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A novel method for the determination of dynamic resistance for photovoltaic modules

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ABSTRACT

Obtaining the maximum power output in real time is indispensable to the operation of grid connected photovoltaic (PV) power systems under given atmospheric conditions. Focusing on the resistance effect of the solar cells, we propose a new and simple method to directly determine the dynamic resistance of the PV modules from an irradiated current–voltage characteristic curve. In our method, we develop the ability to determine the dynamic resistance with a combination of finite series- and shunt-connected resistance. A series of experiments, including numerical simulations and field data tests, are conducted to examine the dynamic behavior of the PV modules during power tracking. Experimental results show that the proposed direct resistance-estimation method allows the PV modules to achieve their maximum power and impedance matching under various operation conditions.

1. Introduction

Many researches on photovoltaic (PV) energy for various applications have been conducted in recent years, as a consequence of the unique properties of PV arrays [1–4]. There have also been extensive studies on improving the characteristics of renewable energy for such PV arrays, which are potentially very important for the reduction of certain carbon dioxide emissions [5–7]. The need for energy-efficient electrical power sources in remote locations is a driving force for the investigation of integrated energy systems. In particular, advancement in wind and PV generation technologies has been applied to wind-alone [8], PV-alone [9,10], and hybrid wind/PV configurations [11–13]. PV arrays have also become a reliable energy source that it is hoped can efficiently mitigate some of the worst effects of global warming [14–16]. Studies related to renewable energy sources, including PV arrays, are especially important for many developing countries around the world.

The PV modules exhibit an extremely nonlinear current–voltage (I–V) characteristic that varies continuously with module temperature and solar irradiation. The main electrical parameters of the solar cell — such as the short-circuit current I_{sc}, the open-circuit voltage V_{oc}, the maximum power P_{mp}, the fill factor FF, and the maximum conversion efficiency η_m — are functions of the resistance of solar cells, i.e., the series resistance R_s and the shunt resistance R_{sh} [17]. This is what causes low energy-conversion efficiency in the PV modules. Hence, it is worth paying more attention to how to efficiently control the operation of PV modules at maximum power output to the extent possible. A series resistance can be caused either by excessive contact resistance or by the resistance of the neutral regions. The series resistance R_s accounts for all voltages that drop across the transport resistances of the solar cell. Usually, R_s connects to a load or an inverter. The series resistance (R_s) can be determined by different methods under various illumination conditions, such as in the dark, constant illumination, and varying illumination, yielding different results [18]. In the standardized measurement method for solar cells, R_s is normally determined by two different illumination levels, the so-called two-curve method [19]. On the other hand, the shunt resistance (R_{sh}) usually results from any channel that bypasses the p-n junction. This bypass can be brought about by damaged regions in the p-n junction or surface imperfections. Shunt resistance R_{sh} occurs in the shunt paths with the diodes of the modeled solar cells. Shunt paths can occur across the surface of real solar cells, at pin holes in the p-n junction, or at grain boundaries. The shunt resistance (R_{sh}) can be obtained using the so-called two points-single curve method from two points on one illuminated I–V curve [19,20]. However, when we consider two operation points on one illuminated I–V curve or two illuminated

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I–V curves, it is found that both methods can lead to large errors because of different operating conditions and complicated mathematical operations. Hence, it is difficult to obtain the dynamic resistances of the PV modules (with low calculation burden), simply by using the two-curve method or two points-single curve method [19]. A less complicated way to find the dynamic resistances of the PV modules through a simpler and more convenient estimation technique is required.

Impedance matching is the practice of designing the input impedance of an electrical load or the output impedance of its corresponding signal source in electrical circuits so as to maximize the power transfer and minimize the reflections from the load. In order to gain the maximum power from a PV module at the current solar irradiance level and temperature, it is mandatory to match the PV source with the load by means of switching from a direct current (DC) to direct current converter (DC–to–DC converter). To ensure the source-load matching, the PV generation system should properly change the operating voltage at the terminals of the PV module according to the actual weather conditions. Due to the nonlinear I–V characteristic curve of PV modules, it is generally difficult to analyze and determine their output impedance, i.e., dynamic resistance. Hence, it is necessary to develop an efficient method for the determination of the dynamic resistance. Such a method should be able to estimate the voltage value corresponding to the maximum power delivered by the PV source and further achieve impedance matching for any kind of PV module.

The dynamic resistance of solar cells and modules can be determined by an I–V characteristic curve. Being a dynamic quantity, the dynamic resistance is normally taken to be the slope or the derivative of the I–V characteristic of a cell or a module and is defined as the change in voltage divided by the change in current as $\Delta V_{pv}/\Delta I_{pv}$ or dV_{pv}/dI_{pv}. Furthermore, the dynamic resistance is composed of the series resistance and shunt resistance. However, the effect of the series resistance and shunt resistance is often ignored in the practical quantification of dynamic resistances. Such inaccuracies of the dynamic resistance will lead to the improper PV control operations and to the tracking of incorrect maximum power point (MPP).

As mentioned above, it is still very complicated to obtain the value of the series resistance and shunt resistance which can be done using the two-curve method and the two points-single curve method. This makes it difficult to determine the dynamic resistance using the electrical parameters of a solar cell, i.e., series resistance and shunt resistance. In most cases, electrical circuits are used as interfaces between the PV generators and the loads, or between inverters and the energy accumulators, and operated in off-line mode. A relatively powerful microcontroller is required to implement the above-mentioned methods due to the complexity of the mathematical operations involved.

Focusing on the resistance effect of the solar cells, we propose a new and simple method to directly determine the dynamic resistance of the PV modules from one point on an irradiated current–voltage characteristic curve. This method is developed based on the p-n junction semiconductor theory of solar cells. Through the direct resistance-estimation method, we elucidate the effects of dynamic resistance on the characteristics of PV modules even if the irradiation intensity or ambient temperature is changed. The model of dynamic resistance with a combination of finite series resistance and shunt resistance is also taken into consideration in this study. The correlation between the dynamic resistance and the ambient factors will be discussed in detail in the following sections.

2. Theoretical basis of the proposed method

The p-n junction recombination mechanism of semiconductors successfully describes the nonlinear characteristics of PV modules [17]. The PV modules exhibit extremely nonlinear voltage–ampere characteristics, which vary continually with module temperature and solar illumination. This fact often causes a great deal trouble leading to a lack of control for the proper operation of the PV modules and the tracking of incorrect MPP. To overcome such problems, we propose a novel and simple method to directly determine the dynamic resistance of the PV modules from an irradiated current–voltage characteristic curve. Using the developed method to directly estimate the dynamic resistance of the PV modules, we can control the MPP and achieve the maximum utilization efficiency of the PV modules.

Fig. 1 depicts the equivalent circuit for the PV modules. Using the symbols shown in Fig. 1, the output current I_{pv} of PV modules is given by [17,21,22]

$$I_{pv} = I_{ph} - I_d - V_d/R_{sh}, \tag{1}$$

where I_{ph} is the light-generated photocurrent (A); R_{sh} is the shunt resistance (ohm); and I_d and V_d are the current and voltage of the p-n junction diode, respectively. The current I_d and voltage V_d of the p-n junction diode can be expressed as

$$V_d = V_{pv} + I_{pv}R_s, \tag{2}$$

and

$$I_d = I_{\text{sat}}\left\{\exp\left[\frac{qV_d}{nkT}\right] - 1\right\}, \tag{3}$$

where R_s is the series resistance (ohm); I_{sat} is the reverse saturation current (A); n is the ideality factor of the diode; q is the electron charge (C); k is the Boltzmann's constant (eVK^{-1}); and T is the ambient temperature (K). The ideality factor (n) of the diode is usually set as 1 when only the diffusion current flows across the junction and 2 when the recombination current dominates [17]. Thus, the ideality factor of the diode could be considered constant, and independent of voltage [17]. After substituting the components associated with the p-n junction diode into Eq. (1), the current I_{pv} of PV modules can be expressed by [17,21,22]

$$I_{pv} = I_{ph} - I_{\text{sat}}\left\{\exp\left[\frac{q(V_{pv} + I_{pv}R_s)}{nkT}\right] - 1\right\} - \frac{V_{pv} + I_{pv}R_s}{R_{sh}}. \tag{4}$$

When the load $R_L = 0$ in Fig. 1, the output voltage V_{pv} is zero, and the short-circuit current I_{sc} is given by [23]

$$I_{sc} = I_{ph} - I_{\text{sat}}\left\{\exp\left[\frac{q(I_{sc}R_s)}{nkT}\right] - 1\right\} - \frac{I_{sc}R_s}{R_{sh}}, \tag{5}$$

or

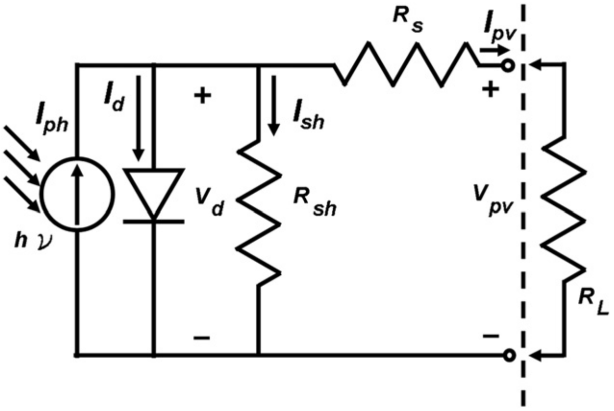

Fig. 1. The equivalent circuit for the PV modules.