A novel MPPT algorithm considering solar photovoltaic modules and load characteristics for a single stage standalone solar photovoltaic system

Hwa-Dong Liu¹, Chang-Hua Lin¹, and Shiue-Der Lu² a)

Abstract This paper proposes a novel maximum power point tracking (MPPT) algorithm that is combined with the advanced three-point weight comparison method (ATPWC) and MPPT limit detect (LD) mechanism and applied to a single stage standalone solar photovoltaic system. The boost converter is connected to the inverter and filter to deliver single-phase AC 110VAC/60Hz to the load. The MPPT LD detects when the system does not need MPPT based on the solar photovoltaic module’s (SPV module) $R_p$ and load $R_l$. In addition, this study performs actual measurements for validation, in which the proposed algorithm is used in the built single-stage standalone solar photovoltaic system and compared with the ATPWC, three-point weight comparison method (TPWC), and conventional perturbation and observation (P&O) for MPPT efficiency. The result shows that the proposed algorithm is better than the other three algorithms. When the system is under a heavy load ($R_p > R_l$), the overall system efficiency is $80\%$, while the efficiency under a non-heavy load ($R_p \leq R_l$) is $99\%$.

Key words: MPPT limit detect, advanced three-point weight comparison method, single stage standalone solar photovoltaic system

Classification: Power devices and circuits

1. Introduction

In recent years, as energy shortages and environmental considerations have risen increasingly, attention has been increasingly paid to renewable energy, especially solar photovoltaic systems (SPV systems), which are free of noise [1], have a service life of 20 years [2], and do not emit CO$_2$, which induces the greenhouse effect [3]. According to the report by the International Energy Agency Photovoltaic Power System Programme (IEA PVPS) in April 2019, the total power generating capacity of solar photovoltaic (SPV) systems in the world has exceeded 500 GW up to 2019 [4].

However, the major defect in solar power generation is that the output power and efficiency of the SPV module decrease significantly under the effect of temperature, irradiance level, shading, and load factors. Therefore, many studies have been aimed at the development of MPPT, so as to increase the overall system efficiency [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19].

Kumar et al. proposed the conventional P&O, which was applied to solar power generation through related theoretical analysis [5]. Wang et al. used the classical TPWC in the MPPT of a photovoltaic power system [6]. Ozturk et al. developed the direct digital synthesis (DDS) MPPT control technique for a miniature converter in a photovoltaic power system [7]. Sangwongwanich et al. proposed the CPG control strategy, which is based on the power control method (P-CPG), the current limitation method (I-CPG), and P&O (P&O-CPG) [8]. Liu et al. proposed an advanced three-point weight comparison method for photovoltaic power systems [9]. Li et al. used a novel overall distribution (OD) MPPT algorithm to search out the maximum power point rapidly and accurately [10]. Saravanan et al. implemented the Radial Basis Function Network (RBFN) MPPT technology, which was combined with a SEPIC power converter for a photovoltaic power system [11]. Chatrenour et al. proposed the double integral sliding mode MPPT controller (IDISMC), which can track the maximum power point accurately and improve the actuation point oscillation amplitude and reduce steady-state errors [12]. Liu et al. discussed PV systems at a low irradiance level and improved the poor MPPT efficiency of the conventional hill climbing method [13]. Hashemzadeh connected multiple photovoltaic panels in series and used a nonlinear equation to work out the maximum power and voltage so as to perform MPPT [14]. Bahrami et al. studied TPWC and fuzzy control technology to accelerate MPPT [15]. Venkataramanan et al. proposed the SPV voltage control system design so as to increase the efficiency of MPPT [16]. Rezkallah et al. used active power control (APC) to increase the MPPT efficiency of a photovoltaic power system [17]. Shukla et al. proposed improving the MPPT time of conventional P&O technology and showed there was no divergence in the environment with variable irradiance levels [18]. Carrasco et al. used a simple multiplier circuit to estimate the MPPT PWM duty cycle and implemented it in a photovoltaic power system MPPT [19].

There are numerous maximum power tracking methods for SPV systems. The conventional P&O method is frequently used due to its simple architecture, low cost, and lack of high-level control chips or complex program operations. However, the algorithm has two significant
defects. First of all, at a fixed irradiance level, the actuation point of the algorithm oscillates nearby the maximum power point, leading to low system efficiency [20]. In addition, P&O uses perturbation for MPPT. At fast-changing irradiance levels, the method cannot remain at the maximum power point, resulting in divergence and power loss [21]. Another common method is TPWC, in which the SPV module delivers three sets of power continuously to compare the weight and MPPT is performed to reduce the MPPT actuation point perturbation problem and avoid unnecessary system power loss. Therefore, TPWC is better than conventional P&O. However, TPWC fails to perform MPPT instantly when the sunshine amount changes rapidly. In order to solve this problem, the TPWC optimization control strategy has been proposed to improve the MPPT efficiency and convergence time at fixed and fast-changing irradiance levels [9].

Based on the theoretical analysis and actual measurement of a single stage standalone SPV system, the findings of this study show that conventional MPPT is not always operated at the maximum power point when the irradiance level is uniform, which is mainly due to the power electronic boost converter characteristic. Therefore, this study proposes an MPPT algorithm combined with ATPWC and MPPT LD, in which the proposed algorithm is embedded in the boost converter and the inverter and output filter are connected in series for actual measurement. The actual measurement validates that the proposed single stage standalone SPV system has high efficiency and is applicable to the power needs for people's livelihoods.

2. Single stage standalone SPV system specification

2.1 Solar photovoltaic module specification

The solar photovoltaic (SPV) module used in this study is SP 75, made by Shell Corp. [22]. The single SPV module $I_{pv}\cdot V_{pv}$ characteristic curves are shown in Fig. 1. This study uses 12 SPV modules, as shown in Fig. 2. Under standard test conditions (irradiance level 1000 W/m², temperature 25°C), the maximum power is 900W, the maximum power voltage is 68V, and the maximum power current is 13.2A. The total number ($n$) of SPV modules used in this study is 12 and is expressed as Eq. (1):

$$n = \frac{P_{mp}}{P_{mp}} = \frac{900}{75} = 12$$

$P_{mp}$ is the output maximum power of the 12 SPV modules, and $P_{mp}$ is the output maximum power of one single SPV module.

The number of SPV modules in series ($n_s$) is four and is expressed as Eq. (2):

$$n_s = \frac{V_{mp}}{V_{mp}} = \frac{68}{17} = 4$$

$V_{mp}$ is the output maximum voltage of the 12 SPV modules, and $V_{mp}$ is the output maximum voltage of one single SPV module.

The number of SPV modules in parallel ($n_p$) is three and is expressed as Eq. (3):

$$n_p = \frac{I_{mp}}{I_{mp}} = \frac{13.2}{4.4} = 3$$

$I_{mp}$ is the output maximum current of the 12 SPV modules, and $I_{mp}$ is the output maximum current of one single SPV module.

![Fig. 1. $I_{pv}\cdot V_{pv}$ characteristic curves for a single SPV module (Shell, model number SP 75): (a) Irradiance level of 1000 W/m², temperatures from 0°C to 70°C; (b) Temperature of 25°C, irradiance levels from 100 W/m² to 1,000 W/m².](image)

![Fig. 2. Stereogram of the SPV modules (12) in this study.](image)

![Fig. 3. Circuit diagram of the proposed single stage standalone SPV system.](image)
Figure 3 shows the architecture diagram of the proposed single stage standalone SPV system, in which 12 SPV modules are connected to the boost converter and the inverter and LC-filter converts the DC power into AC power (110VAC/60Hz). The system uses an MCU to control the boost converter and inverter, the boost converter $S_1$ switching frequency is 30 kHz, and the $S_2$-$S_3$ inverter switching frequency is 60 Hz.

![Architecture Diagram](image)

**Fig. 3.** Architecture diagram of the proposed single stage standalone SPV system.

Figure 4 shows the stereogram of the proposed single stage standalone SPV system, including the boost converter, inverter, filter ($L_2$, $L_3$, $C_2$), MCU, and load $R_o$. The hardware specifications of the single stage standalone SPV system are shown in Table I.

![Stereogram](image)

**Fig. 4.** Stereogram of the proposed single stage standalone SPV system.

### Table I. Hardware specifications of the single stage standalone SPV system.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load $R_c$</td>
<td>15Ω</td>
</tr>
<tr>
<td>Inductor $L_1$</td>
<td>1mH</td>
</tr>
<tr>
<td>Inductor $L_2$</td>
<td>18mH</td>
</tr>
<tr>
<td>Inductor $L_3$</td>
<td>2.2mH</td>
</tr>
<tr>
<td>Capacitor $C_1$</td>
<td>330uF</td>
</tr>
<tr>
<td>Capacitor $C_2$</td>
<td>50uF</td>
</tr>
<tr>
<td>MCU</td>
<td>Brand: Microchip, P/N: 18F452</td>
</tr>
<tr>
<td>Power MOSFETs $S_1$-$S_3$</td>
<td>Brand: APT, P/N: APT5024BVFR</td>
</tr>
<tr>
<td>Diode</td>
<td>Brand: Vishay, P/N: HFA25TB60</td>
</tr>
</tbody>
</table>

**3. Proposed system control strategy**

#### 3.1 Boost converter and SPV MPPT control analysis

The SPV module mostly delivers low voltage, therefore, the system generally uses a boost converter to boost the system voltage and reduce the number of required SPV modules. In addition, the boost converter can boost the voltage without a transformer but one power MOSFET, thus giving high efficiency [23, 24, 25, 26, 27, 28, 29, 30, 31]. Therefore, this study uses a boost converter as the main architecture.

Figure 5 shows the SPV module connected to the boost converter and to load $R_o$. The boost converter architecture comprises inductor $L_i$, diode $D$, power MOSFET $S_o$, and capacitor $C_i$. The MCU executes the maximum power algorithm and delivers the PWM duty cycle to drive the power MOSFET $S_1$ to perform MPPT.

![Schematic Diagram](image)

**Fig. 5.** Schematic diagram of the SPV module connected to the boost converter and load $R_o$.

The $V_o$-$V_{pv}$ relationship and $I_o$-$I_{pv}$ relationship of the boost converter are expressed as Eq. (4) and Eq. (5), respectively:

$$V_o = \left(1 - \frac{1}{D}\right) \cdot V_{pv}$$  \hspace{1cm} (4)

$$I_o = (1 - D) \cdot I_{pv}$$  \hspace{1cm} (5)

According to $R_o=V_o/I_o$ and $R_{pv}=V_{pv}/I_{pv}$, Eq. (4) and (5) are expressed as:

$$R_o = \left(1 - \frac{1}{D}\right) \cdot R_{pv}$$  \hspace{1cm} (6)

The relationship of $D$, $R_o$ and $R_{pv}$ in the PWM duty cycle can be derived from Eq. (6) and expressed as Eq. (7):

$$D = 1 - \sqrt{\frac{R_{pv}}{R_o}} \cdot \frac{1}{R_o}$$  \hspace{1cm} (7)

According to Eq. (7), $R_{pv} \leq R_o$, D range is 0~1, and the MPPT can be performed; on the contrary, when $R_{pv} > R_o$, D will be negative, thus failing the peak power control. Therefore, for the boost converter + maximum power algorithm, when $R_{pv} > R_o$, the MPPT is invalid. In order to solve this problem, this study proposes a boost converter MPPT limitation strategy, which is described in Section 3.2

#### 3.2 Boost converter MPPT limitation description

Table II shows the relationship between a single SPV module $R_{pv}$ and the $R_{pv}$ for the 12 SPV modules (four in series and three in parallel) at a temperature of 25°C and an irradiance level of 100W/m²~1000W/m² transformed from the $I_{pv}$-$V_{pv}$ characteristic curves for a single SPV module, as shown in Fig. 1:

<table>
<thead>
<tr>
<th>Irradiance level (W/m²)</th>
<th>A single SPV module $R_{pv}$ (Ω)</th>
<th>12 SPV modules (four in series and three in parallel) $R_{pv}$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>38.6</td>
<td>51.46</td>
</tr>
<tr>
<td>200</td>
<td>19.3</td>
<td>25.7</td>
</tr>
<tr>
<td>300</td>
<td>12.8</td>
<td>17</td>
</tr>
<tr>
<td>400</td>
<td>9.7</td>
<td>12.93</td>
</tr>
<tr>
<td>500</td>
<td>7.73</td>
<td>10.3</td>
</tr>
<tr>
<td>600</td>
<td>6.44</td>
<td>8.58</td>
</tr>
<tr>
<td>700</td>
<td>5.52</td>
<td>7.36</td>
</tr>
<tr>
<td>800</td>
<td>4.83</td>
<td>6.44</td>
</tr>
<tr>
<td>900</td>
<td>4.29</td>
<td>5.72</td>
</tr>
<tr>
<td>1000</td>
<td>3.86</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Figure 6 is drawn according to the data in Table II and
shows the relation curve of the irradiance level and the 12 SPV modules (four in series and three in parallel). However, this study uses a boost converter. According to Eq. (7), when \( R_{pv} > R_o \), MPPT is ineffective, which is to say, the MPPT controller is not required. Therefore, when \( R_{pv} > R_o \), MPPT is unnecessary; on the contrary, when \( R_{pv} \leq R_o \), MPPT is necessary.

### Fig. 6. Schematic diagram of the relationship between the \( R_{pv} \) for the 12 SPV modules (four in series and three in parallel) and load \( R_o \) at an irradiance level of 100W/m\(^2\)~1000W/m\(^2\).

#### 3.3 Proposed MPPT algorithm and boost converter

Figure 6 shows the relationship of an irradiance level of 100W/m\(^2\)~1000W/m\(^2\) to the \( R_{pv} \) of the 12 SPV modules (four in series and three in parallel) and load \( R_o \). In order to avoid unnecessary loss from an ineffective MPPT when \( R_{pv} > R_o \), the ATPWC must be modified as shown in Fig. 7.

![Fig. 7. The flowchart of ATPWC.](image)

The proposed algorithm flowchart is given in Fig. 8. Three consecutive sets of power (\( P_{pv1} \sim P_{pv3} \)) from the SPV module are detected first, and then parameter \( a \) is confirmed according to Eq. (8) and the correct \( \Delta D \) is selected. If parameter \( a \) is positive, \( \Delta D = 0.01 \); on the contrary, if parameter \( a \) is negative, \( \Delta D = -0.01 \). If parameter \( a \) is 0, \( \Delta D = 0 \) and duty cycle \( D(n) \) is adjusted according to Eq. (9), so as to perform MPPT and reach the maximum power point.

\[
P_{pv}(t) = a \cdot t + b \tag{8}
\]

\[
D(n)=D(n-1)+\Delta D \tag{9}
\]

The blue frame in Fig. 8 shows the MPPT limit detect (LD) decision strategy proposed in this study compared to the original ATPWC algorithm as shown in Fig. 7. Referring to the relationship between Eq. (7) and Fig. 6, when the MPPT LD detects \( R_{pv} \leq R_o \), MPPT is performed to reach the MPP; on the contrary, when MPPT LD detects \( R_{pv} > R_o \), MPPT is invalid, so MPPT stops. When the MCU output duty cycle \( D(n)=0 \), the unnecessary operation of the boost converter power MOSFET \( S_1 \) (Fig. 3) can be prevented, so as to increase the system efficiency.

### Fig. 8. The flowchart of proposed algorithm.

#### 3.4 Proposed single stage standalone SPV system

Figure 9 shows the operation mode of the boost converter, inverter, and filter of the single stage standalone SPV system. Fig. 9(a) shows that the boost converter delivers 155Vdc, inverters \( S_2 \) and \( S_3 \) work, and the filter delivers 110Vrms/60Hz positive half wave AC power. Fig. 9(b) shows that the boost converter delivers 155Vdc, inverters \( S_4 \) and \( S_5 \) work, and the filter delivers 110Vrms/60Hz negative half wave AC power.
4. Experimental result

The proposed algorithm is compared with ATPWC, TPWC and conventional P&O for MPPT by actual measurement. In addition, the proposed single stage standalone SPV system is measured, and the system can be used for civil power utilization.

4.1 MPPT measurement result of the proposed algorithm

The single-stage standalone SPV system architecture for this experiment is shown in Fig. 3, in which load $R_{sc}=15\Omega$. The actual measurement is performed at a temperature of 25°C and an irradiance level of 200 W/m², 300 W/m², 400 W/m², 500 W/m², 600 W/m², 700 W/m² and 800 W/m², respectively. The proposed algorithm is compared with ATPWC, TPWC, and conventional P&O. The experimental results are shown in Fig. 10 and Table III.

![Fig. 9. Proposed single stage standalone SPV system: (a) boost $S_1$, ON, inverter $S_2$, $S_3$, ON, and inverter $S_4$, $S_5$, OFF; (b) boost $S_1$, ON, inverter $S_2$, $S_3$, ON, and inverter $S_4$, $S_5$, OFF.](image)

**Fig. 9.** Proposed single stage standalone SPV system: (a) boost $S_1$, ON, inverter $S_2$, $S_3$, ON, and inverter $S_4$, $S_5$, OFF; (b) boost $S_1$, ON, inverter $S_2$, $S_3$, ON, and inverter $S_4$, $S_5$, OFF.

**Fig. 10.** Comparison of measured MPPT efficiency between the proposed method, ATPWC, TPWC, and conventional P&O techniques.

**Table III.** Actual measurement results of the MPPT efficiency of the four algorithms.

<table>
<thead>
<tr>
<th>Irradiance level (W/m²)</th>
<th>Proposed</th>
<th>ATPWC</th>
<th>TPWC</th>
<th>P&amp;O</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>80%</td>
<td>50%</td>
<td>35%</td>
<td>30%</td>
</tr>
<tr>
<td>300</td>
<td>80%</td>
<td>55%</td>
<td>52%</td>
<td>50%</td>
</tr>
<tr>
<td>400</td>
<td>99%</td>
<td>99%</td>
<td>96%</td>
<td>95%</td>
</tr>
<tr>
<td>500</td>
<td>99%</td>
<td>99%</td>
<td>97%</td>
<td>97%</td>
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<tr>
<td>600</td>
<td>99%</td>
<td>99%</td>
<td>98%</td>
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<tr>
<td>700</td>
<td>99%</td>
<td>99%</td>
<td>98%</td>
<td>98%</td>
</tr>
<tr>
<td>800</td>
<td>99%</td>
<td>99%</td>
<td>99%</td>
<td>99%</td>
</tr>
</tbody>
</table>

As shown in Table III, the efficiency of the proposed algorithm is higher than 80% when the irradiance level is 200 W/m²-300 W/m², which much better than the other three algorithms, because when the irradiance level is 200 W/m²-300 W/m², $R_{pv} > R_{sc}$, the proposed algorithm activates MPPT LD (Fig. 8), and the MPPT stops running. The other three algorithms perform MPPT continuously, the power is lost, and the system efficiency is reduced. Moreover, the efficiency of the proposed algorithm is higher than 99% when the irradiance level is 400 W/m²-800 W/m².

Table IV compares the proposed algorithm with ATPWC, TPWC, and conventional P&O for algorithm complexity, applicability to the boost converter, $R_{pv} > R_{sc}$ efficiency, and $R_{pv} \leq R_{sc}$ efficiency. The proposed algorithm has better applicability to the boost converter and $R_{pv} > R_{sc}$ efficiency than the other three algorithms.

**Table IV.** Comparison of the four MPPT algorithms.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Complexity</th>
<th>Applicable or not</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&amp;O [5]</td>
<td>Very low</td>
<td>Not</td>
<td>30% 95%</td>
</tr>
<tr>
<td>TPWC [7]</td>
<td>Low</td>
<td>Not</td>
<td>35% 96%</td>
</tr>
<tr>
<td>ATPWC [9]</td>
<td>Low</td>
<td>Not</td>
<td>50% 99%</td>
</tr>
<tr>
<td>Proposed</td>
<td>Low</td>
<td>Applicable</td>
<td>80% 99%</td>
</tr>
</tbody>
</table>

The proposed algorithm can greatly increase the efficiency of a single-stage standalone SPV system under a heavy load ($R_{pv} > R_{sc}$), has the advantage of ATPWC, and has high efficiency when $R_{pv} \leq R_{sc}$. Although many studies have been focused on the efficiency of MPPT, the important issue of the MPPT algorithm must match with power converter is still lacking. Therefore, the proposed algorithm compared to previous exiting studies has not only has high efficiency (up to 99%) in light load ($R_{pv} \leq R_{sc}$) but also the efficiency of MPPT has greatly improved to 80% in heavy load ($R_{pv} > R_{sc}$) when the power converter is added MPPT LD. As shown in Table IV.

4.2 Measurement result of the proposed single stage standalone SPV system

In order to validate the proposed single-stage standalone SPV system (Fig. 3) for civil power utilization, the system output is connected to a household electric fan and the output voltage and current are measured, as shown in Fig. 11 and Fig. 12.

![Fig. 11.](image)

**Fig. 11.** Measured voltage $V_{ac}$ of an electric fan connected to a single-stage standalone SPV system: (a) voltage waveform; (b) voltage harmonics.

Figure 11 shows the voltage $V_{ac}$ of an electric fan connected to a single-stage standalone SPV system, Fig. 11(a) shows the measured voltage waveform, and Fig. 11(b) shows the measured voltage harmonics. This system can supply a steady voltage and excellent power quality.


