Solar power plant performance evaluation: simulation and experimental validation

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Abstract. In this work the performance of solar power plant is evaluated based on a developed model comprise photovoltaic array, battery storage, controller and converters. The model is implemented using MATLAB/SIMULINK software package. Perturb and observe (P&O) algorithm is used for maximizing the generated power based on maximum power point tracker (MPPT) implementation. The outcome of the developed model are validated and supported by a case study carried out using operational 28.8kW grid-connected solar power plant located in central Manchester. Measurements were taken over 21 month’s period; using hourly average irradiance and cell temperature. It was found that system degradation could be clearly monitored by determining the residual (the difference) between the output power predicted by the model and the actual measured power parameters. It was found that the residual exceeded the healthy threshold, 1.7kW, due to heavy snow in Manchester last winter. More important, the developed performance evaluation technique could be adopted to detect any other reasons that may degrade the performance of the PV panels such as shading and dirt. Repeatability and reliability of the developed system performance were validated during this period. Good agreement was achieved between the theoretical simulation and the real time measurement taken the online grid connected solar power plant.

1. Introduction

The global environmental, financial and political issues necessitate the use of renewable resources to meet the fast growth in energy demand. Among renewable resources, PV systems have received considerable attentions and it is expected that the penetration of PV energy generation will increase steadily to become a significant proportion of total energy generation [1]. However, the power generated by photovoltaic system suffers from some deficiencies when used as stand-alone energy sources. Natural variations in solar radiation and temperature causes power fluctuations in PV system. To alleviate this problem and to meet sustained load demands during varying natural conditions, energy storage system need to be integrated with the PV system. This paper focuses on the combination of PV panels, MPPT controller; to operate the PV panel at its maximum power point, and battery storage device. As the PV panel output power varies with the solar radiation a battery storage device can be integrated with the photovoltaic system to ensure that the system performs under all conditions.

In power applications and system design, modelling and simulation is essential to optimize control and enhance system performance. Over recent years much research has been carried out on photovoltaic and battery storage. Among them, Kim et al. [2], developed a grid-connected photovoltaic model using PSCAD/EMTDC for electromagnetic transient analysis. El-Shatter et al. [3], employed fuzzy logic control to find the maximum power point tracking for both PV and wind...
energies. Tremblay et al. [4], developed a generic battery model for the dynamic simulation of hybrid electric vehicles; they used only the battery state-of-charge (SOC) as a state variable in order to avoid the algebraic loop problem. Arribas et al. [5], proposed a PV/WT hybrid system performance assessment procedure; based on the existing one for PV systems (IEC-61724). Pietruszko et al. [6], summarized one year of monitoring of a roof-mounted 1kW grid-connected PV system in Poland. Omer et al. [7], presented monitoring results of two examples of building integrated PV (BIPV) systems in the UK. Tsai [8], implemented an insolation-oriented PV model using MATLAB/SIMULINK software package. Gow et al. [9], developed a general PV model which can be implemented on simulation platforms such as PSPICE or SABER. Chayawatto et al. [10], developed a mathematical model of a dc/ac full-bridge switching converter with current control for PV grid-connected system under islanding phenomena; this phenomena occur when the grid system is disconnected for any reason and the distributed generation still supplies to any section of local loads.

Although the SimPowerSystem tool in MATLAB/SIMULINK package conveniently offers a wind farm model, it does not offer a solar power plant model for stand-alone or grid-connected applications. Thus, it is difficult to analyze and simulate in the generic modelling of PV power system. Adding to that, as PV systems age it would be expected that their overall efficiency would decrease, and currently there is few monitoring system available to diagnose faults as they occur. Consequently, these gaps gave the researchers the motivation to evaluate the performance of solar power plant based on a developed model comprises photovoltaic array, battery storage, controller and converters. The flowchart of the developed monitoring technique is shown in figure 1.

![Flowchart of the proposed monitoring system.](image-url)
As shown in figure 1, the proposed monitoring system enables early system degradation to be identified via the calculation of the residual difference in power generation between the model predicted and the actual PV power plant. The outcome of the developed system is then validated and supported by a case study in Section 3.2 through monitoring a 28.8kW solar power plant located in central Manchester.

2. Dynamic model of the solar power plant

In this section, the dynamic simulation model is described for PV/battery power system. The developed model consists of a photovoltaic array, dc/dc converter with an isolated transformer, designed for achieving the maximum power point (MPP) with a current reference control (I_{ref}) produced by P&O algorithm, and Li-Ion battery storage. The excess energy with respect to the load requirement is used for battery charging. The excess power demand of the user is supplied by the battery storage system. The block diagram of the developed PV/battery power system is shown in figure 2.

![Figure 2. Block diagram of the proposed PV/battery power system.](image)

2.1. Modelling and design of a photovoltaic system

The general mathematical model for the solar cell has been studied over the past three decades [11]. The circuit of the solar cell model, which consists of a photocurrent, diode, parallel resistor (leakage current) and a series resistor; is shown in figure 3.

![Figure 3. Single diode PV cell equivalent circuit.](image)

According to both the PV cell circuit shown in figure 3 and Kirchhoff’s circuit laws, the photovoltaic current can be presented as follows [12]:

\[
I_P = I_{dc} + I_{losses} = I_{CC} + I_{C} = I_{PV} - I_{D} = -I_{D} + I_{PV}
\]
\[ I_{pv} = I_{gc} - I_o \left[ \exp \left( \frac{eV_d}{KFT} \right) - 1 \right] - \frac{V_d}{R_p} \]  

(1)

Where \( I_{gc} \) is the light generated current, \( I_o \) is the dark saturation current dependant on the cell temperature, \( e \) is the electric charge = \( 1.6 \times 10^{-19} \) Coulombs, \( K \) is Boltzmann’s constant = \( 1.38 \times 10^{-23} \) J/K, \( F \) is the cell idealising factor, \( T_c \) is the cell’s absolute temperature, \( V_d \) is the diode voltage, and \( R_p \) is the parallel resistance. The photocurrent (\( I_{gc} \)) mainly depends on the solar irradiation and cell temperature, which is described as [12]:

\[ I_{gc} = \left[ \mu_{sc} (T_c - T_r) + I_{sc} \right] G \]  

(2)

Where \( \mu_{sc} \) is the temperature coefficient of the cell’s short circuit current, \( T_r \) is the cell’s reference temperature, \( I_{sc} \) is the cell’s short circuit current at a 25°C and 1kW/m², and \( G \) is the solar radiation in kW/m². Furthermore, the cell’s saturation current (\( I_o \)) varies with the cell temperature, which is described as [12]:

\[ I_o = I_{o\alpha} \left( \frac{T_c}{T_r} \right)^3 \exp \left( \frac{eV_o}{kF} \left( \frac{1}{T_c} - \frac{1}{T_r} \right) \right) \]  

(3)

\[ I_{o\alpha} = \frac{I_{sc}}{\exp \left( \frac{eV_o}{kF} \right)} \]  

(4)

Where \( I_{o\alpha} \) is the cell’s reverse saturation current at a solar radiation and reference temperature, \( V_o \) is the band-gap energy of the semiconductor used in the cell, and \( V_{oc} \) is the cell’s open circuit voltage. In this study, a general PV model is built and implemented using MATLAB/SIMULINK to verify the nonlinear output characteristics for the PV module. The proposed model is implemented, as shown in figure 4. In this model, whereas the inputs are the solar irradiation and cell temperature, the outputs are the photovoltaic voltage and current. The PV models parameters are usually extracted from the manufactures data sheet.

**Figure 4.** Subsystem implementation of the PV model.

An experiment was conducted in order to validate the proposed PV model. The experimental rig consists of one Astronergy CHSM6610P-225 PV module, adjustable load resistance, and some measurement instrumentation. The PV module was placed at an inclination angle of 10°, and azimuth
angle of 30°. Two digital multi-meters were respectively arranged in series to measure output current and in parallel to measure working voltage. The output power is then the product of measured current and voltage. Observation of solar irradiance and temperature were taken and recorded each time the load was changed. Current and voltage of the PV module were recorded after a delay of 1 minute after the resistance was changed. It was found that both simulated and measured results for the output characteristics of PV module are good agreement, as shown in figures 5(a) and 5(b). This proves the correctness of the proposed model.

![Figure 5](image1.png)

**Figure 5.** Results comparison for the simulation and experimental approaches (850W/m², 45°C).

### 2.2. Modelling and design of Li-Ion battery storage

In the literature, several studies have been reported regarding to Li-Ion battery [13]. In this paper the Li-Ion battery is modelled using a simple controlled voltage source in series with a constant resistance, as shown in figure 6.

![Figure 6](image2.png)

**Figure 6.** Battery model equivalent circuit.

The open voltage source is calculated with a non-linear equation based on the actual SOC of the battery.

The controlled voltage source can be presented as follow [4]:

\[
E_{\text{charge}} = E_0 - \frac{Q}{Q_{\text{it}}} i^* t - \frac{Q}{Q_{\text{it}}} i^* t + A \exp(-B i^* t)
\]

\[
E_{\text{discharge}} = E_0 - \frac{Q}{Q_{\text{it}}} i^* t - \frac{Q}{Q_{\text{it}}} i^* t + A \exp(-B i^* t)
\]
- During discharge

\[ E_{\text{batt}} = E_o - K \frac{Q}{Q - it} \left( it - K \frac{Q}{Q - it} i^* + A \exp(-B \ast it) \right) \]  
(5)

- During charge

\[ E_{\text{batt}} = E_o - K \frac{Q}{Q - it} \left( it - K \frac{Q}{it + 0.1Q} i^* + A \exp(-B \ast it) \right) \]  
(6)

Thus, the open voltage source is:

\[ V_{\text{batt}} = E_{\text{batt}} - Ri \]  
(7)

Where \( E_{\text{batt}} \) is the no-load voltage, \( E_o \) is the battery constant voltage, \( K \) is the polarisation voltage, \( Q \) is the battery capacity, \( it \) is the actual battery charge, \( i^* \) is the low frequency current dynamics, \( A \) is the exponential zone amplitude, \( B \) is the exponential zone time constant inverse (Ah\(^{-1}\)), \( V_{\text{batt}} \) is the battery voltage, \( R \) is the internal resistance, and \( i \) is the battery current. Model parameters can simply be deduced from a manufacturer’s discharge curve, as shown in figure 7.

![Figure 7. Nominal current discharge characteristic.](image)

The three necessary points used to extract the model parameters are: the fully charged voltage, the end of the nominal zone (voltage and charge) and the end of the exponential zone (voltage and charge). The exponential part \( (A \exp(-B*it)) \) is calculated with the fully charge voltage \( (E_{\text{full}}) \) and the end of the exponential zone \( (E_{\text{exp}}, Q_{\text{exp}}) \) as follows [4]:

\[ A = E_{\text{full}} - E_{\text{exp}} \]  
(8)

\[ B = \frac{3}{Q_{\text{exp}}} \]  
(9)

The polarisation voltage \( (K) \) can be deduced from the fully charged voltage and the end of nominal zone \( (E_{\text{nom}}, Q_{\text{nom}}) \) [4]:

\[ K = \frac{\left( (E_{\text{full}} - E_{\text{nom}} + A \ast (\exp(-B \ast Q_{\text{nom}}) - 1)) \ast (Q - Q_{\text{nom}}) \right)}{Q_{\text{nom}}} \]  
(10)
Then, the voltage constant \( E_0 \) can be presented as follows \[4\]:

\[
E_0 = E_{full} + K + (R \ast i) - A
\]  

(11)

The modified model of the Li-Ion battery is implemented in MATLAB/SIMULINK using several standard SIMULINK blocks as well as some of the SimPowerSystems blocks \[4\]. In this model, the output is a vector containing three signals: SOC, battery current and voltage. The proposed model is implemented as shown in figure 8.

![Figure 8](image)

**Figure 8.** Subsystem implementation of the Li-Ion battery model.

2.3. **Power control system**

The output characteristics of the PV model with different solar irradiance and cell temperature are nonlinear. Furthermore, the solar irradiation is unpredictable, which makes the maximum power point of the PV module changes continuously. Therefore, a MPPT technique is needed to operate the PV module at its maximum power point. Perturb and observe algorithm is the MPPT control algorithm that will be adapted in this model. The P&O algorithm operates by periodically incrementing or decrementing the PV array operating current, and comparing the PV output power with the previous one. If it’s positive the control system moves the PV array operating point in the same direction, otherwise, it’s moved in the opposite direction.

A MPPT controller model is built and implemented using MATLAB, to operate the PV module at its maximum power point. The P&O algorithm requires two measurements: measurement of the current \( I_{pv} \) and measurement of the voltage \( V_{pv} \). The proposed model is implemented as shown in figure 9(a).

![Figure 9(a)](image)

**Figure 9(a).** Subsystem implementation of the MPPT controller model.

In addition, a dc averaged switch model converter with input current control \( I_{ref} \) is built and implemented using MATLAB/SIMULINK to reduce the switching harmonics and to step up the
photovoltaic voltage to a higher dc voltage. The proposed model is implemented as shown in figure 9(b).

![Figure 9(b). Subsystem implementation of the dc/dc converter model.](image)

3. Simulation results and performance analysis

3.1. PV/Li-Ion battery power system model

In this Section the proposed model was simulated using MATLAB for stand-alone application. The system consists of 3.6kW of PV panels, (200V, 6.5Ah) Li-Ion battery bank, controller and converters. The block diagram of the integrated PV/Li-Ion battery system, and the power controllers are shown in figure 2.

The major inputs for the proposed PV model were solar irradiation, PV panel temperature and PV manufacturing data sheet information’s. In this work, Sharp’s (NU-180) PV panel is taken as example. The Sharp’s (NU-180) key specification is listed in table 1.

| Parameter                  | Variable | Value    |
|----------------------------|----------|----------|
| Maximum power              | $P_m$    | 180 (W)  |
| Open circuit voltage       | $V_{oc}$ | 30  (V)  |
| Voltage at $P_m$           | $V_{amp}$| 23.7 (V) |
| Short circuit current      | $I_{sc}$ | 8.37 (A) |
| Current at $P_m$           | $I_{amp}$| 7.6 (A)  |
| Temp coefficient for $V_{oc}$| $\beta$ | -104 mV / °C |
| Temp coefficient for $I_{sc}$| $\alpha$ | + 0.053% / °C |
| No. of cells and connections| $N_s$    | 48 in series |

During the simulation process, the aim was to observe the proposed model behaviour under different operating condition. The solar radiation and user load profiles are used to test the performance of the proposed system model, as shown in figures 10(a), and 10(b).
Although the photovoltaic power fluctuates due to solar radiation variations, as shown in figure 11, the proposed control system of the solar power plant successfully operates the PV model at the MPP by periodically incrementing or decrementing the PV array operating current \( I_{pv} = I_{ref} \). On the other hand, the dc-dc converter successfully steps up the voltage, with an efficiency of 93%, as shown in figure 12.

According to the power profile depicted in figure 10(b), peak load demands would be observed between 10 to 20 min and from 30 to 50 min. However, during these time intervals the PV power is lower than the demand. To overcome this deficiency and to meet the load demand, battery bank was added to the PV system. Hence the peak load demand is satisfied by battery bank as shown in figure 13. The power met by the battery introduces a current change at the battery bank terminal as depicted in figure 14. When the battery current is positive (time intervals 10–20 min and 30–50 min),
energy is transferred to the load by the battery bank. When the battery current is negative, the battery bank is recharged. Figure 15, shows the SOC of the battery during the simulation. The power delivered to the load side by the PV/Li-Ion battery system is illustrated in figure 16.

![Figure 13. Power satisfied by battery bank.](image1)

![Figure 14. Battery current change with respect to power demand.](image2)

![Figure 15. Battery State-Of-Charge (SOC).](image3)

![Figure 16. Power delivered to load side by the PV/battery system.](image4)

3.2. Case study: performance of PV power stations in Manchester

In 2009, Manchester Metropolitan University (MMU) installed three PV power stations on its campus in Manchester with a combined maximum power of 55.8kW (enough power to light 7200 100-watt light bulbs, power 960 student laptops, boil 40 kettles or supply electricity to 10 houses). Figure 17(a), shows the 28.8kW PV power plant designated as (All Saints building) PV array 1. Figure 17(b) shows the (All Saints building) PV array 2. Both power stations use the Sharp NU-180 (E1) PV panels and they were placed at an inclination angle of 10°, and azimuth angle of 30°.

As shown in figure 17, the solar power plant is divided into two building. Building 1 has its PV system located on the sixth floor with a total of 160 PV panels. Building 2 has its array spread over two floors (floor 6 and floor 4). There are 150 panels in total, 78 PV panels on floor 6 and 72 on floor 4. The total power delivered to the national grid by the PV systems since their commissioning back in 2009 is shown in figure 18.
Furthermore, the proposed PV model was simulated using MATLAB to monitor the 28.8kW grid connected PV power station by calculating the residual difference between the model predicted and the actual measured power parameters. Measurements were taken over 21 month’s period; using hourly average irradiance and cell temperature.

It was found from figure 19(a) that the system has a good performance, since the residual difference between the model prediction and the actual power is less than 1.7kW. The difference caused due to the clouds, dust, wire, and aging. Also it can be observed from figure 19(b) that system degradation will be indicated when the residual difference is above 1.9kW; due to snow cover, shading, or any other reasons that may reduce the efficiency of the PV panels.

![Figure 17(a). All Saints building PV array 1.](image1)

![Figure 17(b). All Saints building PV array 2.](image2)

![Figure 18. PV systems total yield (Sep 2009 – May 2011).](image3)
4. Conclusions
In this paper, solar power plant performance was evaluated based on a developed model for stand-alone and grid-connected applications. The developed model comprises photovoltaic array, Li-Ion battery and an appropriate power flow controller. The model has been implemented using the MATLAB/SIMULINK software package, and designed with a dialog box like those used in the SIMULINK block libraries. Excellent performance was obtained from the simulation model under variable solar radiation and load power requirements.

The outcome of the developed model were validated and supported by a case study carried out using operational 28.8kW grid-connected solar power plant located in central Manchester. The study was carried out through monitoring that system by calculating the residual difference between the model predicted and the actual measured power parameters. Measurements were taken over 21 month’s period; using hourly average irradiance and cell temperature. Good agreement was achieved between the theoretical simulation and the real time measurement taken the online grid connected solar power plant. With this model it is possible to identify PV generation problems quickly and improve system efficiency and performance.

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