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Simplified performance models of photovoltaic/diesel generator/battery system considering typical control strategies

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ABSTRACT

Simplified dynamic models of photovoltaic/diesel generator/battery system using MATLAB line code are presented in this paper. The main purpose of these models is to predict the performance of photovoltaic/diesel generator/battery system through a specific time period. A complex battery model as well as the most recommended control strategies such as load following and cycle-charging dispatch are considered in the proposed models. Finally, the proposed models are validated using simulation and experimental data. Such models are helpful in studies related to hybrid photovoltaic/diesel generator/battery system control, sizing and performance assessments.

1. Introduction

Photovoltaic systems (PV) are considered reliable, cost-effective and environmentally friendly energy power systems. These systems can utilize local renewable energy resources at high security levels especially in remote areas [1]. System simplicity and low required maintenance are the superior advantages of the PV system. However, the uncertainty of the output of PV systems is the major drawback of these systems. On the other hand, diesel generators (DG) are generally inexpensive to purchase but, they are relatively expensive to maintain and operate especially at low levels [2]. Thus, the comprising of PV system and DG provides greater system reliability and reduces the cost of the generated energy by the system [3]. Many researchers indicate that hybrid PV/DG/battery systems are reliable energy sources and represent an economically acceptable compromise between the high capital cost of PV system and high operation and maintenance (O&M) of DG [4–8].

Anyway, accurate modeling of hybrid PV/DG/battery system's components is very important when optimally sizing and controlling these systems. Such system's model must describe the energy or current flow in the system accurately in order to provide accurate performance model of the system.

Currently, there are some commercial softwares that provide performance models for PV/DG/battery systems. The most frequently used software is HOMER software [9–14]. With HOMER, the simulation of PV/DG/battery systems is carried out using hourly meteorological and load demand data. Meanwhile, hourly system's performance is provided in terms of system's output power and battery state of charge. Furthermore, economic and sensitivity analysis are provided. In HOMER, the input load data must be provided based on monthly basis by the user. After that, embedded statistical models are used to generate hourly load demand data. On the other hand, there are two options of providing meteorological data. The user can utilize some online data bases that are based on satellite measurements. Otherwise, the user has to provide monthly average of meteorological data and then similar statistical models are used to generate hourly profiles for these data for a one year time. In order to model the battery, HOMER software utilizes kinetic battery model as described in [15]. Finally, two dispatch strategies are used in HOMER [16]. These strategies are "load following" and "cycle-charging". With the load following strategy, the DG produces only enough power to meet the demand. While with the cycle charging strategy, the DG is operated at full capacity to meet the load demand, while the surplus energy is used to charge the battery [17]. In general, HOMER software is a helpful tool in case of conducting economic or reliability analysis of hybrid PV/DG/battery systems. However, these results may not be accurate as the input data are either estimated by statistical models or generated based on satellite measurements. On the other hand, HOMER software is considered as "Black Box" source code whereas

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the user is not able to use or modify the embedded codes in development studies such as novel sizing and control methods. Thus, there is a need to open source code of these models so as to be able to utilize them in research studies.

To overcome the disadvantages of using specialized commercial softwares, some of the researchers have modeled such a hybrid system using other programming languages such as C++ and MATLAB. In [18] a simulation model is developed for PV/DG/battery system. This model is utilized in sizing and control algorithms. The simulation model is developed using C++ programming language. The proposed model is based on hourly solar radiation data and the hourly load demand. The main aim of the proposed model is to compute the hourly current that is generated by the PV array and the state of charge of the battery. A simple battery model is considered in this program. Furthermore, modeling of PV/DG/battery system is performed in [19]. The proposed model is based on system energy balance and storage battery energy status. The simulation of the hybrid PV/DG/battery system is done with only DC load whereas all of the energy from the diesel generator is used to charge the battery, while the battery is used to power the load. This is to say that the proposed model represents a series topology of the system which has many drawbacks. The series topology requires more power electronic features which may reduce the whole efficiency of the system as well as system's feasibility. In addition, the series topology limits the control of the diesel generator [20]. In addition to that, energy flow model for PV/DG/battery system using MATLAB line code is presented in [21]. The proposed model describes the energy flow in the whole system with a simple battery model. More models of PV/DG/battery system that describe the energy flow with simple battery model can be also found in [22–25].

From the reviewed research work in [9–25], most of the proposed models utilize daily or hourly data. Moreover, simple battery model is considered in most of the cases which does not reflect the dynamic behavior of this device. In addition, most of them modeled the system based on system's energy flow, while, some of these models did not consider any control strategy of the system. This makes these models useful in system sizing and analysis but not in control algorithms. Moreover, none of these researchers has provided the developed code so as to be utilized by other researchers. Finally, none of these models has been validated experimentally.

Based on this, simplified dynamic current flow models of PV/DG/battery system using MATLAB line code is presented in this paper based on minute time interval. The proposed codes consider the most typical control strategies namely, load following and cycle-charging. The main purpose of this model is to predict the performance of PV/DG/battery system through a specific time period. In addition, these models contains complex battery model so as to consider the dynamic performance of the battery. Finally, experimental validation is provided so as to show the accuracy of the proposed models.

2. System's mathematical model

A typical hybrid PV/DG/battery power system usually consists of a PV array that converts the sunlight to a DC current, a DG that provides AC current, storage device to store the excess energy and power electronic features including DC–DC and AC–DC converters. Fig. 1 shows a typical hybrid PV/Diesel/Battery system.

2.1. Photovoltaic array model

Various mathematical models have been introduced in order to describe the output current of a PV array. The general working concept of the PV system is that the incident radiation of the sun on the PV array is collected and converted to a DC current. As a fact, the output current of a PV array has a linear proportioned relation to solar radiation meanwhile a logarithmic relation can describe the relation between the PV module's cells temperature and the output current. Hence, the output current of a PV array can be described as below [26].

$$I_{PV}(t) = I^{*}_{PV}\left[\left(\frac{G_T(t)}{G_{reference}}\right) + \alpha_T[T_c(t) - T_{reference}]\right] \tag{1}$$

where (I^{*}_{PV}) is the maximum PV current under standard testing conditions (STC), G_T is solar radiation in (W/m^2), $G_{reference}$ is the solar radiation at STC, α_T is the temperature coefficient of the PV module's short circuit current, $T_{reference}$ is the ambient temperature at STC. T_c is the cell temperature and it can be calculated by,

$$T_c(t) = T_{amb}(t) + \left(\left(\frac{NOCT - 20}{800}\right) \times G_T(t)\right) \tag{2}$$

where T_{amb} is the ambient temperature in °C and NOCT is the normal operating cell temperature in °C. NOCT is PV module's cells temperature when the ambient temperature is 20 °C, solar radiation is 800 W/m^2 and wind speed is 1 m/s [21].

2.2. Battery mathematical model

Fig. 2 shows an equivalent circuit of the storage battery. The internal voltage of the battery is represented by a voltage source, V_1 and an internal resistance, R_1. The charging or discharging current, I_{bat} depends on the system's voltage levels. If the applied voltage is greater than the battery's voltage, V_{bat}, the current, I_{bat} will flow in the battery as a charging current. Meanwhile, if the applied voltage is less than the battery's voltage battery, the current will flow out from the battery as a discharging current [27].

The state of charge (SOC) of battery is expressed as [28],

$$SOC = 1 - \frac{Q}{C} \quad 0 \leqslant SOC \leqslant 1 \tag{3}$$

For Eq. (3), Q represents the battery charge and C represents the battery capacity.

The depth of charge (DOD) of battery is given by,

$$DOD = 1 - SOC \tag{4}$$

During the charging mode, suppose that $V_1 = V_{ch}$ and $R_1 = R_{ch}$, the charging voltage, V_{ch} is given by [28],

$$V_{ch} = (2 + 0.148\beta)N_s \tag{5}$$

in which,

$$\beta = \frac{SOC_1}{SOCm} \tag{6}$$

SOC_1 represents the initial state of the charge of the battery and SOCm represents the maximum value of battery state of charge. N_s is the number of 2V series cells.

R_{ch} represents the charging resistance and it can be calculated by the following equation [28],

$$R_{ch} = \left[\frac{0.758 + \frac{0.1309}{1.06-\beta}}{SOCm}\right]N_s \tag{7}$$

From Fig. 2, the battery voltage is given by,

$$V_{bat} = V_{ch} + I_{ch}R_{ch} \tag{8}$$

In order to calculate the SOC of the battery during charging mode, Eq. (9) is used.

$$SOC(t + dt) = SOC(t)\left[1 - \frac{D}{3600}dt\right] + K[V_{bat}I_{bat} - R_{ch}I^2_{bat}]dt \tag{9}$$