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Innovative and precise MPP estimation using *P–V* curve geometry for photovoltaics

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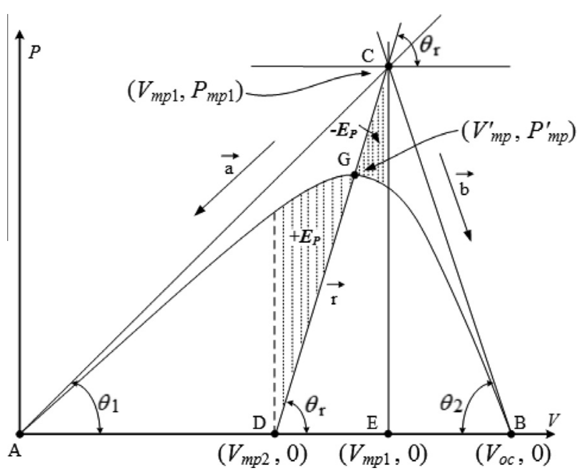
HIGHLIGHTS

- Direct MPP estimation method.
- MPP uses power–voltage curve of a solar cell and quadratic regression.
- Comparison of present MPP method with P&O algorithm in passive mode.
- Method used for wide range of solar photovoltaics cells and modules.

GRAPHICAL ABSTRACT

The paper proposes an innovative and intelligent MPP finding method based on *P–V* geometry of a solar cell or a module using quadratic regression analysis. The method can determine the MPP precisely even though the measured data contains high noise. It is employed for different PV cells and modules and the MPP parameters obtained are in well agreement with those of reported in datasheet. The MPP tracking execution time of method is very small and it outperforms widely used P&O.



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ABSTRACT

This paper elaborates a direct maximum power point (MPP) finding method for solar photovoltaics (PV) based on quadratic regression analysis of the geometry of the power–voltage (*P–V*) curve of a typical PV cell or module. This method works in two stages for determination of the MPP parameters such as voltage (V_{mp}), power (P_{mp}) and fill factor with high level of accuracy. At first, it determines the approximate MPP parameters using a few data collected from the open-circuit and short-circuit regions of a current–voltage (*I–V*) characteristic, and further it refines the obtained parameters using quadratic regression analysis. This method is non-iterative and requires no prior knowledge of the physical and electrical parameters of the cell. Besides high accuracy, the method is also very precise in handling the noise level (up to 20%) in the data. The method was tested on a wide range of PV cells reported in the literature including silicon, copper indium gallium selenide (CIGS), copper zinc tin sulphide selenide (CZTSSe) and organic cells. The estimated MPP parameters are in excellent agreement with those of reported for

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the cells. The method is also employed for an experimental *P–V* characteristic of a 10 W_p silicon module and a synthesized *P–V* characteristic of a 120 W_p silicon module. The estimated fill factor for silicon modules exactly matches with those available in the datasheet specifications. Experimental evaluation of the method as compared to perturb-and-observe (P&O) in the passive mode exhibits quick response. Thus, the method is applicable for a wide category of PV cells to PV modules.

1. Introduction

Solar photovoltaic (PV) is an upcoming power generation technology worldwide as it is renewable and available in abundance. A PV plant is operated by a maximum power point (MPP) controller that makes the load to extract maximum power. The MPP controller is driven by logical and mathematical algorithms. Some commonly used and many advanced algorithms [1,2] for the MPP have been investigated and a few of them are successfully applied in the PV industries. A few examples of the MPP algorithms reported in the literature are discussed in brief here:

(1) The perturb-and-observe (P&O) and incremental conductance (INC) algorithms [3] are very simple to implement but their response is poor in the steady-state operation. Many researchers [4] demonstrated the INC performance better than the P&O. However, in [5], their mathematical and experimental equivalence has been proved.
(2) P&O and INC algorithms track the MPP in steps as the voltage is increased. But, a class of algorithms exists in which the MPP is achieved directly with the help of classical numerical methods such as Bisection, Secant, False position and Newton–Raphson [6]. These methods require a functional relation between *P* and *V* for the entire *V*-range. The numerical methods actually help to find the MPP when the derivative of *P* with respect to *V* (dP/dV) is equated to zero.
(3) Several soft computing optimization algorithms (SCOA) such as genetic algorithm (GA), fuzzy logic (FL) and artificial neural network (ANN) have also been employed for determining the MPP [7]. FL and ANN can handle the imprecise data very easily [8]. Moreover, FL controller performs better than ANN and other different MPP tracking methods [9]. The particle swarm optimization (PSO) algorithm [10] has been proven very efficient to tackle the MPP finding problem when there exist multiple MPPs in case of partial shading of the PV array system.

Though improved versions of the P&O and INC algorithms are suggested [11,12], still there persists oscillatory behaviour when they are employed for the real-time-implementation. These algorithms scan the entire *P–V* curve till the MPP is achieved, of course without any information about the solar irradiance, temperature and PV array parameters. Real-time scanning of entire *P–V* curve makes the system to be disturbed and causes energy loss [4]. In order to track the MPP without disturbing the system, knowledge of the *I–V* and *P–V* curves are required in prior to execute the MPP tracking. A class of algorithms have been developed which calculates the *I–V* and *P–V* curves in advance. They use polynomial fit [13], exponential fit [14] and piecewise *I–V* curve fitting [15]. Recently, Patel et al. [16] demonstrated an *I–V* characteristic evaluation technique using a teaching learning based optimized algorithm (TLBO). In some literatures, the MPP is obtained using classical root finding methods by solving the *P–V* model derived from the non-linear *I–V* relation of a PV cell [17]. The numerical methods require appropriate initial guesses and take large time for the convergence due to their iterative nature. The final convergence may not be guaranteed or may delay the MPP execution process. These methods require knowledge of the irradiance, temperature, and physical parameters, etc. of the PV array which further make the method impractical for the real-time-implementation. SCOA perform better to handle non-linear *I–V*/*P–V* relations than the numerical methods without any assumption for the simplification of the model [7]. They also find the MPP very accurately, but their real-time-implementation is very difficult as they require frequent measurements of the short circuit (SC) current (I_{SC}) and open circuit (OC) voltage (V_{OC}). This results in complexity and increasing cost of the controller. In order to avoid the problem of frequent I_{SC} and V_{OC} measurements, a few researchers [15] have demonstrated the method that predicts the MPP using measurements of four or six (V, I) points selected near the MPP region. The method does not require manufacturer's specifications, irradiance and temperature as it takes on-line (V, I) data points into consideration but neglects the shunt resistance (R_{sh}) of the cell in the computations. This assumption may provide better results for the silicon PV array where R_{sh} is high enough, but the method may fail to predict the MPP if applied to amorphous silicon and other thin film based technologies where R_{sh} cannot be neglected [18].

The aim of the work presented in this paper is to provide a different class of MPP finding methods. An MPP finding method based on the geometry of the *I–V* characteristic is recently published in [19], whereas the method presented in this paper uses the geometry of the *P–V* characteristic. Panchal and Kumar [19] have predicted the MPP using the geometry of an *I–V* characteristic in which a parallelogram is constructed from the OC and SC regions' data and the Lagrangian interpolation is used to determine the MPP. The same authors [20] have also presented a method based on a geometry of the *I–V* characteristic which can handle the noise up to 5% in the data effectively. In one of the methods [21], the maximum possible power rectangle in the *I–V* plane is found based on the characteristic resistances (R_{se} and R_{sh}) of the module. In comparison with the last method, both previous methods do not require the knowledge of the resistances. The proposed method is independent of previous instant voltage/power data unlike in P&O and INC algorithms. Furthermore, the simple quadratic regression analysis is adapted to strengthen the accuracy of the MPP obtained by the *P–V* curve geometry. To check the viability of the method, it is tested on variety of solar cells including silicon, CIGS, CZTSSe, organic and on silicon modules. The method determines the accurate MPP and is better alternative against the other commonly used algorithms for different PV technologies ranging from a cell (with power less than 0.1 W) to a module (with power of 120 W).

Commonly used P&O and INC methods are based on perturbation of the PV voltage under working condition with a definite voltage step (ΔV). These methods make the PV array to operate near the MPP with sustained oscillations in the operating conditions. The SCOA provides the reference voltage for an electrical converter to operate the PV module at the MPP taking physical and electrical parameters of the PV module as inputs. However, the method proposed here takes a few (V, I) data points near the OC and the SC regions to predict the MPP. The voltage at MPP is directly calculated using simple mathematics without using any SCOA. In the first stage of the algorithm, the MPP search range is narrowed and in the