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A novel photovoltaic system control strategies for improving hill climbing algorithm efficiencies in consideration of radian and load effect

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ABSTRACT

This study proposes a novel algorithm for maximum power point tracking (MPPT) in solar-power-generating systems, and compares it with the conventional methods of hill climbing (HC). These conventional algorithms are prone to divergence under low irradiance levels ($< 150\,\mathrm{W/m^2}$), resulting in maximum power point tracking difficulties and a limited effective maximum power point tracking range; the hill climbing algorithm in particular often entraps the actuating point near an inescapable local minimum and causes divergence. The proposed algorithm uses the angle between the sun and the horizon to develop a novel maximum power point tracking technique that extends the maximum power point tracking range to $100\,\mathrm{W/m^2}$, effectively mitigating the divergence problems of the hill climbing algorithms when the irradiance level is low ($< 150\,\mathrm{W/m^2}$). The performance of the proposed algorithm was compared with that of the hill climbing algorithm at varying irradiance levels, and the experimental results confirm the superiority of the proposed algorithm.

1. Introduction

The development of renewable energy has become imperative in the twenty-first century because of global warming and various types of environmental pollution. Renewable energy sources include wind power, hydropower, geothermal energy, and solar power generation. The focus of this study, solar power, is now widely used by both companies and individuals, or applies to related systems as follows: Derrouazin et al. focus on the hybrid solar-wind-storage energy system for savings of electricity coming from the grid with this hybrid generator based on the fuzzy logic smart controller system (FLSC), as a consequence a reduction of the electrical bill [1]. Zhang et al. introduce the grid-connected photovoltaic-battery system for a method that optimizes the battery capacity as well as the rule-based operation strategy is carried out with the multi-objective genetic algorithm and it is reduced the cost of the battery [2]. And the cost of setting up solar power has gradually been decreasing. However, in contrast with the costs of traditional thermal and nuclear energy projects, solar power remains relatively expensive.

Solar energy greatly reduces environmental pollution (e.g., greenhouse gases and air pollution), but it has two major shortcomings. First, solar power output is poor on cloudy days (defined as having an irradiance level below $150\,\mathrm{W/m^2}$) [3]. Second, solar power output is dependent on climatic factors (e.g., irradiance level and temperature). Therefore, a maximum power point tracking (MPPT) controller could considerably enhance solar power efficiency.

There are many MPPT algorithms are proposed as follows: Esram et al. introduce the hill climbing (HC) algorithm with several MPPT techniques taken from the literature is discussed and analyzed herein, with their pros and cons. This study should serve as a convenient reference for future work in PV power generation [4]. Prabaharan et al. present the single phase photovoltaic (PV) based multilevel inverter with double level circuit. Separate solar panels with perturbation and observation (P&O) based MPPT technique is connected in the place of each DC source in the proposed multilevel inverter through boost converters. The proposed multilevel inverter has lesser THD and power losses when compared to the conventional CHBMLI (cascaded H-bridge multilevel inverter without double level circuit) [5]. Mutoh et al. propose the MPPT control method, the optimal current reference needed to converge the output current on the optimal operation point of the prediction line was determined by dividing $P_{pv} - I_{pv}$ characteristics into two control fields using two properties. The MPPT control method indispensable to PV generation systems, which has the ability to generate maximum output power even if weather conditions are changed [3]. Jain et al. focus on a single-stage system for PV power fed pump drive using an induction motor with open-end windings. The proposed

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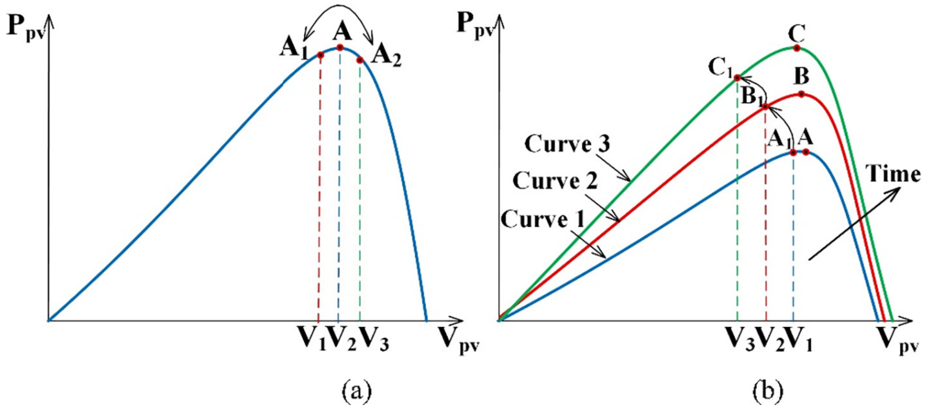

Fig. 1. $P_{pv} - V_{pv}$ characteristic curves of a photovoltaic (PV) module when the HC algorithms are used under conditions of (a) steady irradiance and (b) rapidly varying irradiance.

system is operated by an integrated control algorithm (MPPT + sample-averaged zero-sequence elimination (SAZE) pulse width modulation with V/f control). This control algorithm has the capability of maintaining the system stability even under worst environmental situations [6]. Ramyar et al. present a new method for MPPT of PV arrays under both partial shading condition (PSC) and uniform conditions. By analyzing the solar irradiance pattern and using the HC method, the proposed method tracks all local maximum power points and the accuracy of the proposed method is proved using experimental results [7]. Alajmi et al. introduce the HC search method based on fuzzy logic control (FLC) for MPPT under rapidly changing weather conditions. The proposed MPPT exhibits a faster converging speed, less oscillation around the MPP under steady-state conditions, and no divergence from the MPP during varying weather conditions [8]. Khan et al. develop a novel integrated start-stop MPPT mechanism, which aims to increase the energy harvest by eradicating steady-state oscillations of the heuristic search (HS) algorithms. The proposed algorithm shows advantages that include oscillation-free operation in steady state and ease of implementation [9]. Saravanan et al. propose the Radial Basis Function Network (RBFN) based MPPT algorithm performs better than the conventional P&O methods, as well as the modified SEPIC converter generates maximum power under variable irradiance and temperature condition compared to boost and SEPIC converter [10]. Femia et al. focus on the optimization of the P&O strategy for PV MPPT based on a parabolic prediction of the next operation point based on the last three. The proposed strategies improve P&O performances under constant and varying irradiation levels [11]. Hong et al. develop the MPPT techniques, the adaptively binary-weighted step (ABWS) and the monotonically decreased step (MDS), minimize the power loss under rapidly changing environmental conditions without an additional *ad hoc* parameter [12]. Pragallapati et al. present the adaptive velocity particle swarm optimization (AVPSO) algorithm employs adaptive particle velocity equation, in which the weight factor and the cognitive acceleration coefficient change adaptively. The AVPSO algorithm is also successfully able to alleviate the problem of particles getting trapped in local minima [13]. Ahmed et al. propose a modified P&O scheme to dynamically alter the perturbation size and dynamic boundary condition to ensure that the algorithm will not diverge from its tracking locus [14]. Farhat et al. develop the MPPT design using stable single input fuzzy logic controller (SIFLC), this controller improved the performance of the MPPTs, besides it eliminated the complexity of the classic FLC with 2 inputs and ensured the efficiency of the system by combining the advantage of both the fraction open circuit voltage (FOC) and the FLC [15]. Mahmoud et al. propose an enhanced MPPT method combining the heuristic P&O and model-based MPPT techniques. The main feature of the proposed method is it eliminates the need for temperature measurement, reducing the cost and complexity of the implementation. Moreover, it does not require an irradiance measurement. It uniquely adopts the polynomial based PV model, a recently developed model in the literature featuring reduced computational time, to reduce the computational complexity of the MPPT [16]. Femia et al. focus on the optimization approach lies in the customization of the P&O MPPT parameters to the dynamic behavior of the whole system composed by the specific converter and PV module adopted. In the design of efficient MPPT regulators, the easiness and flexibility of P&O MPPT control technique can be exploited by optimizing it according to the specific system's dynamic characteristics [17]. Chatrenour et al. introduce an improved double integral sliding mode MPPT controller (IDISMC). The IDISMC leads to accurate tracking and very small chattering magnitude and steady-state error [18]. Kim et al. propose a 1-mW solar-energy-harvesting circuit using an adaptive MPPT for wireless sensor network (WSN). To achieve a fast transient response, a small steady-state oscillation, and low-power consumption, the adaptive MPPT using a successive approximation register (SAR) and a counter was developed. The proposed MPPT circuit has high MPPT efficiency of 99.6% [19].

Numerous MPPT algorithms are available for solar energy and have been extensively investigated. The HC and P&O algorithms are the most widely used because they are simple and cost-effective. However, they have several major drawbacks; they converge slowly near the maximum power point (MPP) [8], and when the irradiance is steady, the tracked power point oscillates around the MPP and causes the system to generate less than optimal power [9]. Fig. 1(a) displays the power–voltage ($P_{pv} - V_{pv}$) characteristic curve of a PV module under steady irradiance, where Point A is the MPP. Because both algorithms exhibit perturbing characteristics, the actuating point given by MPPT tends to oscillate around the precise MPP (Point A), namely oscillating between Points A_1 and A_2 instead of remaining on Point A, thus resulting in less than maximal power output. Moreover, on cloudy days, both algorithms have difficulties performing MPPT [11]. In addition, when the irradiance varies rapidly, both algorithms are prone to divergence [12]. Fig. 1(b) displays the $P_{pv} - V_{pv}$ characteristic curves of the PV module under variable irradiance. Curves 1–3 are the characteristic curves at various irradiance levels, and the points A, B, and C are their corresponding MPPs. When the irradiance level increases quickly, the characteristic curve changes from Curve 1 to Curve 2 and then to Curve 3. During this process, the algorithms track the MPP using perturbation; hence, real-time MPPT cannot be accomplished in varying irradiance conditions. The actuating point moves from A_1 to B_1 and then C_1, resulting in the deviation of the actuating point (C_1) from the MPP of Curve 3 (Point C) and leading to divergence.

Recently developed solar MPPT algorithms include the modified HC using FLC [8], the adaptive velocity PSO algorithm [13], and the modified P&O MPPT method with reduced steady state oscillation and improved tracking efficiency [14]. Although these algorithms reduce