A maximum power point tracking strategy applied to building integrated photovoltaics

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Abstract

To solve the problem of permanent-shadow shading of photovoltaic buildings, a maximum power point tracking (MPPT) strategy to determine the search range by pre-delimiting area is proposed to improve MPPT efficiency. The single correspondence between the solar-cell current–voltage (I–V) curve and the illumination conditions was proved by using the single-diode model of photovoltaic cells, thus proving that a change in the illumination conditions corresponds to a unique maximum power point (MPP) search area. According to the approximate relationship between MPP voltage, current and open-circuit voltage and short-circuit current of a photovoltaic module, the voltage region where the MPP is located is determined and the global maximum power point is determined using the power operating triangle strategy in this region. Simulation carried out in MATLAB proves the correctness and feasibility of the theoretical research. Simulation results show that the MPPT strategy proposed in this paper can improve the average efficiency by 1.125% when applied in series as building integrated photovoltaics.

Graphical Abstract

Keywords: photovoltaic power generation; MPPT efficiency; buildings integrated photovoltaic; permanent shadow
**Introduction**

Light curtailment and the long cost-recovery time for photovoltaic power plants in China will result because the transmission of power to load centres in east China will be limited due to transmission costs. Therefore, it is urgent to solve the consumption problem of photovoltaic generation [1–3].

Actually, the consumption problem is hard to solve due to the contradiction between load centres concentrating in the city and the high cost of urban land. This problem is solved to an extent by proposing building integrated photovoltaics (BIPV), which is the integrated planning, design, manufacturing, installation and use of photovoltaic systems in buildings [4]. BIPV buildings not only consume energy, but also produce energy; thus, the traditional functions and meanings of buildings are changed essentially [5]. Cost savings, environmental protection and emission reduction can be achieved by BIPV. However, maximum power production from photovoltaics may be difficult to achieve because of permanent shadowing caused by adjacent buildings [6].

Mismatch losses caused by permanent partial shading can significantly reduce the output power of photovoltaic arrays [7,8], including those used in BIPV [9]. Some studies about partial-shading conditions have been carried out in an attempt to solve this problem [10–12], such as a novel methodology for the detection of partial-shading conditions in photovoltaic arrays [13] and different configuration characteristics under various patterns of shading [14]. There are also many studies about maximum power point tracking (MPPT) to solve power reduction under partial shading.

According to the permanent-shadow direction of movement in BIPV buildings, an arrangement mode of photovoltaic modules associated with the direction of the shadow movement is designed in [15]. This method designs an arrangement of photovoltaic modules according to the direction of shadow movement, so that modules in the same series can be distributed in the same illumination conditions and mismatch phenomena can be avoided effectively; as a result, power-generation effectiveness will be improved. But a more complex arrangement will be required when the shadow conditions are complex. High costs will result because more MPPT modules need to be used to achieve the maximum power. Distributing MPPT and centralizing inverters is adopted in [16] by dividing the BIPV system into many photovoltaic direct current (DC) building modules, distributing MPPT to every module and coupling MPPT modules with inverters using a DC bus. Independent control is achieved by designing a coordinated control strategy based on energy conservation for distributing MPPT and centralizing inverters, and feasibility has been proved by prototype experiment. This scheme starts from the topology and control strategy to maximize the power-generation potential of a BIPV system. But the disadvantage is that distributing MPPT will increase the application cost of the system, and the control strategy based on energy conservation will bring errors when there are many MPPT modules in a BIPV system. Based on the characteristics of a string array, an efficient MPPT algorithm has been proposed in [17]. A novel trapezoidal area called a maximum power trapezium containing all possible MPPs has been defined in [17] and the global maximum power point (GMPP) can be tracked using the maximum power trapezium as well as information about the minimum voltage difference between adjacent local peaks under shadow. Simulation and experimental results show the superior performance of the algorithm. But an adequate minimum sampling frequency needs to be defined in order to avoid skipping any possible power peak in this scheme. Literature [18] has analysed the MPPs of various photovoltaic array configurations containing 250–500 modules based on measured irradiance shadows. The characteristics of GMPP voltages have been analysed for the first time using ~8000 measured irradiance transitions. Literature [19] presents comparative analyses of two proposed GMPP tracking schemes and simulations of these two MPPT algorithms are carried out to compare their tracking time and voltage track. Literature [20] studied the behaviour of GMPP for photovoltaic strings under partial shading by measuring current–voltage (I–V) curves. An experimental study of MPP characteristics under shadow, based on >26 000 measured I–V curves, is proposed in [21]. The MPP closest to the nominal MPP voltage for photovoltaic strings is studied for the first time in [21] and the results of this study are particularly relevant for MPPT schemes when both the efficiency and the power quality of photovoltaic plants are required. All of the above studies have achieved superior performance for MPPT algorithms, but there are still some improvements for an MPPT scheme applied to BIPV.

Especially, a power operating triangle (POT) MPPT strategy has been proposed in [22] in which the POT is determined by voltage and current values, and updated by comparing them with power values. After updating, the search voltage range of the GMPP is reduced continuously, and the MPPT is realized by the disturbance and observation in the determined voltage range. This method is not only simple and efficient, but also can realize global MPPT quickly, and a low application cost as well as high MPPT efficiency can be realized at the same time. However, it can only be used in environments of >0°C due to the cut-off conditions of the strategy. Because of the working principle of the strategy, it is inevitable that large voltage overshoots will occur when the temperature is high, causing power loss.

Aiming to further improve the efficiency of BIPV, an MPPT strategy that employs a define-in-advance search area has been proposed in this paper specifically applied to BIPV. The I–V characteristic in permanent shadow is analysed first in this paper and the one-to-one correspondence between the area of the I–V curve where the GMPP is located and illumination conditions is proved. According to the permanent-shadow characteristics of BIPV buildings, a subregion MPPT strategy based on POT
has been designed and a simulation experiment is carried out in MATLAB. Setting the POT strategy as the control experiment, the feasibility and correctness of the designed strategy are demonstrated finally.

1 I–V characteristics in permanent shadow

The BIPV shadow can be roughly classified into two categories: temporary shadow and permanent shadow. Temporary shadow includes occlusion caused by clouds and birds, for example. This kind of shadow is characterized by randomness and short temporal effects. Permanent shadow is mainly caused by adjacent buildings. This type of shadow has the characteristics of a large occlusion area, with long duration but regularity and predictability. Compared with temporary shadow, permanent shadow has a more significant impact on the photovoltaic generation system [15]. Consequently, an MPPT control strategy based on the POT strategy used to solve the problem of the decrease in BIPV generation efficiency due to permanent shadow is proposed in this paper according to analysis of the I–V curve of the photovoltaic generation system in permanent shadow.

A single-diode model of a photovoltaic cell is shown in Fig. 1 [6]. According to this model, the photovoltaic cell output current I is

\[ I = I_{PV} - I_0 \left[ \exp \left( \frac{U + IR_s}{V_T} \right) - 1 \right] - \left( \frac{U + IR_s}{R_p} \right) \]  

(1)

where \( V_T = \frac{kT}{q} \), \( I_{PV} = \frac{G}{G_{STC}} (I_{PV, STC} + K_i \Delta T) \), with \( I_{PV} \) denoting the light-generated current, \( I_0 \) denoting the diode reverse saturation current, \( U \) denoting the output voltage of the photovoltaic cell, \( R_s \) denoting the series resistance, \( R_p \) denoting the parallel resistance, \( N \) denoting the diode identify factor, \( k \) denoting Boltzmann’s constant, \( T \) denoting the temperature, \( q \) denoting the quantity of electric charge, \( G \) denoting the illumination at a given time, \( G_{STC} \) denoting the illumination in the standard test conditions (STC, irradiation: 1000 W/m², spectrum: 1.5 A, cell temperature: 25°C), \( I_{PV, STC} \) denoting \( I_{PV} \) in the STC, \( K_i \) denoting the short-circuit current temperature coefficient, \( \Delta T = T - T_{STC} \) and \( T_{STC} \) denoting T in the STC. Ignoring \( R_s \) and \( R_p \), then Equation (1) can be written as

\[ I = I_{PV} - I_0 \left[ \exp \left( \frac{U}{V_T} \right) - 1 \right] \]  

(2)

Setting the voltage at MPP as \( U_{MP} \) and the power as \( P_{MP} \), then

\[ P_{MP} = U_{MP} I_{PV} - U_{MP} I_0 \left[ \exp \left( \frac{U_{MP}}{V_T} \right) - 1 \right] \]  

(3)

Differentiating by \( U_{MP} \) in Equation (3) gives

\[ \frac{dP_{MP}}{dU_{MP}} = I_{PV} - I_0 \left[ \frac{U_{MP}}{V_T} \left( 1 + \frac{U_{MP}}{V_T} \right) - 1 \right] \]  

(4)

The derivative is zero at MPP and thus

\[ I_{PV} - I_0 \left[ \frac{U_{MP}}{V_T} \left( 1 + \frac{U_{MP}}{V_T} \right) - 1 \right] = 0 \]  

(5)

Solving Equation (5), then

\[ U_{MP} = V_T \cdot \text{Lambertw} \left[ 0, \left( \frac{I_{PV}}{I_0} + 1 \right) \right] \]  

(6)

The Lambertw function, also called the omega function, is the inverse function of \( f(W) = We^W \). From Equation (6), the \( U_{MP} \) of photovoltaic cells is only related to illumination when \( T \) is constant. That is, for a certain photovoltaic series, the number of ‘steps’ and its distribution of I–V curves correspond to the illumination one by one.

Permanent shadows change throughout a day with the height and angle of the Sun. That is, for the walls of BIPV buildings, the shadow area changes with the height angle of the Sun throughout the day and the corresponding I–V curve will change. Taking a photovoltaic string having \( n \) modules as an example, the ‘step’ current will appear in the I–V curve when the series is influenced by the shadow caused by adjacent buildings, and the position and height of the ‘step’ will change with the movement of the shadow.

Consider a BIPV project established in Beijing, China, by CHN ENERGY Investment Group Co., Ltd, as shown in Fig. 2, for a photovoltaic string in a BIPV building; assuming that there are \( m \) modules outside of shadow at a certain time and \( m \) at another time, then the I–V curve is shown in Fig. 3.

Different global MPP \( GMPP \), and \( GMPP \), result because photovoltaic modules in the shadow area are different.

![Fig. 1: Single-diode model of a photovoltaic cell.](image)

![Fig. 2: Appearance of a BIPV project.](image)
according to the illumination conditions PSC₁ and PSC₂. To further improve the GMPP search efficiency under shadow conditions, the area in which GMPP is located can be pre-determined by analysing the I–V curve, where GMPP can be determined in this area using the POT strategy, which is introduced in [22] in detail.

2 MPPT strategy applied to BIPV

Assuming that the illumination is G₁ at a certain time and G₂ in the shadow area, there are m photovoltaic modules outside of shadow area, and the I–V curve is shown in Fig. 4. According to Equation (7) and the approximate relationship between U_MPP and I_MPP [6], P₁ and P₂ can be obtained as Equations (8) and (9), respectively:

\[ P_{MPP} = U_{MPP} \cdot I_{MPP} \]  
\[ P_1 = 0.8mU_{OC} \cdot 0.9I_{SC1} \]  
\[ P_2 = 0.8nU_{OC} \cdot 0.9I_{SC2} \]

Then

\[ I_{SC1} = \frac{G_1}{G_2} I_{SC2} \]  

\[ P_1 = 0.72mU_{OC}I_{SC} \]  
\[ P_2 = 0.72nU_{OC}I_{SC} \]

Let P₁ = P₂, then

\[ 0.72mU_{OC}I_{SC} = 0.72nU_{OC}I_{SC} \]

Solving Equation (13), then

\[ m = \frac{nG_2}{G_1} \]

Thus, when m > nG₂/G₁, P₁ > P₂, GMPP locates in P₁ and the MPPT search area is determined as [0, mUOC]; and when m < nG₂/G₁, P₁ < P₂, GMPP locates in P₂ and the MPPT search area is determined as [mUOC, nUOC].

For permanent shading, the shadow area is basically fixed at a certain time in 1 year [23]. The variable m can therefore be obtained by counting the shadow region.

3 Simulation research

To verify the correctness and feasibility of the theory, simulation is carried out in MATLAB/Simulink. Setting the illumination at 1000 W/m², the series module n is 6 in terms of the BIPV project. According to the MPPT strategy applied to

| Items | Parameters |
|-------|------------|
| Maximum power (W) | 231.15 |
| U_{OC} (V) | 36.3 |
| U_{MPP} (V) | 29 |
| I_{SC1} (A) | 7.84 |
| I_{SC2} (A) | 7.35 |

![Fig. 3: I–V characteristic curve in partial-shading conditions.](image1)

![Fig. 4: I–V characteristic curve in G₁, G₂.](image2)

![Fig. 5: P–V curve when m = 1.](image3)
the permanent shadow proposed here, the shadow region at the current moment, namely the value of \( m \), should be determined first, then \( G_2/G_1 \) takes the value of 0.5 when the illumination is 1000 W/m\(^2\) in light of [6].

Choosing 1Soltech 1STH-215P photovoltaic modules in MATLAB/Simulink (operation parameters shown in Table 1) to constitute a 6 \( \times \) 1 photovoltaic string, the strategy proposed in this paper is adopted to achieve MPPT at \( m = 1 \) and \( m = 5 \), respectively, taking the POT strategy as the control experiment, and the simulation results are shown in Figs 5–12 as well as Table 2.

When \( m = 1 \), adopting the POT strategy to achieve MPPT, then \( U_{\text{ref}} \) at MPP can be obtained as 194.2 V, differing by 6 V from the theoretical value, calculating \( \delta \% \) of \( U_{\text{ref}} \) as 1.96\%, and the MPPT efficiency is 93.64\%; when the strategy proposed in this paper is adopted, then \( U_{\text{ref}} \) at MPP can be obtained as 196.1 V, differing by 3.9 V from the theoretical value, calculating \( \delta \% \) of \( U_{\text{ref}} \) as 4.33\%, and the MPPT efficiency is 95.21\%. Comparing the above simulations, when \( m = 1 \), i.e. GMPP locates in \( P_2 \), then the strategy proposed in this paper can determine GMPP more exactly compared with the POT strategy and
the error is only 3.9 V; although δ% is slightly higher than in the POT strategy, it is still within the design scope and the MPPT efficiency is improved by 1.57% compared with the POT strategy.

When \( m = 5 \), adopting the POT strategy to achieve MPPT, then \( U_{\text{ref}} \) at MPP can be obtained as 160.9 V, differing by 0.3 V from the theoretical value, calculating \( \delta \% \) of \( U_{\text{ref}} \) as 23.06%, and the MPPT efficiency is 94.07%; when the strategy proposed in this paper is adopted, then \( U_{\text{ref}} \) at MPP can be obtained as 161.7 V, differing by 1.1 V from the theoretical value, calculating \( \delta \% \) of \( U_{\text{ref}} \) as 7.61%, and the

MPPT efficiency is 94.75%. Comparing the above simulations, when \( m = 5 \), i.e. GMPP locates in \( P_1 \), then the error of the strategy proposed in this paper is larger than that of the POT strategy by 0.8 V, but this is acceptable because the MPPT step is 3 V; the \( \delta \% \) of the strategy proposed in this paper is obviously less than that of the POT strategy, restraining overshoot of the voltage response effectively and decreasing the power lost. The MPPT efficiency is improved by 0.68% when the strategy proposed in this paper is adopted.

To sum up, GMPP can be determined more exactly and the efficiency can be improved more obviously by the MPPT strategy proposed in this paper when illumination is weak, i.e. when the photovoltaic system power is small; when illumination is strong, i.e. when the photovoltaic system power is large, the tracking error is slightly larger than that of the POT strategy when the strategy proposed in this paper is adopted, but the error is within one-third of the MPPT step; therefore, it is also acceptable. In this example, the difference between the cut-off conditions of the strategy proposed in this paper and those of the POT strategy is small when GMPP is in \( P_1 \); therefore, the efficiency improvement is not obvious in weak illumination, but overshoot of \( U_{\text{ref}} \) can be restrained more obviously by the strategy proposed in this paper in this illumination condition. Therefore, overshoot of the voltage response can be further decreased and power loss reduced.
Table 2: Simulation result of MPPT in permanent shadow

| Index | \( m = 1 \) | \( m = 5 \) |
|-------|-------------|-------------|
| \( U_{ref}/V \) | 194.2 | 160.9 |
| \( \Delta U_{ref}/V \) | –6 | 0.3 |
| \( \text{Max. } U_{ref}/V \) | 198 | 198 |
| \( \delta \% \) | 1.96% | 23.06% |
| \( H \) | 93.64% | 94.07% |

4 Conclusion
An MPPT strategy that uses a define-in-advance search scope has been designed in this paper according to the permanent-shadow characteristics experienced by BIPV buildings. The search scope of GMPP is divided into two different regions via theoretical calculations; then, the region in which GMPP is located can be determined and GMPP can be found in this region by using the POT strategy. On the basis of a computer simulation, the global MPPT strategy designed in this paper can achieve average efficiency improvement by 1.125% for photovoltaic strings. Furthermore, both the error and the overshoot are acceptable, and it is more adaptive to Copper Indium Gallium Diselenide thin-film photovoltaic modules because one of its main advantages is to maintain high efficiency under weak illumination.

Conflict of interest statement
None declared.

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