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Geometrical prediction of maximum power point for photovoltaics

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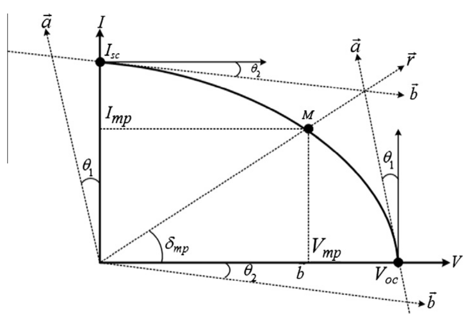
HIGHLIGHTS

- Direct MPP finding by parallelogram constructed from geometry of *I–V* curve of cell.
- Exact values of *V* and *P* at MPP obtained by Lagrangian interpolation exploration.
- Extensive use of Lagrangian interpolation for implementation of proposed method.
- Method programming on C platform with minimum computational burden.

GRAPHICAL ABSTRACT



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ABSTRACT

It is important to drive solar photovoltaic (PV) system to its utmost capacity using maximum power point (MPP) tracking algorithms. This paper presents a direct MPP prediction method for a PV system considering the geometry of the *I–V* characteristic of a solar cell and a module. In the first step, known as parallelogram exploration (PGE), the MPP is determined from a parallelogram constructed using the open circuit (OC) and the short circuit (SC) points of the *I–V* characteristic and Lagrangian interpolation. In the second step, accurate values of voltage and power at the MPP, defined as V_{mp} and P_{mp} respectively, are decided by the Lagrangian interpolation formula, known as the Lagrangian interpolation exploration (LIE). Specifically, this method works with a few (*V*, *I*) data points instead most of the MPP algorithms work with (*P*, *V*) data points. The performance of the method is examined by several PV technologies including silicon, copper indium gallium selenide (CIGS), copper zinc tin sulphide selenide (CZTSSe), organic, dye sensitized solar cell (DSSC) and organic tandem cells' data previously reported in literatures. The effectiveness of the method is tested experimentally for a few silicon cells' *I–V* characteristics considering variation in the light intensity and the temperature. At last, the method is also employed for a 10 W silicon module tested in the field. To testify the preciseness of the method, an absolute value of the derivative of power (*P*) with respect to voltage (*V*) defined as (dP/dV) is evaluated and plotted against *V*. The method estimates the MPP parameters with high accuracy for any kind of PV technologies with different environmental conditions. In future, this method proposes a guide line to construct control scheme for real-time MPPT tracking in the PV system.

1. Introduction

Contemporary reports on energy [1] have shown that present average world energy consumption increases with an annual rate of 3.5% in contrast to a slower population annual growth rate of 1.45% in the developing nations. Rapid boost in the energy consumption rate than in the population growth rate is an outcome of ever increasing life style and comforts in the modern era. This has a deep impact on the fuel price hike, depleting conventional sources of energy and swift change in the earth's environment. Thus, the present energy crisis and high energy demands in future give a momentum to develop technologies based on the alternate sources of energy such as solar PV.

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Sun's energy available in abundance, and can be directly converted into electrical energy using a solar PV cell or a module. In the solar PV system, if an electrical load is directly connected to the system, then it does not perform efficiently. To make the system to perform at its utmost capacity, an interfacing bridge between the solar PV system and the load is required that makes the solar PV system to operate always at its MPP. The bridge is an electrical circuit which continually tracks the MPP. The circuit adjusts the power flow to a maximum value either by electronically or digitally that requires an MPP algorithm.

MPP algorithms are capable of interfacing the PV module and the load during wide variation in light intensity, temperature and shading effects [2,3]. Typically used MPP algorithms [4], such as perturb and observe (P&O) and incremental conductance (IC) are very popular amongst the on-line MPP tracking algorithms. But, these algorithms suffer from a steady state oscillatory behaviour near the MPP. To increase the dynamic response and to reduce the oscillations, a variable step size tracking speed is adapted which is known as modified P&O method [5]. Kim et al. [6] developed an MPP circuit based on successive approximation register algorithm. The method performs well over the P&O technique by reducing the MPP tracking time and improved conversion efficiency. Though the P&O method is said inferior in performance, Hohm and Ropp [7] demonstrated that if P&O is properly optimized then it outperforms with an MPP efficiency of above 97% in comparison with IC and parasitic capacitor algorithms. These algorithms track MPP using trial and error attempts, but Xiao et al. [8] have demonstrated fast dynamic response and smooth steady state operation near MPP using steepest decent method. Other work by the same group [9] discusses a direct real-time MPP identification method based on a solar cell *P*–*V* characteristic solved by recursive least squares method and Newton–Raphson method.

Recently, in the classification of the off-line algorithms, a direct estimation method (DEM) [10] for the MPP has been realized based on the mathematical expression of the electrical characteristic of a solar cell and the data sheet specifications. However, the method requires the shunt resistance (R_{sh}) and the series resistance (R_{se}) of a solar cell that vary with the light intensity and the temperature. To obtain the values of R_{sh} and R_{se} is a tedious task [11,12] and additional computational burden for the MPP tracking algorithm. In one of the literatures [13] on the MPP tracking, the voltage and current at the MPP (V_{mp} and I_{mp}, respectively) are estimated separately using values of R_{se} and the diode ideality factor n. Jiang et al. [14] developed a novel method for thin film modules based on the *p*–*n* junction recombination. The method provides MPP with high accuracy under various light intensity and temperature. However, in some of these reports, R_{sh} is overlooked in the entire analysis and it is worth to note that R_{sh} plays a significant role in precise estimation of the MPP.

Classical root finding methods [15] have been also employed for tracking the MPP. Bracketed methods (Bisection and Secant) are testified better than the open bracketed methods (Regula Falsi and modified Regula Falsi). These methods fumble for the solution of the derivative of the power with respect to the voltage ($dP/dV = 0$). However, in the entire analysis, the replacement of the function dP/dV is not clear. Usually, dP/dV is fitted with 4th or 6th order polynomial function for thin film and silicon modules [16], but the order of the polynomial depends on several conditions such as light intensity, temperature, material used, etc. The orthogonal least square algorithm is employed to identify MPP on an environmentally varying polynomial PV model [17]. This algorithm is very quick but suffers from complex mathematical calculations during fitting process.

Because of the limitations of the aforementioned methods such as handling non-linear *P*–*V* relations under varying environmental conditions, a new class of MPP methods based on soft computing algorithm (SCA) is used. Several SCA [18], such as fuzzy logic, artificial neural network, genetic algorithm, particle swarm optimization (PSO), chaotic exploration, predictor technique have been brought on for the MPP tracking. MPP methods based on SCA can tackle non-linear *P*–*V* relation very efficiently and they do not require accurate mathematical models [19]. Partially shaded PV array exhibits non-linear behaviour with multiple peaks in the *P*–*V* curve. Ishaque et al. [20] utilised PSO method to achieve the global MPP under different intensities. Amongst all the SCA, the chaotic exploration is most efficient but complex while the predictor technique is simplest for finding the MPP. The SCA are slower than the conventional algorithms because of more complexity involved and large number of iterations requirement. To employ SCA for a real-time MPP tracking is tedious and expensive as the complex SCA require fast computing, ample memory allocating. Moreover, the complexity involved in computations requires complicated and costly hardware for the interface with the solar PV system and the load. Therefore, most of the SCA are actualized using simulations.

Published reviews on P&O, IC and SCA MPP methods report that each algorithms have their unique advantage, but they need physical parameters of a PV module, large voltage–current (V, I) data, complex mathematical computations. At this stage, there is a demand of an algorithm which requires a few (V, I) data and less computations. Moreover, most of the literatures describe the MPP algorithms based on the knowledge of physical parameters such as R_{sh}, R_{se} and n of the PV cell model or based on SCA demanding large execution time and iterations. This paper presents a straight forward MPP tracking method which determines direct value of V_{mp} without trial and error process and without any knowledge of the physical parameters of the cell/module. Normally, most of the MPP algorithms work with data from the *P*–*V* curve, but the proposed method requires data from the *I*–*V* curve and thereby avoiding a step of *I*–*V* data conversion into *P*–*V* data. The method works with a couple of (V, I) data points near the OC and SC regions and the geometry of the *I*–*V* characteristic of the cell. The methods were tested for several silicon cells and a module, CIGS, CZTSSe, DSSC and organic cells. This paper describes the real-time implementation of the method with block diagram. This method was further employed for silicon cells tested under different light intensities and temperatures and for a 10 W silicon module. To testify the preciseness of the method, an absolute value of the derivative of power (P) with respect to voltage (V) defined as (dP/dV) is evaluated and plotted against V.

2. Mathematical insight of the method

The estimation method presented here, requires handful (V, I) data points near V_{oc} and I_{sc} regions for MPP tracking. In the first step, the values of V_{mp} and P_{mp} are calculated from the geometry of the *I*–*V* characteristic. This step is termed as parallelogram exploration (PGE). However, the MPP calculated by PGE is in the close vicinity of the actual MPP. Consequently, in order to get the precise values of MPP, a Lagrangian interpolation is used as the second step, which is termed as Lagrangian interpolation exploration (LIE).

2.1. Parallelogram exploration

Fig. 1(a) depicts the geometry of the *I*–*V* characteristic of a typical solar cell/module. A vector $\vec{a}$ passing through the OC point V_{oc} and making tangent at V_{oc}, forms an angle θ_1 with respect to the vertical *I*-axis. Similarly, another vector $\vec{b}$ passing through the SC point I_{sc} and making tangent at I_{sc}, forms an angle θ_2 with respect