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Novel simplified hourly energy flow models for photovoltaic power systems

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ABSTRACT

This paper presents simplified energy flow models for photovoltaic (PV) power systems using MATLAB. Three types of PV power system are taken into consideration namely standalone PV systems, hybrid PV/wind systems and hybrid PV/diesel systems. The logic of the energy flow for each PV power system is discussed first and then the MATLAB line codes for these models are provided and explained. The results prove the accuracy of the proposed models. Such models help modeling and sizing PV systems.

1. Introduction

Based on the fact that PV systems are clean, environment friendly and secure energy sources, the installation of PV systems has played an important role worldwide. However, the drawback of PV systems is the high capital cost compared with conventional energy sources. Currently, many research works are carried out focusing on the optimization of PV systems so that the number of PV modules, capacity of storage battery, capacity of inverter and PV array tilt angle can be optimally selected. The size and performance of PV systems strongly depend on meteorological variables such as solar energy, wind speed and ambient temperature and therefore, to optimize a PV system, extensive studies related to the meteorological variables have to be carried out [1,2].

The modeling of PV components such as PV module/array, battery, inverter and wind turbine plays important roles in optimizing PV systems. Research works related to PV system size optimization including PV system modeling can be found in [3–12]. In [3], the probabilistic approach is used to optimize PV systems by considering a probability function which is expressed as the probability of losing load (the case when the energy source is not able to fulfill the load demand) in terms of battery, PV array energy output and load demand. Therefore, the determination of an optimum storage battery is based on the reliability of the PV system, the optimum PV array size is calculated using the worst month method. In Europe, optimization of PV systems is done for three sites in which optimization considers PV array sizing curves derivation and minimum storage requirement in order to fulfill the desired load demand. The sizing curves of the PV array were helpful in calculating the PV array size based on the required energy production by the system [4]. To avoid any load interruption, the PV array size is designed based on the worst monthly average of solar energy. As for finding the minimum storage requirement, the same method for plotting sizing curves is used and the minimum storage requirement is calculated for each year of the used historical data. In [5], a PV system model has been developed to optimize its size based on a well defined solar energy potential and load. The developed model contains models for PV array, storage battery and charge regulator. However, the optimization considers the combined minimum cost with minimum loss of load probability. In [6], optimization of PV systems in Delhi has been done using the loss of power supply probability. A defined load and daily solar energy has been used to calculate the loss of power supply probability. Then a sizing curve is generated based on the calculated loss of power supply probability. The number of PV modules and battery capacity are also evaluated based on the minimum cost. An analytical method for sizing PV systems based on the concept of loss of load probability has been also developed [7]. The method considers the standard deviation of the loss of load probability as well as annual number of system failures and the standard deviation of the annual number of failures. The optimization of the PV array tilt angle is also done so as to maximize the collected yield.

In the previous works, models for the PV components have been suggested in order to optimally design these systems, none of these works has presented an operational model for PV system in order to validate the suggested results. On the other hand some of the models proposed in the literature such as the works presented in [8–12] mainly focus on the output power of the PV array only,

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meanwhile, none of these models have considered the energy follow in the whole system. Based on this, this paper presents energy flow models for three types of PV systems, namely standalone PV systems, Hybrid PV/wind systems and hybrid PV/diesel system using MATLAB. The main objective of these models is to predict the performance of PV systems through a specific time period which helps validate PV system sizing techniques.

2. Energy flow modeling for standalone PV power systems

Modeling of standalone PV system, (SAPV) is very important in sizing system's energy sources. Therefore, many mathematical models have been described for SAPV systems. Fig. 1 shows a typical PV system consisting of a PV module/array, power conditioner such as charge controller or maximum power point tracking controller (MPPT), batteries, inverter and load.

In general, a PV array collects energy form the sun and converts it to DC current. The DC current flows through a power conditioner to supply the load through an inverter. The daily output power produced by a PV module/array is given by,

$$P_{PV}(t) = \left[P_{peak}\left(\frac{G(t)}{G_{standard}}\right) - \alpha_T[T_c(t) - T_{standard}]\right] * \eta_{inv} * \eta_{wire} \quad (1)$$

where $G_{standard}$ and $T_{standard}$ are the standard test conditions for solar radiation and ambient temperature, respectively, and α_T is the temperature coefficient of the PV module power which can be obtained from the manufacturer datasheet. η_{inv} and η_{wire} are the efficiencies of inverter and wires, respectively.

The temperature (T_c) in Eq. (1) is the cell temperature. The cell temperature can be calculated by,

$$T_c(t) - T_{ambient}(t) = \frac{\text{NOCT-20}}{800} G(t) \quad (2)$$

where NOCT is the nominal operation cell temperature which is measured under 800 W/m^2 of solar radiation, 20 °C of ambient temperature and 1 m/s of wind speed.

The calculation of energy produced by the PV array (E_{PV}) depends on the time step of the weather data used. In other words if the input solar radiation data are hourly then the power produced by the PV array, $P_{PV}(t)$ is equal to PV energy production E_{PV} (t). Meanwhile if the input data are daily solar energy then,

$$E_{PV}(t) = P_{PV}(t) * S \quad (3)$$

where S is the day length which can be given by

$$S = \frac{2}{15}\cos^{-1}(-\tan L \tan \delta) \quad (4)$$

where L is the latitude and δ is the angle of declination, given by

$$\delta = 23.45 \sin\left[\frac{360(284 + N)}{365}\right] \quad (5)$$

where N is the day number (the counts of days starting from the 1st of January, e.g., N for the 1st of February is 32).

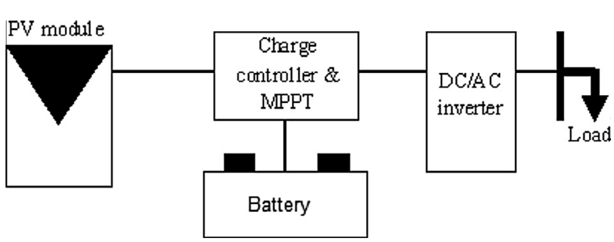

Fig. 1. Typical PV system components.

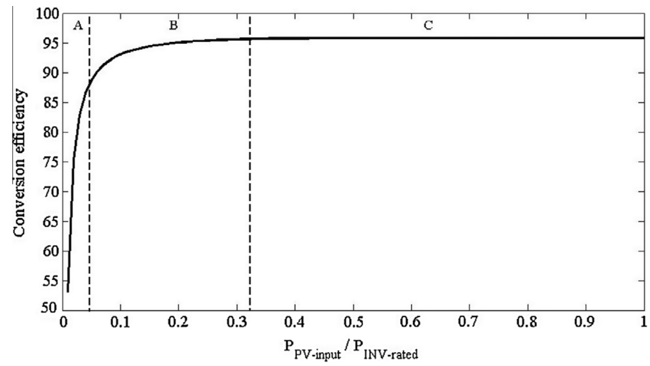

Fig. 2. Typical efficiency curve of an inverter.

As for the calculation of the inverter's conversion efficiency, Fig. 2 shows an efficiency curve for a commercial inverter obtained from the manufacturer datasheet. The curve describes the inverter's efficiency in terms of input power and inverter rated power.

The efficiency curve can be described by a power function as follows,

$$\left\{\begin{array}{ll} \eta = c_1\left(\frac{P_{PV}}{P_{INV_R}}\right)^{c_2} + c_3 & \frac{P_{PV}}{P_{INV_R}} > 0 \\ \eta = 0 & \frac{P_{PV}}{P_{INV_R}} = 0 \end{array}\right\} \quad (6)$$

where P_{PV} and P_{INV_C} are the PV module is output power and inverter's rated power respectively while c_1–c_3 are the model coefficients. The MATLAB fitting tool can be used for calculating coefficients, c_1–c_3. Fig. 3 shows the logic diagram for modeling standalone PV system.

The energy at the front end of a SAPV system or at the load side is given by,

$$E_{net}(t) = \sum_{i=1}^{366}(E_{PV}(t) - E_L(t)) \quad (7)$$

where E_L is the load energy demand.

The result of Eq. (7) is either positive ($E_{PV} > E_L$) or negative ($E_{PV} > E_L$). If the energy difference is positive then there is an excess in energy (EE), if negative then there will be an energy deficit (ED). The excess energy is stored in batteries in order to be used in case of energy deficit. Meanwhile, energy deficit can be defined as the disability of the PV array to provide power to the load at a specific

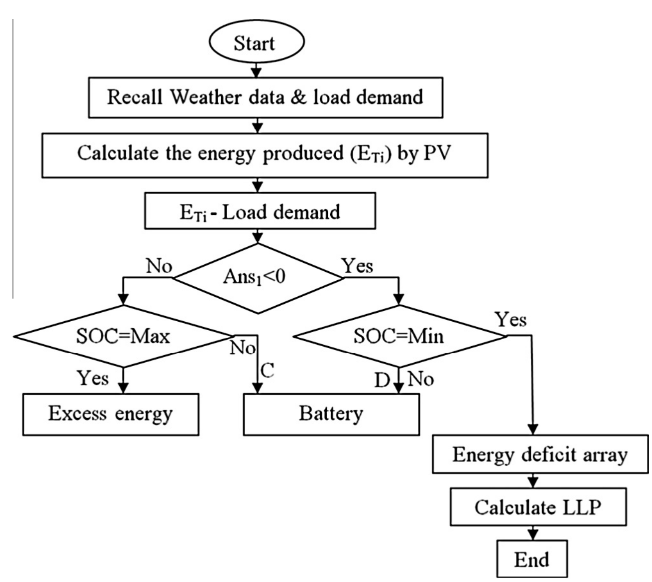

Fig. 3. Logic diagram for modeling standalone PV system.