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Simulation of solar off- grid photovoltaic system for residential unit

Jasim Abdulateef

Mechanical Engineering Department, Diyala University, Diyala, Iraq

Email address:
jmabdulateef@gmail.com (J. Abdulateef)

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Abstract: The aim of this study is to design a solar off-grid PV system to supply the required electricity for a residential unit. A simulation model by MATLAB is used to size the PV system. The solar PV system is simulated with the case of maximum solar radiation on a sunny day. The results show that the average daily load requirement of the selected residential unit is 36 kWh/day. This load requirement can be meet by using an array of 44 solar panels. During the day time, the PV system supplies the desired 12.4 kWh of energy. During the night time, a battery storage system of 23.6 kWh (48V, 350 Ah) is used to meet the night load.

Keywords: Solar PV, Off-Grid, MPPT Controller, Isolated Places

1. Introduction

Photovoltaic system installation has played a big role in renewable energy because PV systems are pollution free, economically reliable for long-term operation and secure energy source. The major obstruction of PV technology is its high capital costs compared to conventional energy sources.

In isolated regions and because of the scarcity of means, it is necessary to optimize the solar off-grid (stand-alone) PV system in order to minimize the costs and to make the PV systems competitive with the other forms of renewable energies. Modeling and simulation techniques can be used to assess the performance of PV system components before installation in place hence reducing the overall system costs. Therefore, many research studies have focused on the optimization of PV systems [1-8].

This study presents an optimization procedure to design solar off-grid PV systems for a residential unit to find the effective way to use solar energy at the lowest cost possible. The proposed system may provide highly efficient, and clean solar powered electricity that can meet the daily load demands of the residential unit. Sizing of the off-grid PV systems based on the specific residential load requirement is also done. The area selected is a typical residential unit located in the campus of mechanical engineering department at Diyala University. The simulation is performed using the MATLAB software to validate the design results.

2. Residential Load Profile

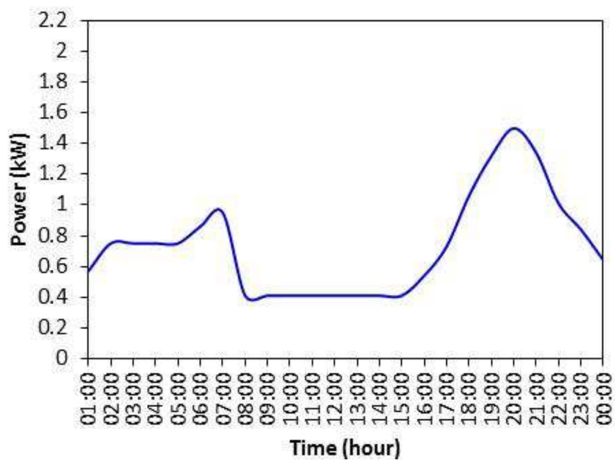

Figure 1. *Proposed residential load profile*

The remote area residential unit is simple and does not require large quantities of electrical energy used for lighting and electrical appliances. Figure 1 shows the proposed residential load profile. The Load profile was proposed considering the general hourly based load usage. At midnight hours, the power consumption for the residential unit comes down where only basic electrical appliances are consuming power. The load demand rises up during morning hours when everybody gets ready either to leave for schools or offices. Throughout the noon hours the load demand levels are minimum as most of the family members are outside. Again, during the evening hours when all the family members are present, the power consumption rises as everyone switches on various entertainment appliances.

The average energy consumption of electrical appliances of a typical residential unit is assumed 547 kWh/month, i.e. 17.64 kWh/day. According to the load profile shown in Fig. 1, the load requirement considered should be maximum hourly load consumption. Thus the proposed solar off-grid PV system should produce 36 kWh/day (1.5kW * 24h).

3. Meteorological Data of the Selected Site

Iraq is among the countries with remarkable potential in solar energy. The solar off-grid PV system of the interest area (Latitude 33.75°, Longitude 44.63°) that located in the campus of mechanical engineering department at Diyala University is simulated with average global solar radiation per year equal to 5.5 kWh/m^2/day [9]. Assuming that the solar panels will be placed on the roof with a possible inclination corresponding to the latitude of the selected area.

4. PV System Modeling

The proposed block diagram of a solar off-grid PV system that provides the required electricity for a residential unit is shown in Fig. 2. The main components of the system are namely PV array, controller, battery, inverter and load. The solar PV system is simulated such that the PV module charge the battery through the controller and battery also provides the power to the load when the solar radiation is insufficient. DC/AC inverter provides AC electricity to the required residential AC loads.

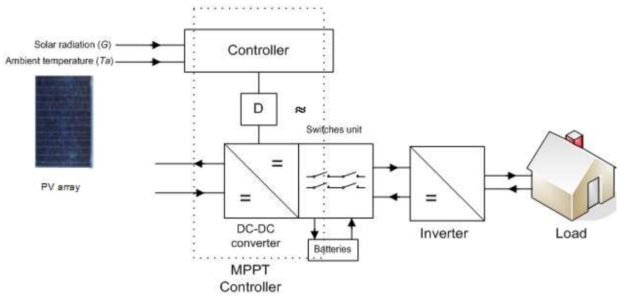

Figure 2. *Solar off- grid PV system configuration*

4.1. PV Panel Model

Table 1 shows the electrical specification of the PV module that was selected for a MATLAB simulation model [10]. The PV module is derived from the equivalent electric circuit of a solar cell [11]. The equation that describes the *I-V* relationship of the PV cell is written below [12].

$$I = I_{sc} - I_o \left[e^{q\left(\frac{V+I.R_s}{nkT}\right)} - 1 \right] \tag{1}$$

where

I Cell current

I_o Reverse saturation current of diode

I_{sc} Short-circuit current

k Boltzman's constant (13,807 10 kJ)

n Diode quality factor, (n=1-2)

N_s Number of PV modules

q Electronic charge (1.6022 10^{-19} C)

R_s Series resister

T Cell temperature

V Cell voltage = V_m/N_s

V_m Voltage at maximum power (P_{max})

Table 1. *BP SX 150 PV module specifications*

Characteristic	Rating
Maximum power (P_{max})	150W
Voltage at P_{max} (V_{mp})	34.5V
Current at P_{max} (I_{mp})	4.35A
Open-circuit voltage (V_{oc})	43.5V
Short-circuit current (I_{sc})	4.75A
Maximum system voltage	600V
Area	1.2 m^2
Efficiency	15 %

4.2. Battery Model

The battery model that used in the PV system was based on a lead-acid battery PSpice model [13]. The battery model has two modes of operation: charge and discharge. The battery is in charge mode when the current into the battery is positive, and discharge mode when the current is negative. The code of battery model was written in MATLAB and used to simulate the performance of solar PV system during charging and discharging.

The storage capacity of the battery was calculated using the following relation [14,15]:

$$Storage\ capacity = \frac{N_C E_{Load}}{DOD.\eta_b} \tag{2}$$

where

DOD Maximum permissible depth of battery discharge

E_{Load} Average energy consumed by the load

N_C Largest number of continuous cloudy days of the interested area

η_b Efficiency of the battery

The proposed off-grid PV system is intended to supply 1.5 kW/48 V for 24 hours (36 kWh). The largest number of continuous cloudy days N_C in the selected site is about 1 day. Thus, for a maximum depth of discharge for the battery DOD of 0.8 and battery efficiency 80%, the storage capacity using eq. (2) becomes 56.3 kWh. Since the selected DC bus voltage is 48 V, then the required ampere-hours of the battery =56.3 kWh/48 ≈ 1173 Ah. If a single battery of 12 V and

350 Ah is considered, then 4 batteries are connected in series; to give an overall number of 4 batteries required for the PV system.

4.3. Converter Model

The most basic DC-DC converter is based on the idea that the power is converted while altering the current and voltage. A DC-DC converter is used to increase the efficiency of the PV system by matching the voltage generated by PV array to the voltage required by the load. The output power (P_{out}) of DC-DC converter is given by:

$$P_{in} = P_{out} \tag{3}$$

Assuming the efficiency factor of x:

$$P_{in}.x = P_{out} \tag{4}$$

Substituting $V.I$ for P results:

$$V_{in}.I_{in}.x = V_{out}.I_{out} \tag{5}$$

For the DC-DC converter used in this model:
V_{in}= voltage across the PV array
I_{in}=current output of PV array
x=0.9 (assume 90% efficiency)
V_{out}=V_b= Battery voltage
I_{out}=current output from converter when all other values are known.

The output voltage is related to the input voltage as a function of duty cycle of the switch (D)[16]. For the Cuk converter [17], the relationship is expressed as:

$$\frac{V_{out}}{V_{in}} = \frac{D}{D-1} \tag{6}$$

4.4. Controller Model

The MPPT controller is modeled in based on the DC-DC converter which is controlled by the MPPT algorithm in order to operate the PV array at its maximum power point. The MPPT algorithm has three inputs; PV module voltage (V_{PV}), ambient temperature (T_a) and solar radiation (G) to give two outputs which are the duty cycle and the optimum voltage at MPP. The block diagram of the MPPT controller model is shown in Fig. 3.

The number of controllers required for the off-grid PV system, [18] is calculated using:

$$Total\ max\ power\ of\ PV = P_{max} \cdot N_{PV} \tag{7}$$

$$Controller\ max\ power = V_b \cdot I_{controller} \tag{8}$$

$$Number\ of\ Controller\ required = \frac{Total\ max\ power\ of\ PV}{Controller\ max\ power} \tag{9}$$

where
$I_{\text{controller}}$ Maximum current the controller which can handle from the PV system to the battery bank
N_{PV} Total number of PV modules required to meet the residential load

Perturb and Observe algorithm is used for MPP tracking because it has a simple feedback structure and fewer measured parameters.

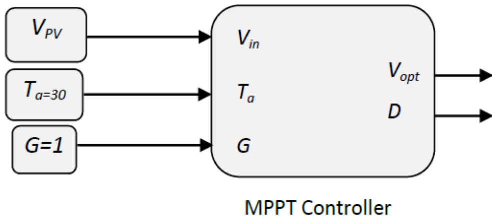

Figure 3. *Block diagram of the controller*

4.5. Inverter Model

The role of the inverter is to keep on the AC side the voltage constant at the rated voltage 230V and to convert the input power (P_{in}) into the output power (P_{out}) with the best possible efficiency. The inverter efficiency is thus expressed as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{ac} I_{ac} \cos\phi}{V_{dc} I_{dc}} \tag{10}$$

where I_{ac} is the output current by the inverter on the AC side. I_{dc} is the current required by the inverter from the DC side (for example, from the controller) to be able to keep the rated voltage on the AC side (for example on the load). V_{dc} is the input voltage for the inverter delivered by the DC side, for example by the controller.

4.6. Load Model

The load existing in a solar PV system is an AC load with an equivalent resistance given by:

$$R_{load} = \frac{V^2}{P} \tag{11}$$

The load current can be modeled as:

$$I_{load} = \frac{V}{R_{load}} \tag{12}$$

5. Results of the PV System Simulation

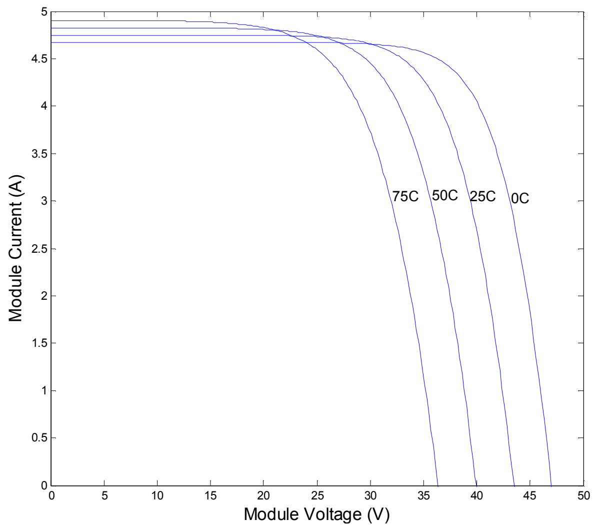

Figure 4. *I-V curves of the PV module at different temperatures (1kW/m²)*

The simulation results of PV module using MATLAB are compared with the PV model data provided by the specification data sheet [10]. Figures 4 and 5 show the current-voltage characteristics of the PV module obtained from simulation. The results of the characteristics of the PV module obtained from simulation are almost identical to the PV specifications from data sheet [10].

The size of PV modules (N_{PV}) required to meet the load demand can be calculated by using the following equation:

$$N_{PV} = \frac{E_{load}}{E/m^2 \; A_m \eta_m} . factor\ of\ safty \quad (13)$$

where

A_m PV module area

E/m^2 Average energy received by PV module on a horizontal mode during solar days

η_m Efficiency of the PV module

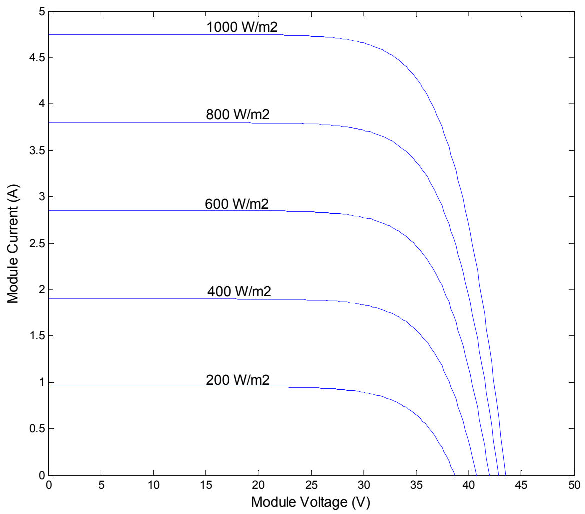

Figure 5. *I-V curves of the PV module at different irradiations (25°C)*

The safety factor used in eq. (13) has a value in the range of 1.2-1.3[19]. The PV system requires to supply1.5 kW/48 V for 24 hours (36 kWh). The solar radiation incident on one square meter in the selected site is considered equal to 5.5 kWh/m^2. By using eq. (13), an array configuration of 44 solar PV panels is required to meet the daily load demand of the residential unit. The required characteristics of the solar off-grid PV system used in this study are given in Table 2.

Table 2. *Solar off-grid PV system specifications*

Solar system type	**off-grid**
Average solar radiation	5.5 kWh/m^2/day
Daily load requirement	36 kWh/day
Number of PV modules needed	44
Power produced by PV panels	6.6 kW
PV area	52.8 m^2

It must be sure when selecting a controller; it has an output voltage rating equal to the nominal battery voltage. Also the maximum PV voltage should be less than the maximum controller voltage rating [20].

The controller which has been chosen has a maximum output current of 80 Amps and a maximum controller voltage of 150 V. By using eq. (9), the total number of controllers required for the proposed PV system that connected to a battery bank with a voltage of 48V is two. If we have 44 PV modules, one sub arrays of 22 PV modules and one sub-array of 22 PV modules should be configured and connected in parallel to each one of the controllers.

In order to study the state of charge of the battery (SOC %) for the given sunny day, we need to simulate our model for the whole day (24 hours) and compare it with the solar PV power and residential load profile. When the power generated by PV system exceeds the load power, the battery is charged with an increase in its SOC. If the solar power falls below the load power, the battery discharges with a decrease in its SOC. Figure 6 shows the battery performance on a sunny day in terms of the SOC.

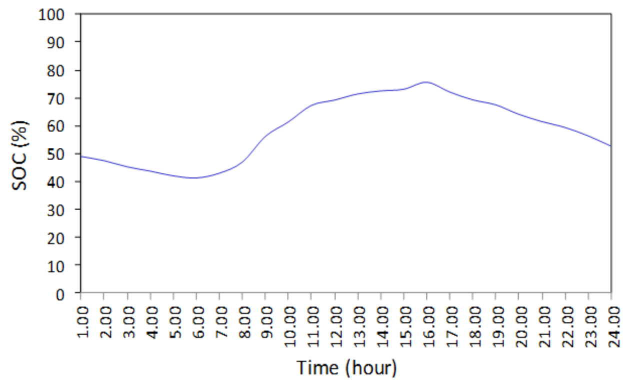

Figure 6. *SOC vs. Time on a sunny day*

During the day time, the PV system supplies the desired 12.4 kWh of energy. During the night time, battery storage system of 23.6 kWh (48V, 350 Ah) is employed to meet the night load.

It can be seen that during the daytime the power produced from the solar irradiation is used to meet the residential load requirements as well as charge the battery. Considering the whole 24 hours scenario, the SOC decreases as the battery discharges during the night hours, and the solar radiation tends to increase during the day while the SOC tends to follow it as well.

Finally, the charging of the battery is performed on a major scale during the afternoon to evening hours where the solar irradiation is at high level and the residential load requirement is less. Then it is clear that after reaching the peak, the SOC decreases with the increase in the residential load requirement and decrease in the sun radiation level during the evening to morning hours.

6. Conclusions

This study presents a simple but efficient off-grid photovoltaic system for a residential unit that can meet the residential daily load demands. The results show that the average daily load requirement of a residential unit of 36 kWh/day. In order to meet this load demand, an array of 44 solar panels. During the day time, the PV system supplies the desired 12.4 kWh of energy. During the night time, battery storage system of 23.6 kWh (48V, 350 Ah) is employed to meet the night load.

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