A high-performance MPPT algorithm combining advanced three-point weight comparison and temporary stopped running strategy for PV systems

Hwa-Dong Liu¹, and Shue-Der Lu² a)

Abstract This paper proposes a new maximum power point tracking (MPPT) control strategy, including a boost converter temporary stopped running (TSR) strategy and an advanced three-point weight comparison method (ATPWC). The proposed ATPWC was used to detect three power points of a photovoltaic (PV) module output, and a microcontroller unit (MCU) was used to calculate the slope of the three power points and to perform MPPT so as to improve the system’s conversion efficiency. The proposed method was successfully applied to an independent solar power generation system, in which the PV module was connected to a boost converter and then connected in series with an inverter to a single-phase 110Vrms output and connected to the power grid. The measured results showed that, in terms of the TSR control strategy, when the system output met a load of 110Vrms, TSR could reduce switching loss and conduction loss and result in a 10% higher overall system conversion efficiency than that of traditional control. In terms of the MPPT algorithm, actual measurements were carried out under an irradiance level of 100 W/m²–700 W/m². Versus traditional hill climbing (HC) algorithm, the efficiency of the proposed ATPWC was better.

Key words: maximum power point tracking, temporary stopped running, advanced three-point weight comparison method, photovoltaic

Classification: Power devices and circuits

1. Introduction

In the context of energy shortages and the rise of environmental protection awareness, renewable energy, dominated by solar energy and wind power, has received more attention in recent years. Currently, over 100 countries have installed ground-based or building-based PV systems. According to the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) data, the power generation capacity of PV systems installed worldwide in March 2015 expanded to 227GW and is expected to reach 500GW by the end of 2020 [1]. As a clean energy source, solar power does not emit CO₂ or cause environmental pollution. In addition, solar power generation systems make virtually no noise and PV modules have a service life of 20 years [2, 3, 4].

A PV module’s output power is, however, plagued by irradiance levels, temperature, loads, and so on, which undoubtedly impair conversion efficiency. A number of studies in the literature have addressed such problems and improved the overall conversion efficiency of a PV system [5-27]. Ahmed et al. proposed a design strategy of perturbation parameters based on the HC algorithm for PV MPPT control [5]. Femia et al. utilized the perturbation and observation (P&O) MPPT algorithm with theoretical analysis to maximize PV arrays’ output power [6]. Karami et al. reviewed the three-point weight comparison (TPWC) method [7]. Xenophontos et al. introduced a model-based analytical method for locating the maximum power point (MPP) of PV panels [8]. Kumar et al. presented a new version of P&O tracking algorithm, including self-predictive and decision taking abilities for PV maximum power extraction [9]. Al-Soeidat et al. introduced an analog. BJT-tuned voltage reference MPPT method for PV modules [10]. Kumar et al. proposed a new version of an incremental conductance algorithm for maximum power harvesting (MPH) from the PV array, which has inherent decision taking and self-adaptive ability [11]. Ahmed et al. set up an enhanced adaptive perturb and observe (EA-P&O) MPPT algorithm for the PV system [12]. Goud et al. presented a hybrid MPPT algorithm, including single current sensor hill climbing (SCHC) and artificial bee colony (ABC) algorithms for constant voltage load applications by using a single current sensor to track the MPP [13]. Yang et al. offered a novel MPPT algorithm through dynamic leader based collective intelligence (DLCI) [14]. Valenciaga et al. gave a closed-loop MPPT method based on the combination of a second order sliding mode observer (SOSMO) and a traditional PI controller [15]. Bhattacharjee et al. presented a real-time flow control integrated solar PV MPPT [16]. Lasheen et al. introduced a hybrid technique, consisting of the adaptive neuro-fuzzy inference system (ANFIS) and HC. The technique combines the advantages of the ANFIS and HC methods to increase the generated PV electrical energy [17]. Liu et al. proposed the angle between the sun and the horizon to develop a new MPPT technique [18]. Labar et al. used a new MPPT based on detection and partial shading phenomena that can permit a partial
shading detection for increasing PV output [19]. Zhang et al. presented a novel memetic reinforcement learning (MRL) based MPPT scheme for PV systems [20]. Guo et al. introduced a new MPPT method based on a modified cat swarm optimization (MCSO) to achieve MPP [21]. Mirza et al. utilized a novel MPPT technique, including adaptive cuckoo search optimization algorithm (ACSOA), general regression neural network (GRNN) with fruit fly optimization algorithm (FFOA), and dragonfly optimization algorithm (DFOA), to track the MPP [22]. Li et al. presented a current sensorless MPPT algorithm [23]. Eltamaly et al. introduced a new MPPT algorithm combining the gray wolf optimization (GWO) with two new initialization techniques for a PV system [24]. Veerapen et al. used a novel hybrid MPPT algorithm combining the particle swarm optimization (PSO) and the P&O [25]. Carrasco et al. provided a complete analog implementation of robust electronic controls the variations of duty cycle [26]. Zhang et al. proposed an MPPT scheme for keeping the capacitor voltage balance and realizing the function of constant current and voltage [27].

While there are numerous MPPT algorithms, the HC and P&O algorithms are mostly used for simple architecture and low design cost. They do have some weaknesses: firstly, in cases of a steady-state irradiance level, the algorithm is prone to vibration at the MPP point due to its disturbance characteristics, resulting in power loss [28]; secondly, under a low irradiance level (irradiance level <150W/m²), the MPPT actuation point may be trapped at a local minimum power point [29]; thirdly, in cases of fast-changing irradiance levels MPPT will diverge [30].

The disadvantage of the above methods, especially in traditional HC and P&O algorithms, is that the actuating point oscillates around the MPP during the steady state. The three-point weight comparison (TPWC) method can be used to avoid the oscillation problem and runs periodically by considering the PV voltage and output power.

Figure 1 shows the schematic diagrams of nine combinations of TPWC. Here, \( P_{pv1} \) is the first measured PV module output power, \( P_{pv2} \) is the second measured PV module output power, and \( P_{pv3} \) is the third measured PV module output power. This algorithm disturbs PV voltage and compares PV output power at three points of \( P_{pv1} \sim P_{pv3} \) characteristic curves, so as to perform MPPT. As shown in Fig. 1, when the two are positively weighted, the duty-cycle increases; on the contrary, the duty-cycle decreases when the two are negatively weighted, and the duty-cycle remains if there are one positively weighted and one negatively weighted [7]. This algorithm is different from the HC and P&O techniques, which perform MPPT by perturbation, and thus the actuation point oscillation is improved.

The ATPWC proposed herein, differing from TPWC (which uses three PV module output powers to compare positively weighted and negatively weighted and controls the variation of duty cycle), uses the slope of three PV module output powers to adjust the duty cycle. It is easier to perform MPPT, and the defect in which it is difficult for TPWC track MPP as the irradiance level changes rapidly is remedied.

Table I lists the comparisons of ATPWC with the existing 3 methods. The steady-state irradiance level’s convergence speed and the fast-changing irradiance level’s convergence speed of ATPWC are superior to the HC algorithm, P&O technique, and TPWC. Finally, the stand-alone photovoltaic power system of this study combines ATPWC with the TSR control strategy and compares it to TCS. The efficiency of the proposed control strategy is 98% when the irradiance level is 700 W/m², and the efficiency is 90% when the irradiance level is 100 W/m², which are better than TCS.

### Table I. Comparison of the MPPT techniques.

| Algorithm | Parameters’ knowledge | Complexity | Steady-state irradiance level convergence speed | Fast-changing irradiance level convergence speed |
|-----------|-----------------------|------------|-----------------------------------------------|-----------------------------------------------|
| HC [5]    | Unnecessary           | Very low   | Slow                                          | Slow                                          |
| P&O [6]   | Unnecessary           | Very low   | Slow                                          | Slow                                          |
| TPWC [7]  | Unnecessary           | Low        | Medium                                       | Slow                                          |
| ATPWC     | Unnecessary           | Low        | Rapid                                        | Rapid                                          |

2. The proposed ATPWC MPPT method and TSR control strategy

2.1 The advanced three-point weight comparison method (ATPCW)

Figure 2 presents an ATPWC flowchart. ATPWC uses MCU to measure the PV module output power \( (P_{pv1} \sim P_{pv3}) \) for the first to third times, adopts equation (1) to analyze the slope of three power points so as to identify the change of \( \Delta D \) and to determine the current required duty cycle \( D(n) \), and then compares the power between the three points to complete MPPT.
When the actuating point reaches MPP, the duty cycle $D(n)$ was therefore set to +0.01; when $a<0$ (negative slope), the value of duty cycle $D(n)$ remains, $D(n)=D(n-1)+\Delta D$.

Figure 4(a) shows when the irradiance level changes rapidly that ATPWC can judge the changes in $P_{pv}$ characteristic curves according to parameter $a$ of equation (1); the positive slope or negative slope of the actuating point is determined, $\Delta D$ is adjusted, the duty cycle is adjusted according to equation (2), and MPP is tracked rapidly. Curves A–C are the characteristic curves at fast-changing irradiance levels, and points A, B, and C are their corresponding MPPs. When the irradiance level increases quickly, the characteristic curve changes from Curve A to Curve B and then to Curve C. The actuating point also moves from A to B and then to C.

Figure 4(b) shows the $P_{pv}$ characteristic curves of the PV module under fast-changing irradiance levels. Traditional HC and P&O algorithms track MPP using perturbation, and so MPP cannot be tracked instantly. Curves A–C are the characteristic curves at fast-changing irradiance levels, and points A, B, and C are their corresponding MPPs. When the irradiance level increases quickly, the characteristic curve changes from Curve A to Curve B and then to Curve C. The actuating point moves from A1 to B1 and then to C1, thus deviating the actuating point (C1) from MPP of Curve 3 (Point C) and leading to divergence [30].

2.2 Temporary Stop Running (TSR) Control Strategy

In order to improve the conversion efficiency of a PV power generation system, the proposed TSR control strategy was employed to reduce boost converter switching and conduction losses. As shown in Fig. 5, in order to introduce the proposed TSR into an independent solar power generation system, the PV module was connected to a boost converter and connected to an inverter in series, and 110VAC/60Hz power was provided to the load ($R_s$) through the LC filter. The proposed ATPWC used MCU to detect the trend of the three power points’ output by the PV module and further calculated the MPP and duty cycle to drive the boost converter to execute MPPT. The TSR control strategy could reduce the switching loss and conduction loss of the boost converter, thereby improving system efficiency, which reached 98% through actual measurement.
To avoid any MOSFET switching loss, this paper proposes TSR (as shown in Fig. 7). In the case of \( t_1 \sim t_3 \), \( t_3 \sim t_5 \), and \( t_5 \sim t_7 \), boost converter \( S_i \) cannot operate, indicating that boost converter output voltage \( V_o \) meets the requirement of a 110Vrms load; at the same time, inverters \( S_1 \sim S_3 \) run continuously, outputting 110Vrms/60Hz of power. This control strategy reduces \( S_i \) switching loss and conduction loss, reduces MCU control complexity, and also improves system efficiency.

Figure 8 shows an example of the solar power generation system with a TSR control strategy during \( t_3 \sim t_5 \) in Fig. 7. The voltage of capacitor \( C_1 \) is \( V_o=155\text{Vdc} \), and the boost converter \( S_i \) stops working (OFF). Fig. 8(a) presents that during Fig. 7 \( t_1 \sim t_4 \), the inverter \( S_3 \), \( S_5 \) ON, boost \( S_i \), and inverter \( S_3 \), \( S_5 \) OFF, \( V_{ac} \) delivers positive half wave AC power supply; Fig. 8(b) shows during Fig. 7 \( t_4 \sim t_5 \) that the inverter \( S_3 \), \( S_5 \) ON, boost \( S_i \), and inverter \( S_3 \), \( S_5 \) OFF, \( V_{ac} \) delivers negative half wave AC power supply. The TSR control strategy can reduce the switching and conduction losses of boost converter \( S_i \), thus increasing system efficiency.

3. Experimental result
3.1 Experimental data
The solar module used in this research was a Shell SP 75, and a single PV module with \( I_{pv}-V_{pv} \) characteristic curves is shown in Fig. 9 [32]. When the irradiance level was 1000W/m² and the temperature was 25 °C - that is, standard test conditions (STC) - the specifications of the single PV module were the same as those of the 12 solar modules used in this research (four series connections and three parallel connections), and the overall detailed specifications are shown in Table II. The specifications of the related power electronic components of the PV system architecture are shown in Table III.
3.2 Experimental system structure

Figure 10 shows the overall system physical architecture, including 12 PV modules, boost converter, inverter, filter (L2, L3, C2), MCU, load Rs, power supply, power harmonic meter, oscilloscope, and other measurement equipment.

3.3 Measured results of boost converter ATPWC MPPT

This paper applied the proposed method to an actual solar power generation field and measured ATPWC and compared it with a traditional HC technique in the irradiance level range of 100 W/m²~700 W/m². Here, $P_{pv1}$, $P_{pv2}$, and $P_{pv3}$ were measured by ATPWC, respectively. Parameter $a$ was calculated based on equation (1), and $\Delta D$ of duty cycle $D(n)$ was calculated so as to stably execute MPPT at MPP. Fig. 11 shows the measured result of ATPWC with an irradiance level of 100 W/m²~700 W/m² and a temperature of 25 °C. When the irradiance level was above 600W/m², the MPPT efficiency could reach 99%, and when the irradiance level was below 100 W/m², the MPPT efficiency could reach at least 95%. The measured ATPWC efficiency is therefore better than the HC technique.

3.4 Measured results of introducing the proposed control strategy into an independent solar power generation system

The irradiance level in this experiment was in the range of 100 W/m²~700 W/m². The proposed ATPWC MPPT algorithm and TSR control strategy were compared with the traditional control strategy (TCS). The results showed that in terms of TSR, when the output voltage $V_o$ of the boost converter was 155Vdc, inverters $S_1$–$S_2$ would run continuously, providing 110Vrms/60Hz of power. This control strategy reduces the $S_1$ switching loss and conduction loss of the boost converter, reduces the complexity of MCU control, and improves system efficiency. Fig. 12 shows that when the irradiance level was at 700 W/m², TSR efficiency could reach 98%, and when the irradiance level was at 100 W/m², TSR was better than TCS by 10%.

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**Table II. PV module output characteristic specifications.**

| Item                  | Specifications                                      | Elements | Specification |
|-----------------------|-----------------------------------------------------|----------|---------------|
| 1 Open-circuit voltage $V_{oc}$ | 21.7V                                               | 12 PV Modules | 900W          |
| 2 Short-circuit current $I_{sc}$ | 4.8A                                               | Inductor $L_2$ | 1mH           |
| 3 Maximum power voltage $V_{mp}$ | 17V                                               | Inductor $L_2$ | 18mH          |
| 4 Maximum power current $I_{mp}$ | 4.4A                                               | Inductor $L_3$ | 2.2mH         |
| 5 Maximum power $P_{max}$ | 75W                                               | Capacitor $C_1$ | 330uF        |
| 6 Capacitor $C_2$ | 50uF                                               | Load Rs | 100Ω          |

**Table III. Specifications for the power electronic components of an independent solar power generation system.**

| Item                  | Elements                                      | Specification |
|-----------------------|-----------------------------------------------|---------------|
| 1 Optical couplers 1 and 2 | Vishay (model number PC817) | 12 PV Modules | 900W          |
| 2 Current transducer | Lem (model number LASS5F) | Inductor $L_2$ | 1mH           |
| 3 Power MOSFETs $S_1$–$S_3$ | APT (model number APT5024BVFR) | Inductor $L_2$ | 18mH          |
| 4 Diode | Vishay (model number HA25TB60) | Inductor $L_3$ | 2.2mH         |
| 5 Gate driver 1 | Toshiba (model number TLP250) | Capacitor $C_1$ | 330uF        |
| 6 Gate driver 2 and 3 | Infineon (model number IR2110) | Capacitor $C_2$ | 50uF         |
| 7 MCU | Microchip (model number 18F452) | Load Rs | 100Ω          |
4. Conclusions

This research has proposed and successfully applied ATPWC and TSR to an independent solar power generation system. As shown by the measured results, the proposed methods were superior to traditional HC algorithm and TCS. For MPPT, the efficiency of ATPWC could reach 99% when the irradiance level was over 600W/m² and could reach 95% when the irradiance level was low (100 W/m²), which was better than HC by 10%. For TSR, the efficiency could reach 98% when the irradiance level was 700 W/m² and reach 90% when the irradiance level was 100 W/m², which was better than TCS by 10%. This experiment verified in an independent solar power generation system that the conversion efficiency of the overall power generation system could be improved through the proposed method. In future research, battery charging technology can be introduced to explore the efficiency of the proposed method under a shade environment in order to apply the system to various harsh weather environments.

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