

# Modeling of Off-Grid Hybrid Power System under Jordanian Climate

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## Abstract

The foreseeable shortages due to the increased population and the industrial activities in the world, and today's already unreliable and distinctly expensive fossil resources are forcing a diversification of energy sources and driving the demand toward renewable technologies in the near term. Based on the fact that many remote and isolated sites in Jordan are located far away from the national electric grid and cannot be connected to it in the near future. Therefore, a hybrid power system (HPS) is proposed in this paper to supply an off-grid village in Jordan. The hybrid power system (HPS) represents photovoltaic (PV) system and wind farm which represent clean and renewable energies. The present study utilizes Matlab Simulink tool to select and analyze proper Photovoltaic (PV) systems and wind turbines to supply the required load in an off-grid village. It is found that Matlab Simulink tool with Graphic User Interface (GUI) can plan to acquire a proper HPS to supply variable load with different utilities and can simulate and predict the output of the power system under different conditions.

**Keywords:** Photovoltaic system, wind turbines, renewable energy, hybrid power system Matlab simulink tool, Graphic User Interface.

## 1. Introduction

Electricity production using wind and solar energy are one of the main research areas at present in the field of renewable energies, the significant price fluctuations are seen for the fossil fuel in one hand, and the trend toward privatization that dominates the power markets these days in the other hand, will drive the demand for hybrid technologies in the near term (Katti *et.al.*, 2007).

Jordan is one of the non-petroleum producing countries in Arab region and is strategically dependent on oil. The current fluctuating in energy prices has a direct impact on the country's national economy and puts its energy sector security at risk. The cost of imported crude oil and oil products in the year 2006 was around JD 1755 million, thereby forming 18.9% of the Gross Domestic Product (GDP) (MEMR, 2006). Consequently, a clear policy should be adopted for the forthcoming phases to secure energy supplies by diversifying the energy sources and using hybrid power systems.

Jordan has an excellent mean solar radiation on horizontal surfaces of 5.5-6 kWh/m<sup>2</sup>/day in comparison to that in Europe and most of North America, which amounts to 3.5 kWh/m<sup>2</sup>/day, i.e., about 60% of that falling over a square meter in Jordan (Badran, 2007). Moreover, according to the measurements taken by Durisch of the Paul Scherrer Institute (PSI) in Switzerland between May 1990 and April 1991, the total annual direct normal irradiation in Jordan ranges from 2400 kWh/m<sup>2</sup> year to over 2700 kWh/m<sup>2</sup> year and is counted among the best insolated areas in the world (Badran, 2006).

There are many studies have been conducted to plan for installing off-grid hybrid power systems; Carrión et al proposed an environmental decision-support system for selecting optimal sites for grid-connected photovoltaic power plants. Their methodology combines multi-criteria analysis and the analytic hierarchy process with geographical information systems technology and at the same time takes into account environment, orography, location, and climate factors (Carrión *et.al.*, 2008).

Katti and Khedkar studied different sites in India for a stand-alone Wind, PV, and integrated wind-PV systems to determine the optimum generation capacity and storage needs. They used annual average hourly values for load, wind speed, and insolation for analysis. The results are used to justify the use of renewable energy source as a reliable option for remote areas (Katti *et.al.*, 2007)

Moustris et al applied neural networks to meteorological time-series data sets, recorded during 1991–2000 at different sites in Greek to create appropriate solar data information. They used neural networks for creating missing mean, maximum and minimum global and diffuse solar irradiance hourly data, when educated with other known meteorological time-series hourly values (Moustris *et.al.*, 2008).

The present research utilizes Matlab Simulink tool with Graphic User Interface to plan and acquire a proper HPS to supply Jordanian village and to simulate and predict the output of the power system under different conditions.

## 2.0 Methodology

MATLAB Simulink tool is used in the current research. It is an effective tool of mathematical simulation and research of many engineering systems (Patrick *et. al.*, 2003).

### 2.1 Modeling Of PV System

In Matlab Simulink Tool, Blocks which describes the PV module are designed, there are two main input variables for PV model; ambient temperature ( $T_a$ ), and irradiance ( $G_a$ ) and the outputs are terminal voltage of the PV cell, and the drawn current ( $I_a$ ), as shown in Figure. 1. This block represents a mask block in MATLAB in which contain many blocks combined together to perform the main function of PV generator as in practical life.

The block (Figure 2) is designed on the basis of PV mathematical equations and datasheets to reflect an identical image to the real PV generator. The required data is summarized as follows (Anca *et. al.*, 2001) (Dunlop *et. al.*, 1995):

- 1- Short circuit current (photon current)
- 2- Open circuit voltage.
- 3- Number of parallel cells.
- 4- Number of series cells.
- 5- Temperature coefficient of short circuit current.

### 2.2 Modeling of Wind Turbines

The modeling of wind turbine on Matlab requires two inputs, Wind speed ( $V$ ) and Pitch angle, and one output, Mechanical Torque ( $T$ ) (Figure 3).

Where:

( $V$ ) is Wind velocity [m/s].

( $\beta$ ) is Pitch angle [degree].

( $T$ ) is Torque [N.m].

The Matlab Simulink Model is based on mathematical equations that correlate mentioned variables as in Figure 4 (Mukund, 1999) (DWIA, 2003).

The next step is to select proper wind turbine and to enter the manufacturing parameters.

### 2.3 Modeling Of Battery

Each type of the battery has a certain model because of their internal construction. The famous kinds of these batteries (Linden, 2002) are:

- a- Lead acid battery.
- b- Lithium – Ion.
- c- Nickel – Cadmium.
- d- Nickel – Metal – Hydride.

The equation which represents the battery system is:

$$V_o = E_o - K * \frac{Q}{Q - it} + A * e^{-B*it} \quad (1)$$

Where:

E = No load voltage (V)

E0 = Constant voltage (V)

K = Polarization voltage (V)

Q = Battery capacity (Ah)

A = Exponential voltage (V)

Where:

E = No load voltage (V)

E0 = Constant voltage (V)

K = Polarization voltage (V)

Q = Battery capacity (Ah)

A = Exponential voltage (V)

B = Exponential capacity (Ah)

The Simulink model that represents equation (1) is shown as in Figure 5:

### 2.4 Graphic User Interface (Gui)

A graphical user interface (GUI) in Matlab is a type of user interface item that allows people to interact with programs in more proper and easy ways to make the end user more comfortable with the application. GUI enriches the application with images rather than text commands. Also it offers graphical icons, and visual

indicators, as opposed to text-based interfaces, typed command labels or text navigation to fully represent the information and actions available to a user. The actions are usually performed through direct manipulation of the graphical elements (Galitz, 2007).

A GUI is made to combine between load calculations, PV design, wind turbine selection to simulate the actual off-grid village requirements and behavior. The preface of the HPS GUI dialogbox is shown in Figure 6.

### 2.5 System Connection (Simulink)

In the final stage, PV system, wind turbines, proper charging system are connected to the load which represents the village consumption. The system is consisted of the following (Figure 7):

- 1- PV array: it contains group of PV modules.
- 2- Wind farm: which contains a group of wind turbines.
- 3- Charge controller: which used to regulate the voltage, the charging and the discharging of battery.
- 4- Group of batteries in series and parallel.
- 5- Loads of a village.

### 3. Results And Discussion

In the current section, some assumptions are made to determine the consumption behavior of the village. Through “Load Calculation” button in HPS program (Figure 6) the following data are entered to describe the load consumption pattern:

Number of houses = 20	Number of clubs = 0
Number of hospital = 0	Number of supermarkets = 4
Number of barbing shop = 1	Number of mosque = 1
Number of clinics = 1	Number of commercial building = 0
Number of schools = 1	

The next step is to describe the area of each building, the program will ask about the area of each building after entering the numbers of each building as follows:

Area of hospital = 0*	Area of clubs = 0*
Area of barbing shop = 40 m <sup>2</sup>	Area of supermarket = 30 m <sup>2</sup>
Area of clinics = 60 m <sup>2</sup>	Area of mosque = 100 m <sup>2</sup>
Area of schools = 300 m <sup>2</sup>	Number of commercial building = 0*

The area of non-existing building in the village shall be entered zero.

The resultant consumed energy of the village is 3.36MWh per day which equals to 1400 A. After that the operating voltage of the village shall be entered; in this case it is chosen to be 100V DC which equals to 220V AC as in the following equation:

$$V_{dc} = 2 * \frac{Vm}{3.14} \quad (2)$$

And

$$V_{ac} = \sqrt{2} * Vm \quad (3)$$

After that a proper type of PV system shall be selected and its parameters shall be entered through the program (“PV-Module Characteristic” button) to go further with the calculation and to examine the system. In our system, it is found that Bp-SX 150S PV module - 150W with operating voltage 24V residential system to be proper and cost effective (BP Solar Global Marketing, 2001)..

The next step is to enter the site weather details. The ambient temperature ( $T_a$ ) is assumed to be 25°C and irradiation ( $G_a$ ) is about 1000 W/m<sup>2</sup>. After that the I-V, P-V characteristic of the PV module will be shown and examined (Figure 8).

Under the mentioned conditions, the current of each PV unit will produce 4.75 A (Figure 8) the power that generated by each PV module is around 113 W.

Irradiation factor plays an important role in affecting the resultant power and current, the more irradiation (W/m<sup>2</sup>) the more produced power-current as shown in Figure 9:

The same procedure will be performed on wind turbines starting from selecting “Wind Turbine Characteristics” button from HPS program, the program will appear in new window that has two axis, one for power /velocity characteristics and the other for Cp-lambda characteristics. INNOAIR100 is found to be a proper wind turbine for the village (Innovative Air Solutions Inc). The wind speed is assumed to be 7 m/s where the wind turbine is working on 5o pitch angle. After entering these values, then power velocity and Cp – lambda characteristics shall be configured to get the curves shown in Figure 10.

As can be seen from Figure 10, the more wind speed the more delivered mechanical power on the turbine shaft, therefore a good wind resources sites shall be selected at high speed wind sites, the blades shall be adjusted by increasing the pitch angle to protect the wind turbine from working on over-rated speed and decreasing the pitch angle at low wind speed to extract the maximum available power (Figure 11).

#### 4. System Analysis

As a case study, the hybrid power system is studied to supply off-grid village under Jordanian. Rawdet elnabdan village is located at 22 km away from electric grid climate and it is found to be proper to be supplied by the proposed hybrid power system (MEMR, 2008) (Google Earth, 2011).

The system is analyzed as follows:

##### 4.1 PV Modules

As discussed, the output power of the PV modules depends on the atmospheric factors of the village, i.e. temperature T and irradiance G.

The irradiance of the Rawdet elnabdan village is changing regarding to the day hours under almost constant weather temperature as shown in Figure 12 (Trieb et., al., 23).

FIGURE

As can be seen from Fig. 20 the irradiance of the Rawdet elnabdan village is as the following:

- G=1500 W/m<sup>2</sup> for three hours.
- G=3000 W/m<sup>2</sup> for five hours.
- G=2000 W/m<sup>2</sup> for two hours.
- G=zero W/m<sup>2</sup> for 14 hours (at night).

The next step is to determine the number of parallel PV module needed to supply the required load of the village. As calculated before, the required load needed for the village is equal to 1400A.

In the proposed hybrid system, the load is divided equally on both sources PV modules and wind turbines. So the PV modules in our project are required to produce 700A through the whole day. But for safety purposes, 700A will be multiplied by safety factor Ks=1.1. So that now the current required from PV module is 770A.

The average value of the current produced by single PV module under the irradiance village and temperature can be calculated by the following equation:

$$I_{ave} = \frac{I_1 * T_1 + I_2 * T_2 + I_3 * T_3 + I_4 * T_4}{24 Hrs}$$

$$I_{ave} = \frac{11.3A * 3Hrs + 23.7A * 5Hrs + 15.3A * 2Hrs + 0A * 14Hrs}{24 Hrs}$$

$$I_{ave} = 7.625A \quad (4)$$

The average current produced by single PV module is equal to 7.625A, but as mentioned before, the generated current by PV modules shall be 770A. Therefore, the number of parallel PV modules shall be:

No. of Parallel PV modules= 770A/7.625=101 PV modules.

The number of series PV modules in the system depends on the voltage of the system, as explained before, the open circuit voltage of single PV module is equal to 24.8 V, therefore, the required number of series PV modules needed in our system to produce 100V is 5 PV modules.

Now, we have PV array, this PV array has 101 PV modules connected in parallel and 5 PV modules connected in series to supply the load. The number of PV modules in the whole system is equal to 101\*5= 505 PV modules (Faruqi et., al., 2005)..

- Area that required by PV modules

The required area to cover PV modules space can be determined from the total PV modules numbers. The area of each PV module is around 1.31 m<sup>2</sup> [19], as mentioned before, the total number of required PV modules is 505 units.

Now the total occupied area by PV is:

$$\text{Total Area} = \text{PV module Area} * \text{NO. of PV modules} = 1.31 * 505 = 661.55 \text{ m}^2$$

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##### 4.2 Wind Turbines

As explained, the extracted output power of wind turbines depends on both pitch angle and on the wind speed in the village. The wind speed pattern in Rawdet elnabdan village is shown as in Figure 13 (MEMR. 2008).

As shown in the last figure, the wind speed values during the day are:

- V=8 m/s for 5 hours.
- V=6 m/s for 6 hours.
- V=7.5 m/s for 6 hours.
- V=87m/s for 7 hours.

As calculated before, the required load for the village is equal to 1400A. This load value is divided equally to be supplied by PV modules and wind turbines. Therefore wind turbines have to generate 700A. But for safety purposes, 700A will be multiplied by safety factor  $K_s=1.1$ . to get 770A.

The average value of the current produced by single wind turbine under the wind speed village and pitch angle can be calculated by the following equation:

$$I_{ave} = \frac{I_1 * T_1 + I_2 * T_2 + I_3 * T_3 + I_4 * T_4}{24 \text{ Hrs}}$$

$$I_{ave} = \frac{25.5A * 5Hrs + 11.7A * 6Hrs + 21.57A * 6Hrs + 34.3A * 7Hrs}{24 \text{ Hrs}}$$

$$I_{ave} = 23.63A \quad (5)$$

Therefore, the average current produced by single wind turbine is equal to 23.63A. So the number of parallel wind turbine is as following:

$$N_{\text{of parallel wind turbines}} = 700A / 23.58 = 30 \text{ wind turbines.}$$

The area of each wind turbine will be calculated depending on the dimension listed in data sheet [20]. Moreover, spacing between wind turbines will be taken into consideration and that requires more space.

The length of the wind turbine almost equals to 1.318m and the width is 0.994m.

Land Area = Length \* Width = 1.318 \* 0.994 = 1.31m<sup>2</sup> for each turbine. As known, the spacing between horizontal wind turbines is 4 times rotor diameter [11], while the spacing between perpendicular wind turbines is 7 times rotor diameter.

$$\text{Wind farm Area} = \text{length} * \text{width} = 11.6 * 6 * 20.3 * 4 = 5651.52 \text{ m}^2.$$

#### 4.3 Battery

The ratings of the battery can be determined form (Dunlop *et. al.*, 1995) (Linden, 2002):

$$\text{Battery Rating} = \text{current} * \text{hours}$$

The total current in our system 1400 A, and battery ratings is:

$$\text{Battery Rating} = 1400A * 24hrs = 33600 A * hrs$$

The State of Charge (SOC) of the battery shall not be less than 20% and more than 80% to lengthen the battery life, consequently the ratings shall be multiplied by a safety factor ( $K_{cmp}=1.6$ ) and the new battery ratings will become (Linden, 2002):

$$\text{Battery Rating} = 33600 * 1.6 = 53760 A * hrs$$

The voltage of the battery is 11.1 V and the rating of the battery is equal to 1000mAh. The number of parallel batteries shall be determined next to achieve the required current.

$$\text{NO. of parallel batteries} = \frac{\text{battery bank rating}}{\text{single battery rating}}$$

$$= \frac{53760}{1} = 53760 \text{ battery}$$

After that, the number of series batteries shall be determined to achieve the required voltage depending on the voltage of battery and bank of batteries. Voltage of the bank is 100V while voltage of each battery equals 11.1V. The number of series batteries would be determined as the following (Linden, 2002):

$$\text{NO. of series batteries} = \frac{\text{Battery bank voltage}}{\text{single battery voltage}} = \frac{100}{11.1} = 9 \text{ batteries}$$

The number of batteries used in the system would be equal the product of the number of series batteries by the number of parallel batteries  $\text{NO. of batteries} = \text{NO. of series batteries} * \text{NO. of parallel batteries} = 9 * 53760 = 483840 \text{ batteries}$

The area of each battery is calculated as the following:

$$\text{Area of battery} = \pi r^2 = \pi * (0.009)^2 = 2.544 * 10^{-4} \text{ m}^2$$

Considering that the battery bank consists of 20 layers of batteries, the number of batteries in each layer is equal to:

$$\text{NO. of batteries in each layer} = \frac{\text{NO. of batteries}}{20 \text{ layers}} = \frac{483840}{20} = 24192 \frac{\text{battery}}{\text{layer}}$$

$$\begin{aligned} \text{Battery bank AREA} &= (\text{NO. of batteries in each layer}) * (\text{AREAO f battery}) \\ &= 24192 * 2.544 * 10^{-4} = 6.25 \text{ m}^2 \end{aligned} \quad (6)$$

The total hybrid power system area that required to supply Rawdet elnabdan village in Jordan is:

$$\begin{aligned} \text{AREA of the system} &= \text{AREA of PV module} + \text{AREA of wind turbine} \\ &\quad + \text{AREA of battery bank} \\ &= 661.55 + 5651.52 + 6.25 = 6319.32 \text{ m}^2 \end{aligned} \quad (7)$$

## 5.0 Conclusion

The good solar and wind potential of Jordan on one hand and the price fluctuation of the fossil resources on the other hand, will drive the Jordanian government towards renewable energy and Hybrid power systems. The present study utilizes Matlab Simulink tool to select and analyze proper Photovoltaic (PV) systems and wind turbines to supply the required load in an off-grid village. It is found that Matlab Simulink tool with Graphic User Interface (GUI) can plan to acquire a proper HPS to supply variable load with different utilities and can simulate and predict the output of the power system under different conditions.

It can be concluded that Rawdet elnabdan village in Jordan has good solar and wind resources and that could enhance the chances of increasing the generated power out of the hybrid power system.

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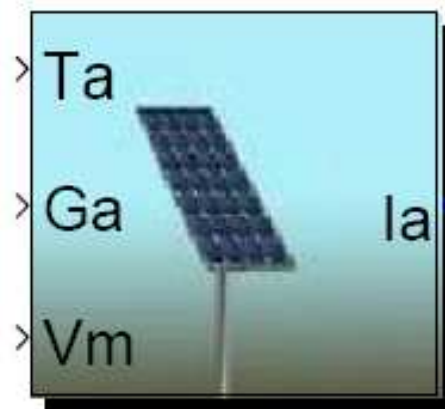


Figure 1. PV generator

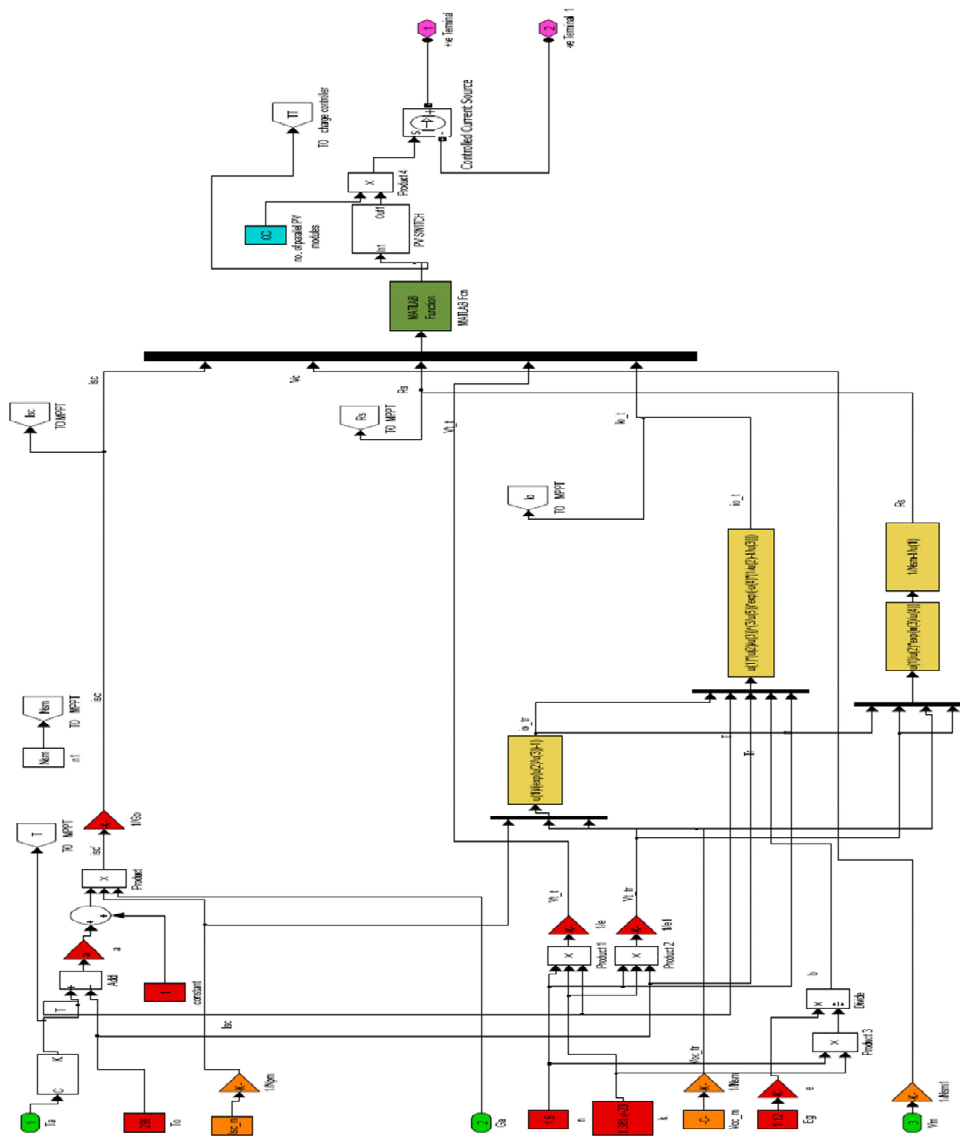


Figure 2. PV model under mask

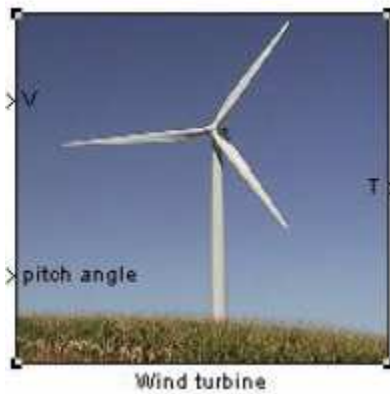


Figure 3. Wind turbine Input/Output



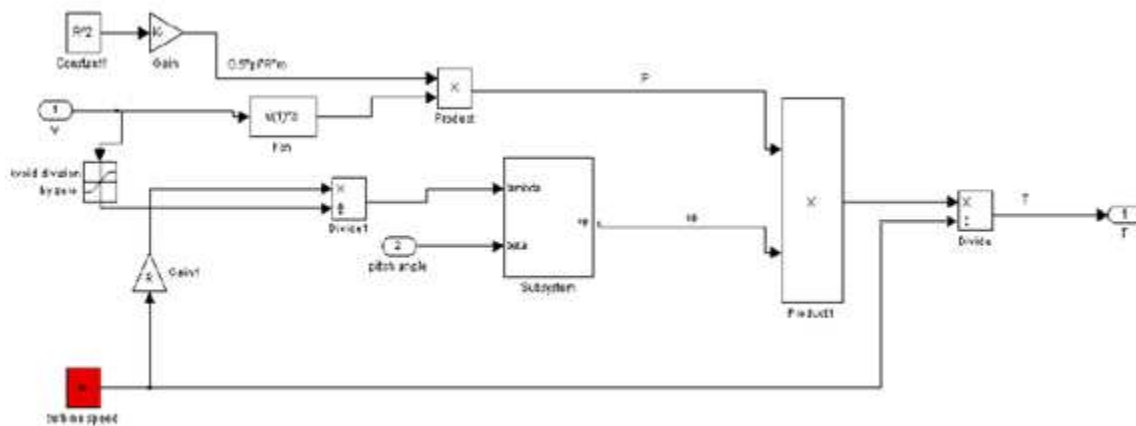


Figure 4. Simulink Model of wind turbine

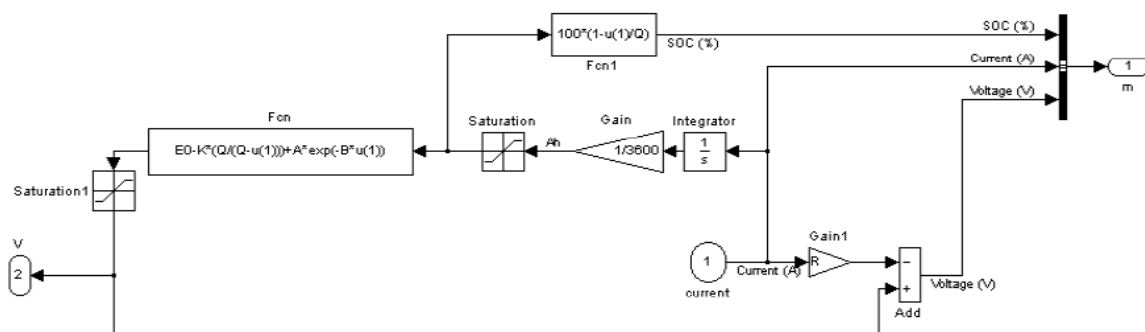


Figure 5. Simulation of basic equation of battery

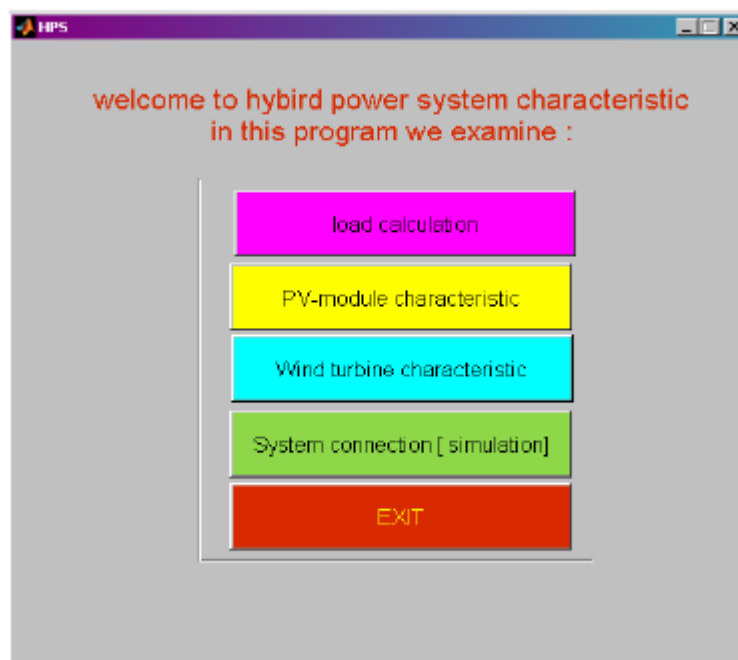


Figure 6. HPS program preface

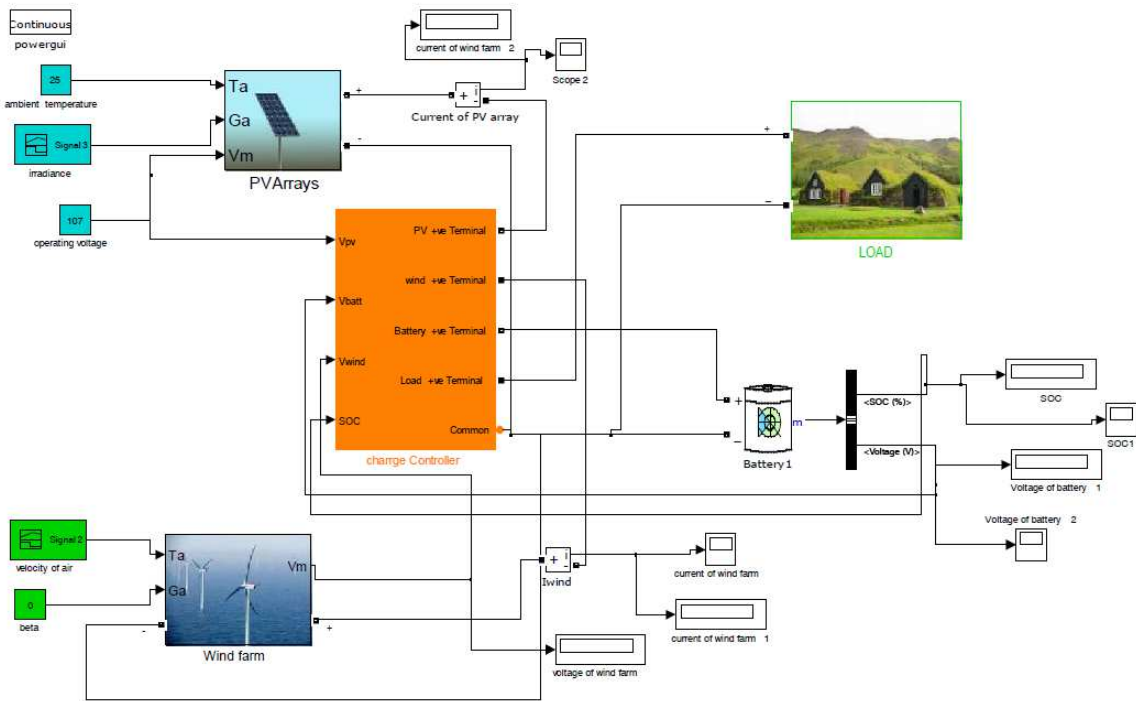


Figure 7. Hybrid power system connection

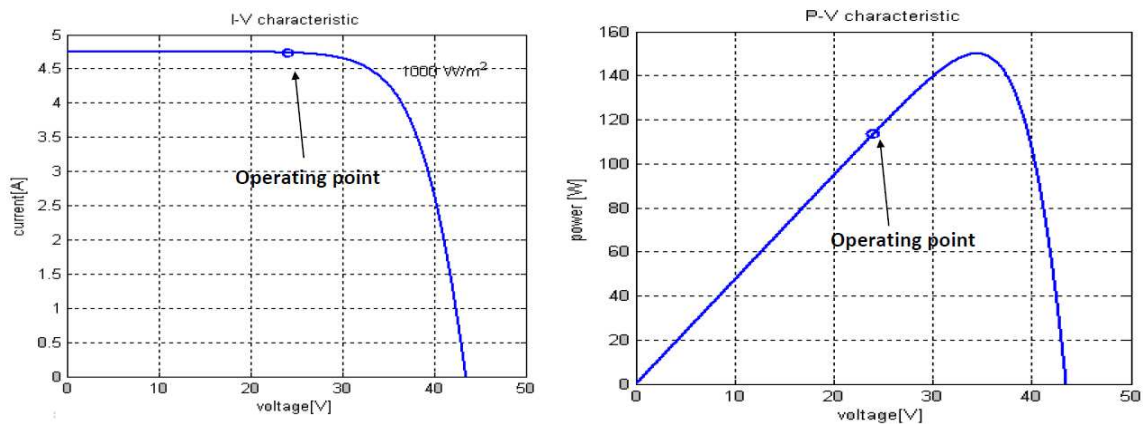


Figure 8. I- V, P-V characteristic of PV module

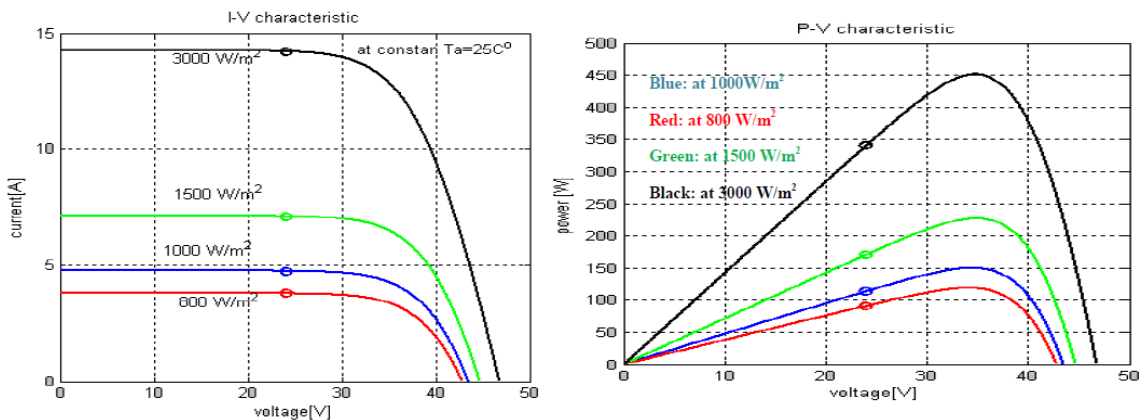


Figure 9. I- V, P-V characteristics of PV module at different irradiances

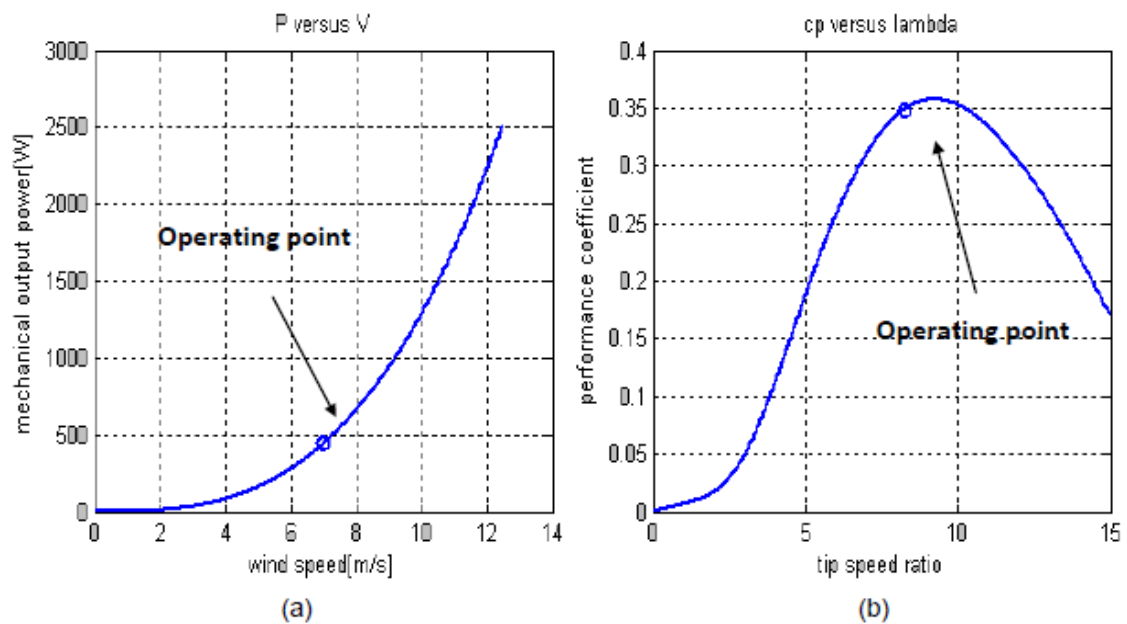


Figure 10. Power-velocity & Cp-lambda characteristic of wind turbine , (a) power- velocity characteristic (b) Cp versus lambda characteristic

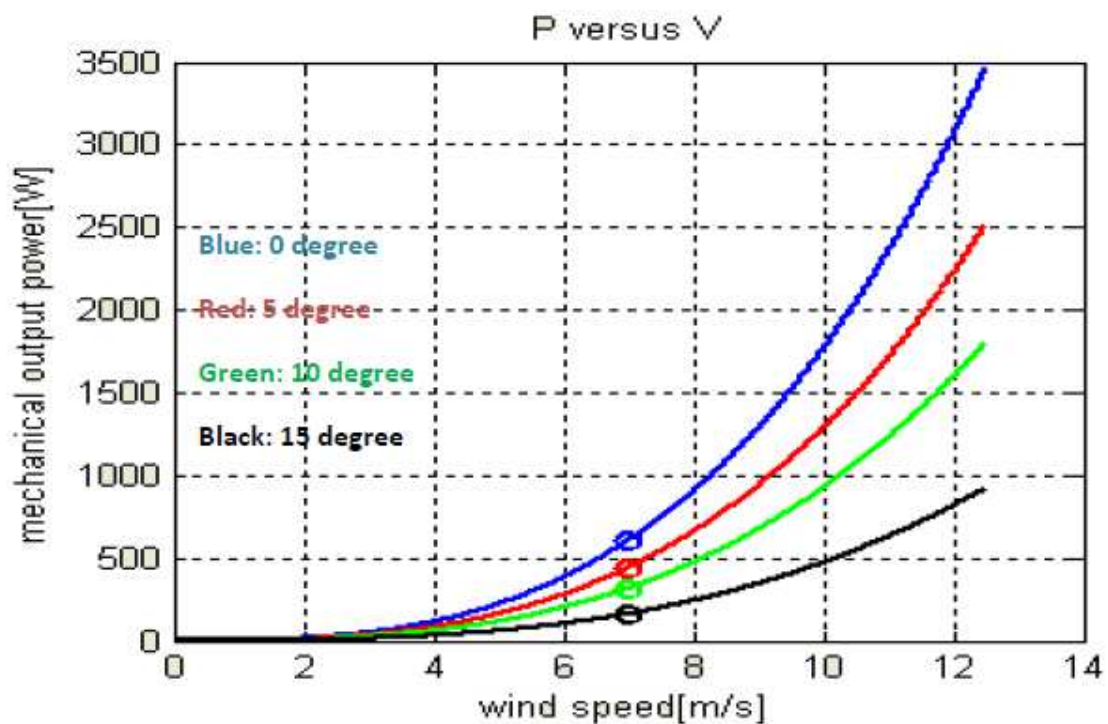


Figure 11. Power - velocity characteristic of wind turbine at different pitch angles

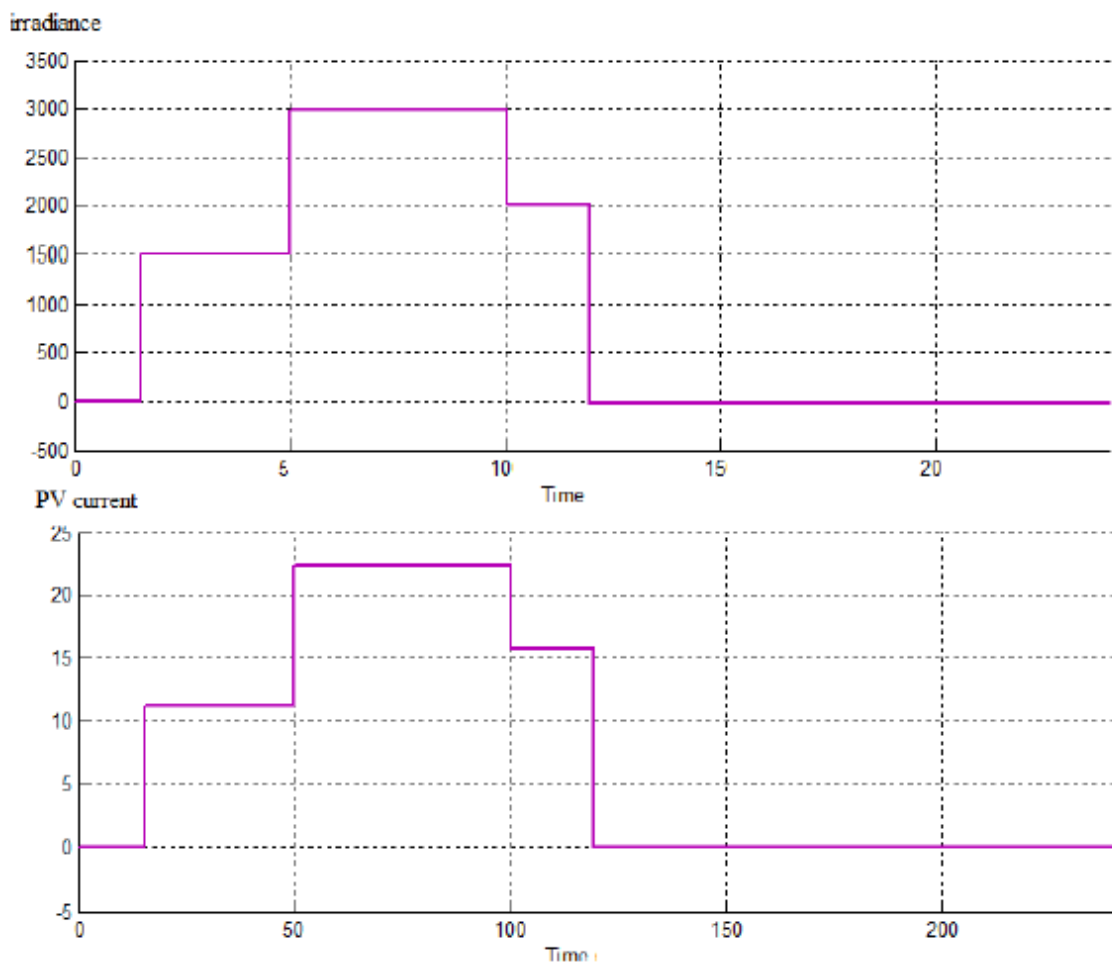


Figure 12. Irradiance-Current during 24 hours in Rawdet elnabdan village (day)

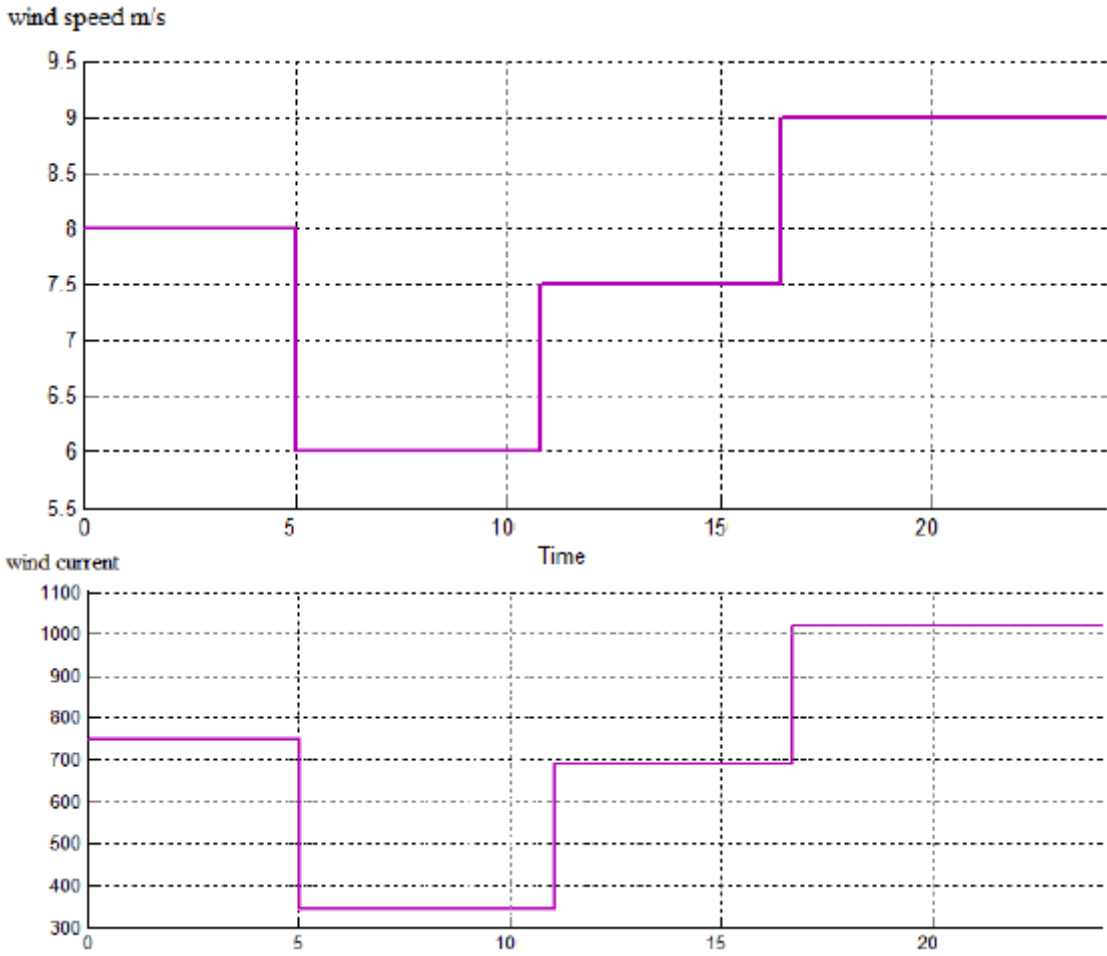


Figure 13. Wind speed-Wind turbines current pattern in the Rawdet elnabdan village

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