Dynamic Modeling and Simulation of a Photovoltaic System for a House in Qassim, Saudi Arabia

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***Abstract*—This study presents a dynamic modeling of a photovoltaic (PV) system for a residential application using Simulink. The PV system designed here consists of 56, 300W, 24 V PV modules, 52, 200Ahr, 12V batteries, a maximum power point tracking (MPPT) charge controller and an 11 kW inverter to power a house. This paper proposes a boost converter; (MPPT) to be applied to the system. Additionally, varying weather curves data were implemented in the design to simulate potential conditions, namely radiation and temperature. A step-up transformer is used to achieve the house required voltage. The simulation results prove that such a PV system would work smoothly without grid connection at a location such as Qassim, Saudi Arabia.**

***Index Terms*—PV system, modeling, renewable energy, MPPT, solar energy.**

I. Introduction

People are not surprised when they read that Saudi Arabia is one of known countries to have high directional normal sun radiation [1]. The energy produced by the sun is also known as a clean energy source. Because of the high level of solar radiation routinely experienced at Qassim, houses use air conditioners at maximum levels, relative to other locations with more cloudy conditions [2]. A block diagram of a typical house size PV system is shown in Fig. 1. A DC/DC boost converter is used in the PV system; its main purpose to achieve a higher dc voltage level. A DC to AC inverter is used to change the constant voltage signal to a sinusoidal wave voltage signal. The MPPT feature will extract the maximum power output of the system, by controlling the duty cycle of the boost converter and algorithm implementation [3]. The proposed PV power system is modeled using Simulink [4], as shown in Fig. 1.

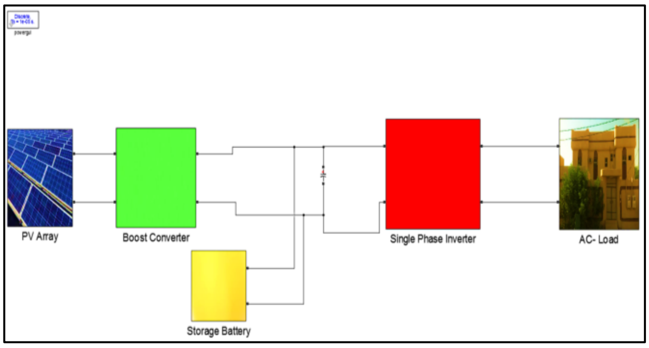

Fig. 1. The block diagram of a PV system for residential applications.

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II. System Sizing

In order to design an electric system, it is necessary to size that system and determine the necessary operation requirements by using simulation software such as Homer software [5]. The software results will estimate one or more optimal electrical and economical solutions. Homer can recognize which renewable energy configuration can be beneficial to the system [6]. The renewable fractions in this system should be equal one, due to no grid connection availability. It is necessary to consider one of the main motivation of the energy production output, which is providing an optimal design of installation for maximum solar irradiance. The first step is sizing the system parameters, which includes PV, load, batteries and the inverter as shown in Fig. 2.

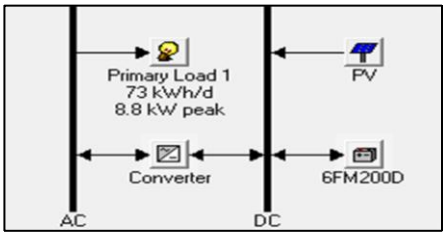

Fig. 2. System block diagram.

The amount of power or electricity produced from the solar panel count on the amount of sunlight that reaches the solar cells. When there are no enough sun rays to the photovoltaic cells, less or no power is generated from the cells. The solar radiation data for Qassim can be uploaded to Homer, to determine the correct power output of the PV system.

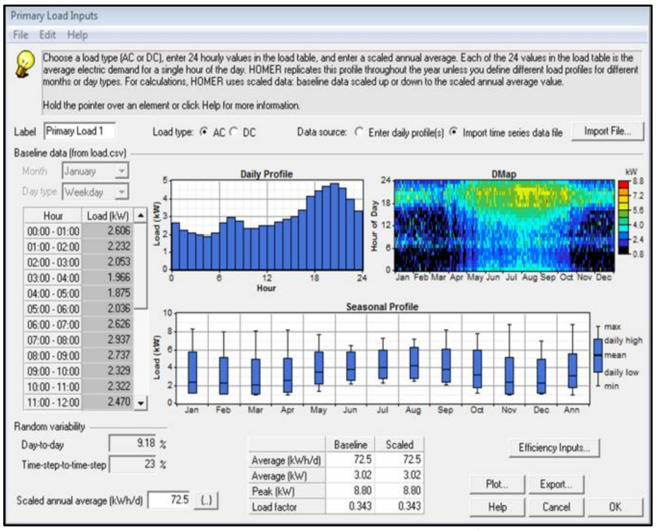

Fig. 3. Monthly average energy consumption for the site.

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Load data is the main factor that homer requires to find the optimization result. Calculating the daily house kW consumption was done using electricity bills of the house, Fig. 3 shows the monthly average kWh used in the house. Analyzing the electricity usage every month, to decide if the renewable energy system should operate on or off the electric grid.

The average daily used power was 72.5 kW, and the peak was 8.8 kW; these two values are needed to design the PV and inverter size accordingly. When seeking a simulation, Homer will evaluate the energy production and consumption each hour during the year, to determine the system possible scenarios results per the cost estimation values. After entering all required data to Homer, the simulations results can be obtained as shown in Fig. 4.

PV (kW)	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
22.75	44	10	LF	$ 40,800	9,101	$ 199,275	0.449	1.00	0.04
19.50	52	12	CC	$ 40,600	9,114	$ 199,308	0.449	1.00	0.04
19.50	52	12	LF	$ 40,600	9,114	$ 199,308	0.449	1.00	0.04
20.80	48	12	CC	$ 40,480	9,135	$ 199,545	0.448	1.00	0.04
20.80	48	12	LF	$ 40,480	9,135	$ 199,545	0.448	1.00	0.04
22.75	44	12	CC	$ 41,000	9,108	$ 199,606	0.450	1.00	0.04
22.75	44	12	LF	$ 41,000	9,108	$ 199,606	0.450	1.00	0.04
18.85	56	10	CC	$ 41,160	9,120	$ 199,966	0.451	1.00	0.04
18.85	56	10	LF	$ 41,160	9,120	$ 199,966	0.451	1.00	0.04
18.85	56	12	CC	$ 41,360	9,127	$ 200,298	0.451	1.00	0.04
18.85	56	12	LF	$ 41,360	9,127	$ 200,298	0.451	1.00	0.04
18.20	60	10	CC	$ 41,920	9,096	$ 200,314	0.454	1.00	0.05
18.20	60	10	LF	$ 41,920	9,096	$ 200,314	0.454	1.00	0.05
19.50	48	16	CC	$ 42,500	9,078	$ 200,570	0.455	1.00	0.05
19.50	48	16	LF	$ 42,500	9,078	$ 200,570	0.455	1.00	0.05

Fig. 4. The system simulations results.

Some external variables will lead Homer to generate the sensitivity results; local utilities prices, net present cost (NPC) and load needs. To figure out the best electrical solution to the system, there is a feature in the software used to identify the optimum solution based on the mentioned factors, as shown below:

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
18.85	52	10	CC	$ 39,760	8,901	$ 194,747	0.441	1.00	0.05

Fig. 5. The system optimum simulations results.

The results of the simulations show the optimal combination as being: 18.85 kW PV, 52 battery unit and 10 kW converter, as shown in Fig. 5. By using this model, the house can expect a monthly bill reduction by 100%. Among all the generated results, Homer chose only one optimum solution with specific configuration, such as the inverter data as examples shown here in Table I.

TABLE I: INVERTER RESULTS

Quantity	Inverter	Units
Capacity	10	kW
Mean output	2.9	kW
Minimum output	0	kW
Maximum output	8.8	kW
Capacity factor	28.9	%

III. PHOTOVOLTAIC ENERGY STRUCTURE

The primary goal of using PV system is to extract electric energy from the sun radiation, the core device in that system is the PV cell. The cells combine to make a module, and a group of modules create the PV array. In this design, there are two modules in series and twenty-eight in parallel to generate 48V DC bus and 16.8 kW to the system as shown in Fig. 6. During the day hours, the load energy source is the PV arrays while in parallel charging the battery bank. Moreover, during the night hours, the battery bank will supply the load by electricity as discharging process.

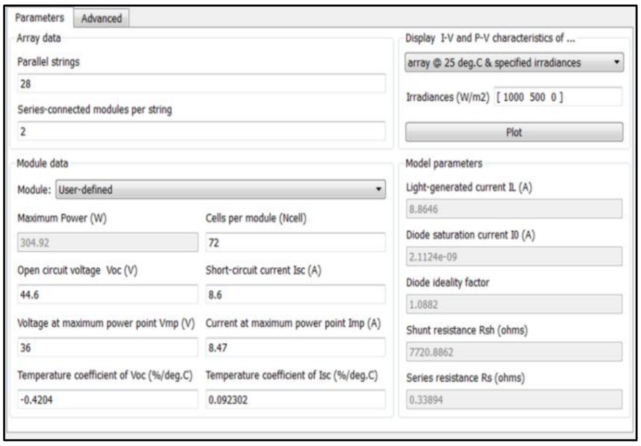

Fig. 6. Screenshot of PV parameters in Simulink.

Two of the main factors that affect the PV module's output are the temperature and sunlight. In this design, the sun irradiation and temperature fluctuate. However, the value of irradiance fluctuates around 1000 W/m^2, and the temperature curve also oscillates around 25 C^o, as shown in Fig. 7.

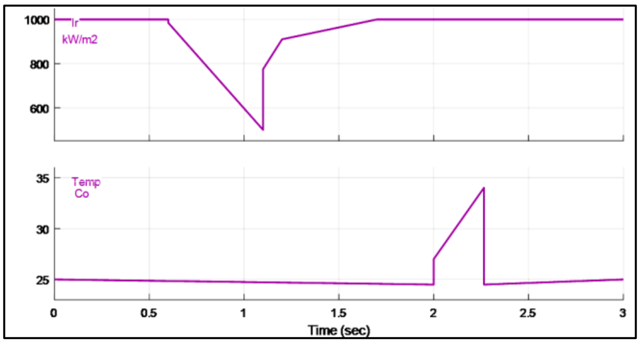

Fig. 7. The irradiance and temperature data.

(MPPT) is implemented using the "Perturb and observe" method by controlling the duty cycle of the boost converter [7]. It is a widely-used method, whereas voltage and current are applied to the function which controls the duty cycle value according to the relation given here:

$$D = 1\text{-}Vi/Vo \qquad (1)$$

Since output voltage is nearly constant (as defined by battery voltage), the variations in the duty cycle balance the changes in the input voltage. As such, this maintains the current. The algorithm detects the point at which maximum power point can be tracked, hence:

$$P_{\max} = V_{\max} \times I_{\max} \qquad (2)$$

For a given intensity of sunlight the duty cycle is depending on PV voltage and current values [8].

The main key of this method is choosing a reference voltage, and keep changing the output PV voltage signal to decrees the power variation. (MPPT) is applied between the energy source and load, due to utilizing the available maximum power output of the PV. The algorithm is implemented according to the flow chart given here:

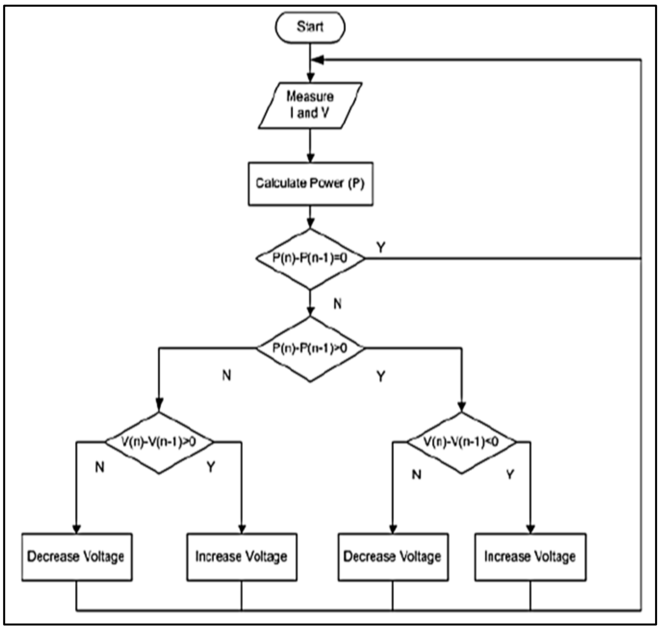

Fig. 8. Perturb and observe algorithm [9].

IV. Results and Discussion

A. Boost Converter Design

The DC to DC converter will allow the required voltage level between the PV and the storage system. The boost converter will charge the 48V battery bank. The main parameters in the converter are: MPPT, PWM, Inductor and capacitor. The designed boost converter can deliver 17 kW DC power. There are equations for the boost converter, in order to find the input and output capacitors' values through equations (3) and (4) as follows [8]:

$$C_{\mathrm{in}} \geq \frac{I\max * D\max}{0.02 * [(1-D\max) * V\mathrm{in} \text{ x } Fsw]} \tag{3}$$

$$C_{\mathrm{out}} \geq \frac{I\max * D\max}{\Delta V * Fsw} \tag{4}$$

where, $D_{\max}$ = maximum duty cycle, F_{sw} = switching frequency, ΔV = voltage ripple. Please refer to the Boost converter diagram as shown in Fig. 9.

To make the inductor accumulate and raise the current, the frequency switch is implemented in the design. The capacitor stores and increases the DC voltage through an electric field effect. The Pulse Width Modulation (PWM) drive is implemented in the model to stabilize the converter output voltage. A capacitor unit is added to the system to store and smooth the voltage signal; refer to Fig. 11. An online calculator is used to obtain the values of the inductor and capacitor parameters, as shown in Fig. 10, the proposed value for L is achieved when these two conditions (5) and (6) apply [10]:

1) ΔI_L=0,4 * I_{out} *for* >$V_{\mathrm{in\_max}}$ (5)

2) The lowest value of L is achieved if ΔI_L=2*I_{in} for V_{in_min} (6)

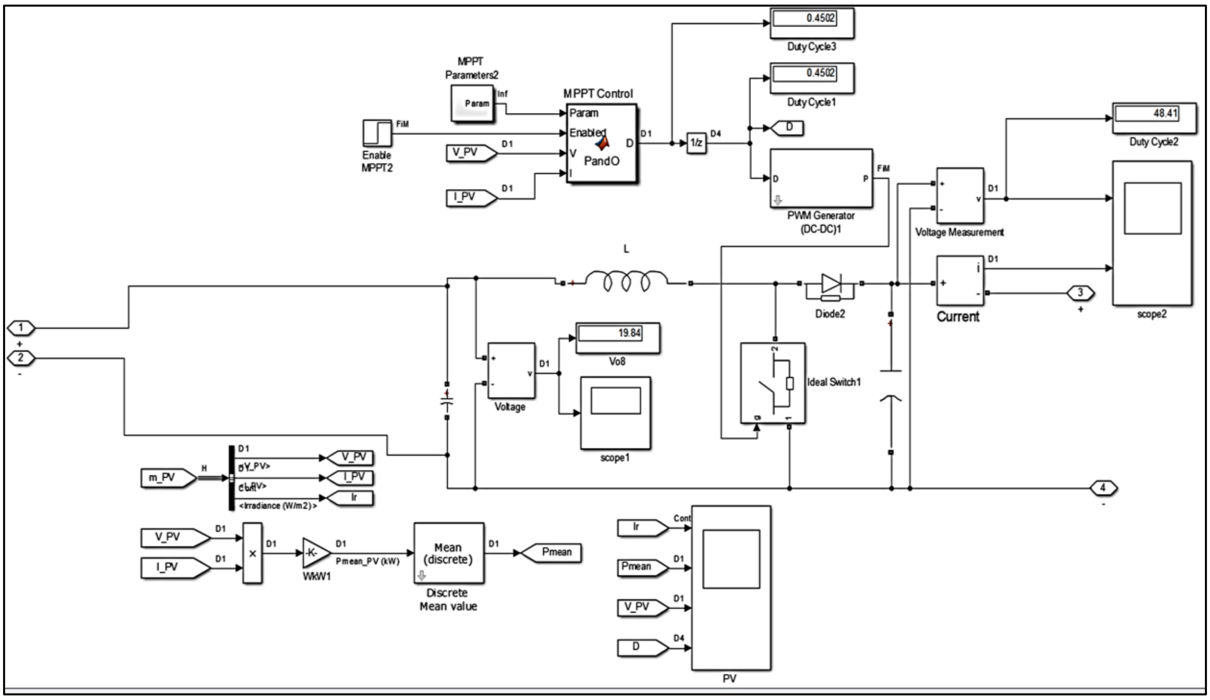

Fig. 9. The boost converter circuit.

During the simulations, the ideal switch turns on and off systematically within milliseconds, to maintain the ideal voltage output with high efficiency. The switching inductor increases the output voltage by two times, as shown in the boost converter output voltage in Fig. 11.

In order to minimize the power losses by decreasing the number of instruments, no signal filters were used in the boost converter designed system. In spite of this, the signal was still high as shown in the Fig. 9, at around 48. The output voltage is boosted from a minimum of 19.48 V DC to

48.41 V DC as shown in Fig. 11, its semi-stable voltage signal is due to the inductor voltage ripples.

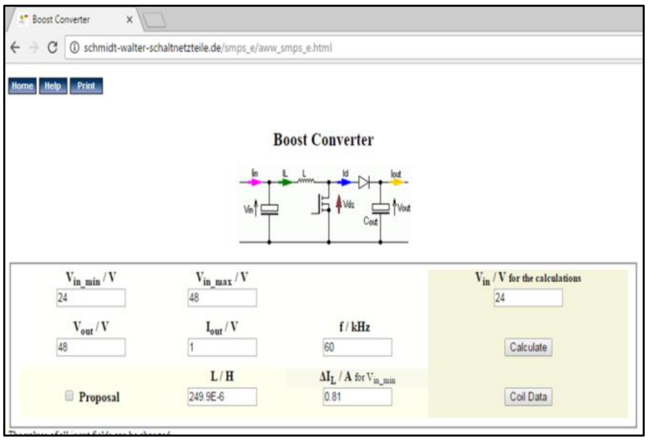

Fig. 10. Boost converter parameters values [10].

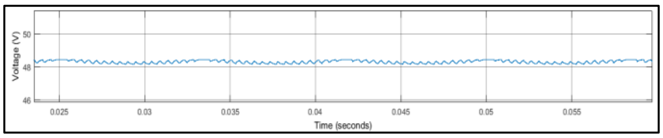

Fig. 11. The boost converter output voltage.

B. Battery Design

The battery bank size is significantly increased for an off-grid situation, to meet the demand requirements. The known battery type used for standalone PV system is lead acid, each battery from the total 52 has same specifications that are shown in Table II below:

TABLE II: BATTERY PARAMETERS

Maximum capacity (Ah)	208.33
Cut-off Voltage (V)	9
Fully charged voltage (V)	13.06
Nominal discharge current (A)	40
Capacity (Ah) at nominal voltage	62.05
Internal resistance (Ohms)	0.0006

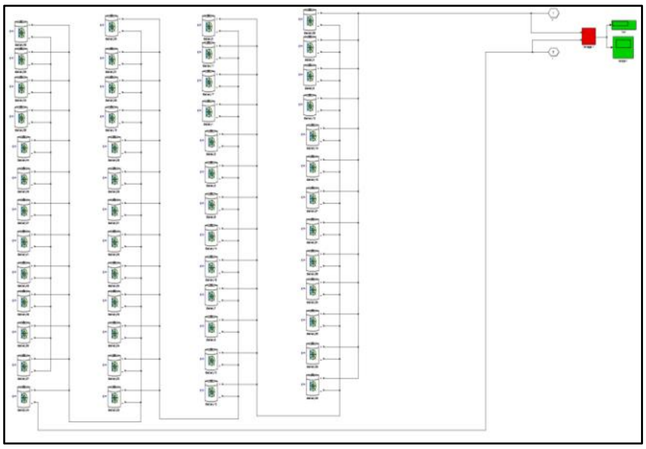

Fig. 12. Battery model.

The battery model as shown in Fig. 12, has 13 batteries in parallel, and 4 in series. Each battery is lead-acid, and has a nominal 12 V and 200 Ahr, the DC bus of these batteries carries 48 V DC. The maximum output values of the voltage and current are obtained by the nominal conditions of the load and discharging of the batteries [11].

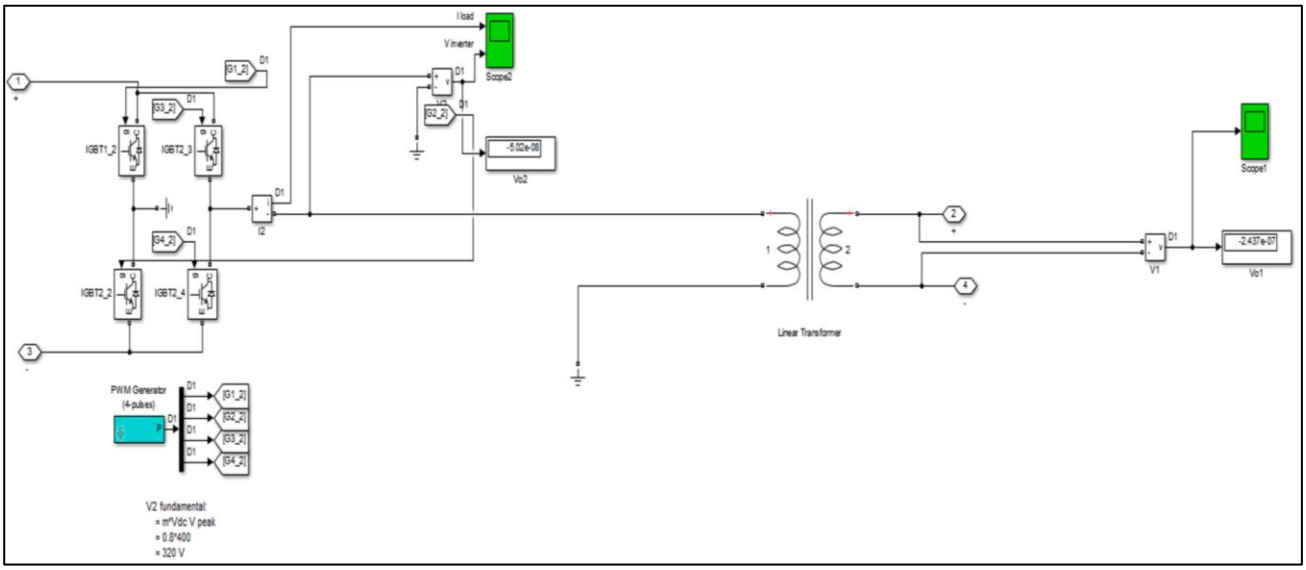

Fig. 13. Screenshot of the Inverter design.

C. Inverter Design

The working principles of this inverter are as follows: there are four IGBT's switches (S1, S2, S3 and S4). When S1 and S4 operate under switching impulses, the transformer connection point voltage will have a positive voltage value. However, when S2 and S4 operate at the same time at the connection point of the transformer, it will have a negative polarity. This technique will generate an AC sinusoidal wave output voltage [8]. Two PV panels need to be in series to obtain the required input voltage 48V. The discharging voltage signal of the capacitor between the boost converter and the inverter, is the power signal source of the inverter. A block diagram of the inverter is shown below in Fig. 13.

The output voltage and current of the inverter are shown in Fig. 14. AC values of the voltage and current are (48.41 V, 360 A) peak respectively, but it still does not meet the load requirements. As such, the step transformer is added to the design. The high current value is a result of the current of the batteries and PV array. The inverter output power is presented as square waves of odd and even values, to obtain a pure sinusoidal wave form a high filtering circuits must be applied.

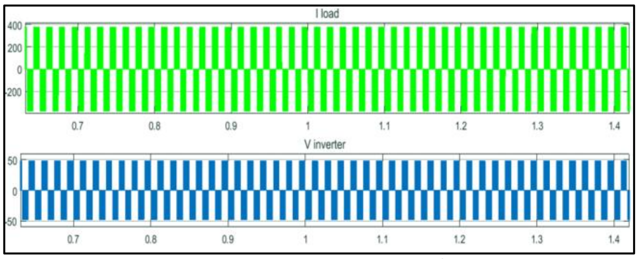

Fig. 14. The output voltage and current of the inverter.

D. Transformer Design

The need for using a transformer in the model is to increase the AC voltage from 48 V to 230 V, which is the standard for houses' voltage in Qassim, Saudi Arabia. The step-up transformer is applied between the inverter and the load, both are using alternating voltages buses. The voltage conversion between 48 V to 230 V could be done through the boost converter instead of the transformer. However, in this case the output curve of the boost converter at 230 V occurs with more harmonics than the transformer output

E. Load Design

The load design here has resisitance and inductor in series; this simulates the actual load structure. With 5.8 ohm resisitance and 0.5 mH, the model will resist aginst the flowing current, similar to the actual load. The equivlant circuit of resistor and inductor indicate an AC load, which is the chosen application from the system here. The resistor value was obtained by ohm law $P=V^2/R$, inductor value were taken from a load with same speacifcation [12]. The design is shown in Fig. 15.

Fig. 16 shows that the rms value of the voltage curve is 230 V AC, which is synchronizing with the standard voltage in Saudi Arabia. The rms value law (7) is given here:

$$V_{rms} = V_{out}/\sqrt{2} \tag{7}$$

The load power curve is obtained by the product of the voltage and current curves in Fig. 16. Moreover, the output power curve shows maximum value 19 kW which is the PV production, it will also cover the load average hourly consumption 9.9 kWh. The minimum output power is zero, which indicates it is night time, with no sun light and empty charge batteries. Fig. 16 shows the control system output rejected the sunlight and temperature decreased pulses, as noted in Fig. 7.

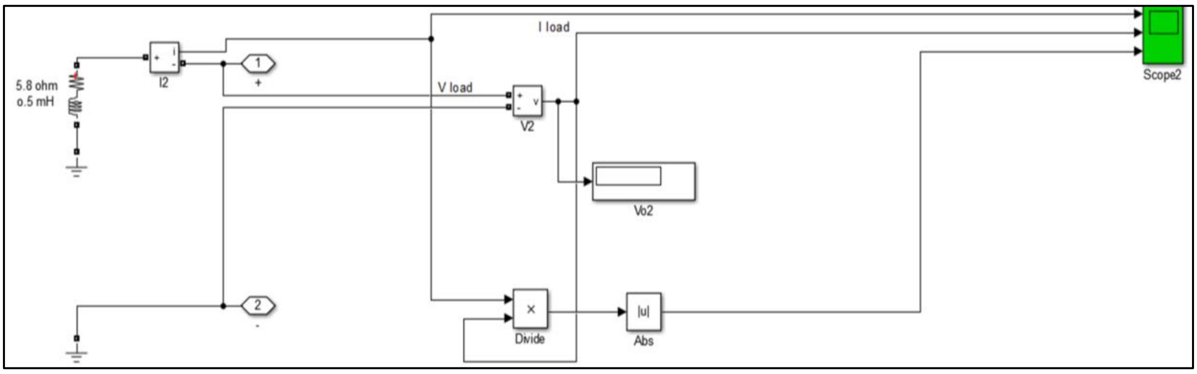

Fig. 15. Load design parameters.

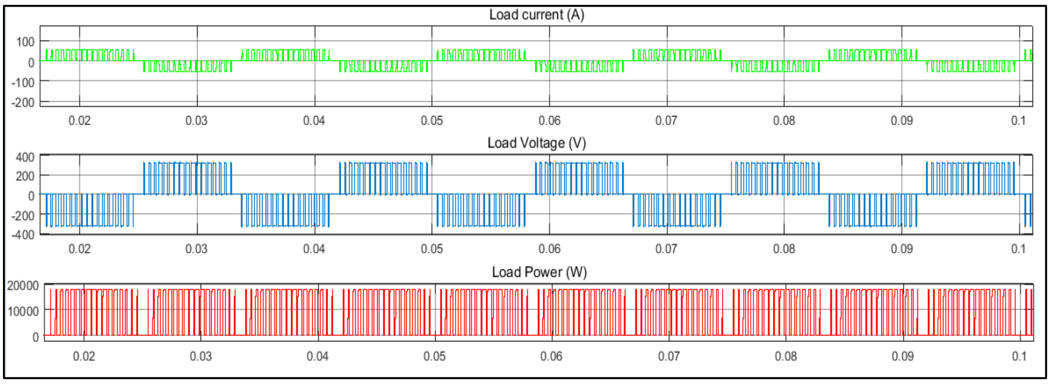

Fig. 16. Load output voltage, current and power.

V. Conclusion

Many people in Saudi Arabia are considering using a PV system to provide electricity for their home, and this is their long-term goal [13]. The outline, which is covered in this paper, is the solar panel producing 48 V DC, and after designing and connecting the model to the system with the boost converter, MPPT, DC to AC inverter and step up transformer. The result was AC sinusoidal wave of 230 V. This design is ready to be converted to an actual system. The ripples in the voltage and current DC curves was due to the PWM inverter used in the model. Designed PV system can meet all energy needs of a typical house in Saudi Arabia. Simulink simulation provides details of power electronics and expected harmonics in the system. Due to air conditioning house load is inductive as assumed in the simulation. Design and implementation of such a system can greatly help house owners in Saudi Arabia to reduce their depending on oil.

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