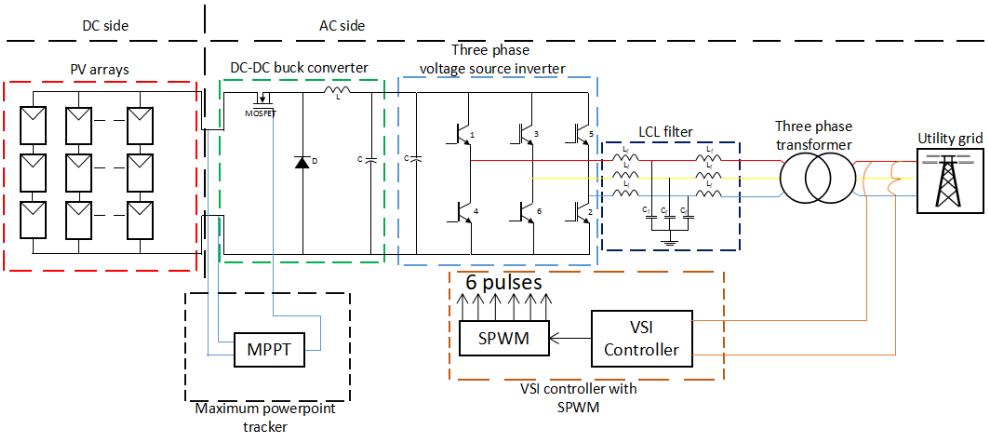

Figure 5: TSB grid-connected PV system

The parameters in the model are explained briefly. I_{ph} is the photo generated current in Amperes. I_{ph0} is the photo generated current at the nominal radiation. I_0 is the diode dark saturation current. I_D is the diode dark current. I_{sh} is the shunt current. R_s is the series resistance. R_{sh} is the shunt resistance. G is the solar radiation in W/m^2. The G_{nom} is the radiation the PV module is calibrated at. n is the ideality factor. e is the electron charge. k is Boltzmann's constant. V_g is the semiconductor energy gap. V_{th} is the thermal voltage. K_0 is the short-circuit current temperature coefficient. The manufacturer provides the following: N_s (the number of cells in series), N_p (the number of cells in parallel), the short-circuit current, the open-circuit voltage, the short-circuit current temperature coefficient.

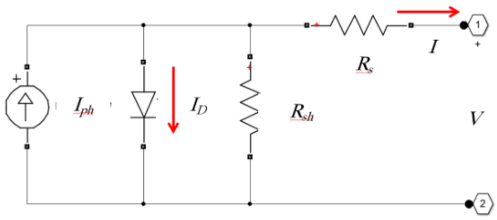

Figure 6: Circuit model of a solar cell

3.2 The DC/DC Converter and the MPPT

The main role of the DC-DC converter is to match the PV array to the load and to achieve maximum power point tracking. The value of the filter inductance that determines the boundary between the continuous conduction mode (CCM) and discontinuous conduction mode (DCM) is given by the following equation [26]:

$$L_b = (1-D)R/(2f) \qquad \textbf{(10)}$$

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Where; L_b is filter inductance, D is the duty cycle, R is resistance, f is the switching frequency. L should be less than L_b. In order to limit the peak-to-peak value of the ripple voltage below a certain value of the ripple voltage, V_r, the filter capacitance, C must be greater than the minimum capacitance, C_{min} which can be found using the following formula [24]:

$$C_{min} = (1-D)V_o/(8V_r L f^2) \quad \textbf{(11)}$$

Where; C_{min} is minimum capacitance, V_o is output voltage, L is filter inductance. The Perturb & Observe (P&O) technique is widely used method for MPP tracking due to its simple structure and ease of implementation and it is implemented in this simulation model.

3.3 Three-phase Voltage Source Inverter (VSI) with LCL Filter

The three phase VSI provides a three phase voltage, where the amplitude, phase, and frequency of the voltage should always be controlled. The main function of the LCL filter is to reduce the high-order harmonics in the output side of the inverter. The filter circuit consists of specially designed inductor and capacitor to block certain unwanted harmonics. The control strategy of the VSI controller consist of the inner control loop and outer control loop. The inner control loops independently regulate the output current in the rotating reference frame, whilst the outer loop works in the voltage control mode to produce the d-q axis current references for the inner loop by regulating the voltage at given reference values. The block diagram of the inverter controller is shown in Figure 7. The input DC voltage is regulated by PI controller. The output of this loop is the reference I_d current and is given by:

$$I_d^* = K_p(V_{dc}^* - V_{dc}) + K_I \int (V_{dc}^* - V_{dc})dt \quad \textbf{(12)}$$

The reference voltage Vd and Vq are generated by two different loops given by:

$$V_d^* = RI_d + V_d - \omega L I_q + Ld(I_d)/dt \quad \textbf{(13)}$$

$$V_q^* = RI_q + V_q + \omega L I_d + Ld(I_q)/dt \quad \textbf{(14)}$$

By substituting (12) into (13) and (14):

$$V_d^* = RI_d + V_d - \omega L I_q + K_{pd}(I_d^* - I_d) + K_{Id}\int (I_d^* - I_d)dt \quad \textbf{(15)}$$

$$V_q^* = RI_q + V_q + \omega L I_d + K_{pq}(I_q^* - I_q) + K_{Iq}\int (I_q^* - I_q)dt \quad \textbf{(16)}$$

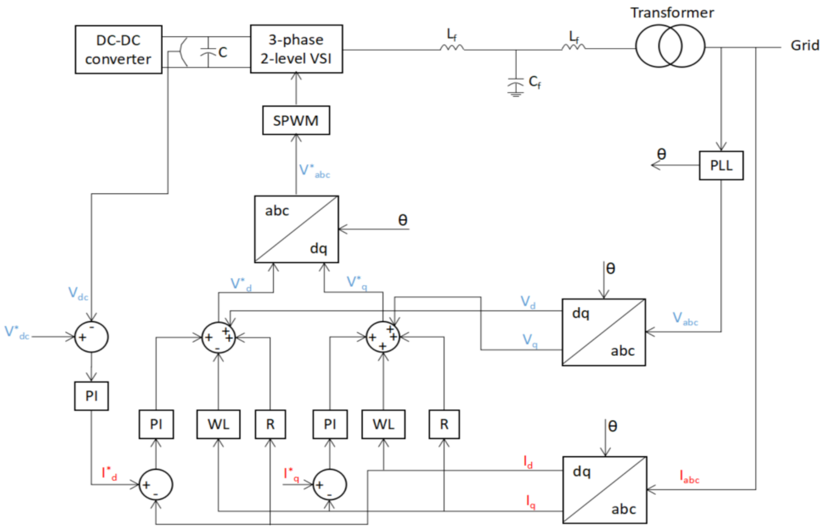

Figure 7: The structure of the three-phase grid-connected inverter

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4. Results and Discussions

The model has been implemented in Matlab/Simulink as shown in Figure 8. The parameters of the system are given in Table 1-3. The PV array current and the PV array output power are shown in Figure 9 and 10, respectively. The radiation and the temperature are varying. It can be seen that the PV array current and PV array power increase as the radiation increases. The output voltage of the inverter is shown in Figure 11, and it is clear that the AC voltage signal has a stable amplitude and stable frequency with low harmonics. The output voltage of the transformer is shown in Figure 12 and 13. From Figure 13, the output voltage is maintained at 11 kV even with the change in the temperature and the radiation, which shows successful operation of the inverter controller.

Table 1: The parameters of the PV array

Number of series modules	18	Maximum Power Voltage, V	23.7
Number of parallel modules	62	Maximum Power Current, A	7.6
The PV module Type	NUS0E3E	αPmax	-0.485 %/C
Number of series cells	48	αIsc	+0.053 %/C
The open-circuit voltage, V	30	αVoc	-104 mV/C
The short-circuit current, A	8.37	Efficiency	13.7 %
Maximum Power, W	180		

Table 2: The parameters of the DC/DC converter

Switching device	MOSFET	Filter Inductance	10 mH
Switching frequency	20 kHz	Filter Capacitance	1.042 µF

Table 3: The parameters of the three-phase inverter

Filter inductance, L1	5 mH	K_{pd}	0.4	K_P	5
Filter inductance, L2	22 µH	K_{Id}	20	K_I	5
Filter capacitance	10 mF	K_{pq}	0.4	K_{Iq}	20

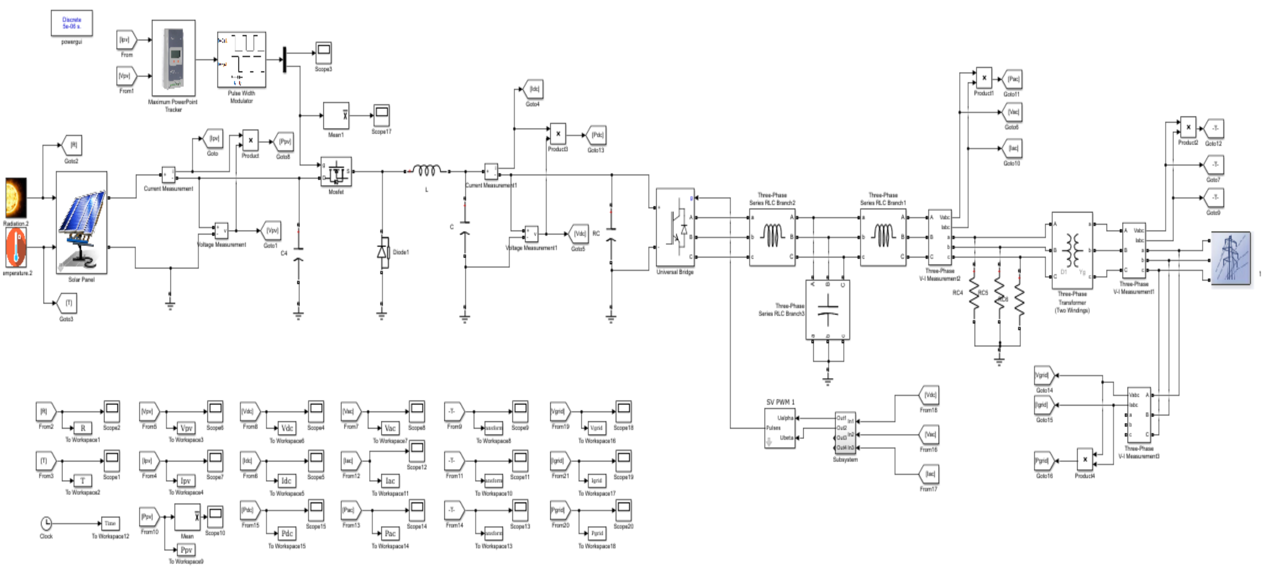

Figure 8: The structure of the three-phase grid-connected inverter

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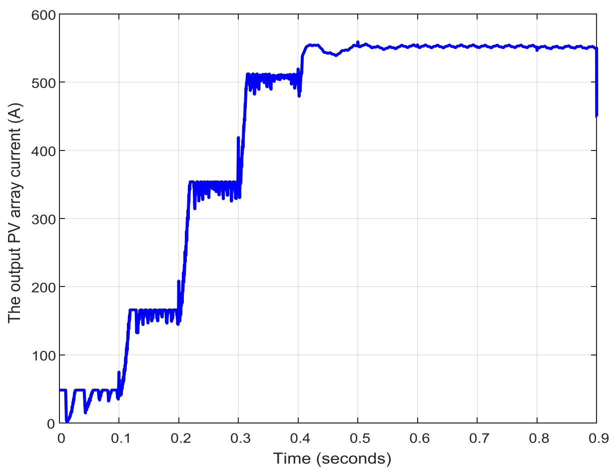

Figure 9: The PV array current

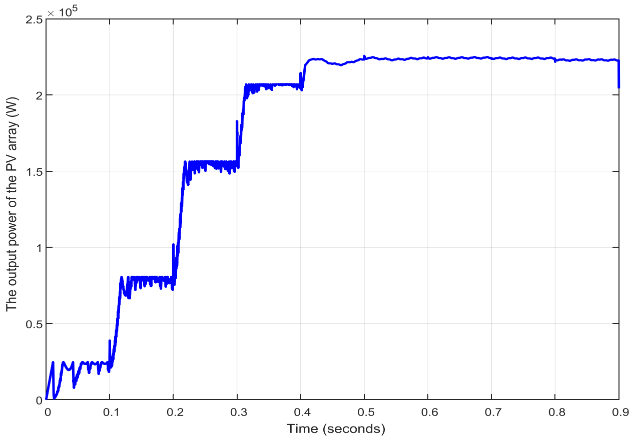

Figure 10: The PV array power

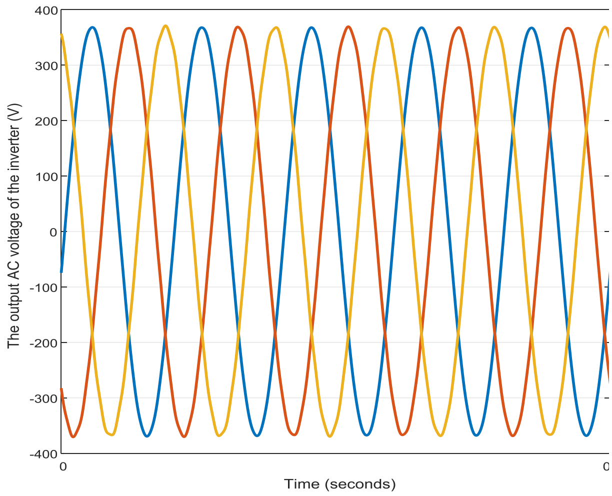

Figure 11: The output voltage of the inverter

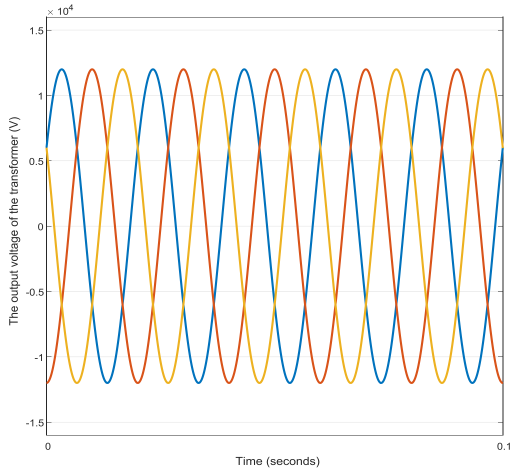

Figure 12: The output voltage of the transformer

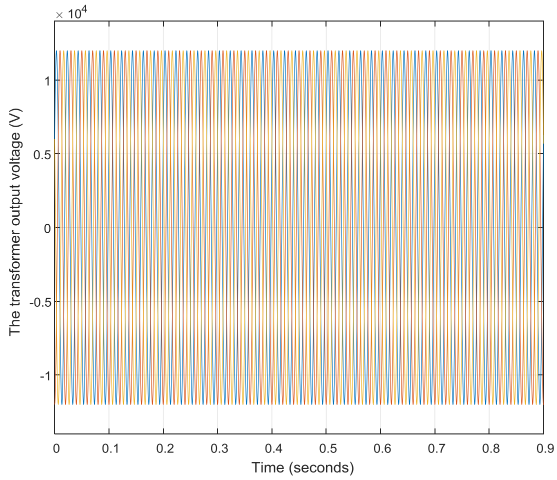

Figure 13: The output voltage of the transformer

Conclusion

In this paper we present a model for grid-connected PV system. The PV array, the DC/DC converter with MPPT, the DC/AC inverter and the transformer are mathematically modelled and implemented using Matlab/Simulink. The output of the DC/AC inverter has a constant magnitude and constant frequency even when the solar radiation and the temperature are varying. The results of the simulation show a successful operation of the system model and the controller. The output power increases with increasing the radiation which proves the successful operation of the

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MPPT. The output of the inverter has very low harmonics which shows a correct selection of the filter parameters. The proposed simulation model will be validated with the real measurement data from TSB PV power plant. This model will be used to investigate and improve the performance of the real system.

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