Abstract—Photovoltaic (PV) power has been successfully applied for over three decades. PV cell provides power for systems in many applications on earth and space. PV cell exhibits nonlinear voltage-current characteristics and its maximum power point varies with solar illumination and ambient temperature. With the development of power electronics technology, it is now possible to operate photovoltaic system with its maximum power point (MPP) in order to increase the overall system efficiency. This paper presents a novel algorithm for maximum power point tracking in PV systems based on the optimal gradient method. The algorithm can track maximum power point quickly and accurately. In this paper, the method of optimal gradient for maximum power point tracking (MPPT) is deduced, and the algorithm has been verified based on simulation results in Matlab. The simulation shows the novel algorithm significantly improves the efficiency during the tracking phase compared with a conventional algorithm. The novel algorithm is especially suitable for fast changing environmental conditions. The proposed algorithm can be implemented on any fast controller such as the digital signal processor.

Keywords—photovoltaic generation; maximum power point tracking (MPPT); the optimal gradient method; simulation

1. INTRODUCTION

With the quick development of society, the rapid trend of industrialization of nations and increased interest in environmental issues has led recently to consideration of the use of renewable forms such as solar energy. Solar energy is a clean, a maintenance-free, and an abundant source of energy. Photovoltaic (PV) arrays produce electric power directly from sunlight. In fact, together with the continuing decline in the world’s conventional sources of energy, implies a promising role for PV power-generation systems in the near future. In recent years, as it is an environmentally renewable energy source, grid-connected photovoltaic generation has gained increased importance, due to advantages such as the absence of air pollution and fossil-fuel consumption as well as no noise and low maintenance resulting from the absence of moving parts. Additionally, in grid-connected applications the energy demand from the grid is not big, which shaves the peak load demand [1]. With the advent of silicon P-N junction during the 1950s, the photoelectric current was able to produce power due to the inherent voltage drop across the junction [2]. This produces the well-known nonlinear relationship between the current and voltage of the photovoltaic cell. Because PV arrays have nonlinear power sources by nature, their power output varies with depending mainly on the level of solar radiation and ambient temperature corresponding to a specific weather condition.

From the nonlinear relationship between the current and the voltage of PV cell, it can be observed that there is an unique maximum power point at a particular environment, and this peak power point keeps changing with solar illumination and ambient temperature [3]. This peak power point is the so-called maximum power point. An important consideration in achieving high efficiency in PV power systems is to match the PV source and load impedance properly for any weather conditions, thus obtaining maximum power generation. The technique is called maximum power point tracking (MPPT). Because of the nonlinear voltage-current characteristics of PV cells, the power versus voltage (P–V) curve in solar cells has more complicated nonlinear relationship when solar illumination and ambient temperature change, so the MPP is difficult to solve analytically, and therefore numerous techniques have been proposed to realize MPPT. Several approaches have been devised for tracking MPP accurately for PV cells. Some of the popular methods are the constant voltage method, the perturb-and-observe (or hill-climbing) method, the incremental conductance method, and so on. At last, these algorithms modify the actual voltage in order to increase the power output.

It can be observed that the MPP is in the neighborhood of a constant when solar illumination is changing and temperature’s change is omitted. So the MPP’s voltage \( V_m \) can be designed to be constant. This is the constant voltage tracking (CVT) [4]. This method is very simple and can be easy implemented. But the constant voltage can’t track MPP when solar illumination changes, so the constant voltage method is not often used in the true MPPT strategy. The perturb-and-observe method (P&O) is based on the principle of perturbation and observation [5]. Small perturbations are introduced in the system in order to vary the operating point such that the maximum power point is achieved. However, this method has several drawbacks such as slow tracking speed and oscillations about MPP, making it less favorable for rapidly changing environmental conditions. The incremental conductance (IncCond) method is based on the fact that the slope of the PV array power curve is zero at the MPP, positive on the left of the MPP, and negative on the right [6]. By
derivation, it can be gained the relationship between the instantaneous conductance ($I/V$) and the incremental conductance ($\Delta I/\Delta V$). The MPP can be tracked by comparing $I/V$ to $\Delta I/\Delta V$. It can be supposed that $V_{ref}$ equals to $V_{app}$ at the MPP. Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in $\Delta T$ is noted. The algorithm decrements or increments $V_{ref}$ to track the new MPP when atmospheric conditions change.

It must be pointed out that all the conventional tracking methods use fixed, small iteration steps, determined by the accuracy and tracking speed requirements. If the step-size is increased to speed up the tracking, the accuracy of tracking suffers and vice versa. To overcome above limitation, the optimal gradient method is applied in MPPT of photovoltaic (PV) generation in this paper. The proposed scheme offers the fast MPPT and accurate MPP over the existing schemes.

II. CHARACTERISTIC OF PHOTOVOLTAIC CELL

Photovoltaic cells consist of a silicon P-N junction that when exposed to light releases electrons around a closed electrical circuit. From this premise the circuit equivalent of a cell can be modeled through the circuit shown in Fig. 1. Electrons from the cell are excited to higher energy levels when a collision with a photon occurs. These electrons are free to move across the junction and create a current. This is modeled by the light generated current source ($I_{ph}$). The intrinsic P-N junction characteristic is introduced as a diode in the circuit equivalent [7].

![Figure 1. Photovoltaic cell equivalent circuit](image)

The photo current $I_{ph}$ generated in the PV cell is proportional to level of solar illumination. $I$ is the output current of photovoltaic cell. The current ($I_d$) through the bypass diode varies with the junction voltage $V_j$ and the cell reverse saturation current $I_0$. $V$ is the output of the photovoltaic cell. $R_{sh}$ and $R_s$ are the parallel and series resistances, respectively. Parallel resistance $R_{sh}$ is very large while the series resistance $R_s$ is small. There are relevant mathematical equations expressing as following:

$$I = I_{ph} - I_0 \left( e^{q(V_j+IR_s)/nkT} - 1 \right) \frac{V + IR}{R_{sh}}$$  \hspace{1cm} (1)

$$I_{ph} = I_{sc} \left( \frac{S}{1000} \right) + C_r (T - T_{ref})$$  \hspace{1cm} (2)

Where $I_{ph} = I_{sc} \frac{T}{T_{ref}} \left( e^{qE_v/2nkT} - 1 \right)$, $q = 1.6022 \times 10^{-19} C$ is the electronic charge, $n$ is the emission coefficient of diodes, $k = 1.3807 \times 10^{-23} JK^{-1}$ is Boltzmann’s constant, $T$ is ambient temperature in Kelvin, and $T_{ref}$ is reference absolute temperature. $I_{sc}$ is the short current, $S$ is the level of solar illumination, $E_v$ is the energy of the band gap for silicon which is (1–3) eV, $C_r$ is the short-circuit-current temperature coefficient (≈0.0016A/K), $I_{rev}$ is the reverse current of diode.

Generally, a PV module comprises of a number of PV cells connected in either series or parallel. And From equation (1), it is known that $S$ and $T$ are variables. Change in these variables cause the current-voltage ($I/V$) curves of photovoltaic module to change as well. As illustrated in Fig. 2, where $S$ symbolizes the solar illumination, $S$ variation from 200W/m² to 1000W/m² is reported, and temperature $T$ is constant $20^\circ$C. Besides the solar illumination, another important factor influencing the characteristics of a photovoltaic module is ambient temperature, as shown in Fig. 3, where the solar illumination is constant 1000W/m², and temperature $T$ is changing from 20°C to 100°C.

![Figure 2. Simulate current-voltage curves of PV module influenced by solar illumination](image)

![Figure 3. Simulated current-voltage curves of PV module influenced by temperature](image)
constant 20°C, as shown in Fig. 4, and the characteristic of output power changes with the ambient temperature’s variation when the solar illumination is constant 1000W/m², as shown in Fig. 5.

Supposed n-dimensional function \( f : E^n \) in Euclid space, and function \( f \) is successive and differentiable, so there is a n-dimensional row vector \( \nabla f(x) \), \( \nabla f(x) \) is defined as gradient and as follow:

\[
\nabla f(x) = \left[ \frac{df}{dx_1}, \frac{df}{dx_2}, ..., \frac{df}{dx_n} \right]^T
\]

Defined a n-dimensional column vector \( g(X) = \nabla f(x)^T \), in order to expression’s convenience, define \( g_k = g(x_k) = \nabla f(x_k)^T \), the iteration algorithm of the optimal gradient can be defined as follow:

\[
X_{k+1} = X_k + \alpha_k g_k
\]

Where \( \alpha_k \) is a non-negative constant, searching maximum of P-V characteristic curve is towards to direction of the positive gradient \( g_k \). From the characteristic of PV cell, if the series resistance is omitted, it can be obtained the relationship between power and voltage as follow:

\[
P(V) = V(I_{ph} - I_{0}(e^{\eta V/R_a} - 1)) - \frac{V}{R_s}
\]

Where function \( P(V) \) is a nonlinear function, this function is successive and has one order differentiable, and \( V \) is an unique variant in function \( P(V) \). Now \( g_k \) is as follow:

\[
g_k = \frac{dP(V_k)}{dV} \bigg|_{V=V_k}
\]

Equation (8) is shown as follow:

\[
\frac{dP(V_k + \alpha_k g_k)}{d\alpha_k} = 0
\]

According to equation (7), the iteration algorithm can write as follows:

\[
V_{k+1} = V_k + \alpha_k g_k
\]

\( \alpha_k \) can be calculated through equation (8).

In the P-V characteristic curve, it can find that voltage has boundary, so MPPT of PV cell based on the optimal gradient method search MPP which is in global region.

In the MPPT by using the optimal gradient method, there are several steps as follows:

1) Initial point \( V_0 \), allowable errors \( \epsilon \) and \( \eta (\epsilon > 0, \eta > 0) \) are given, make number of step \( k \) is zero;
2) The gradient of objective function \( P(V) \) is calculated when \( V \) is equal to \( V_k \);
3) If \( \|V P(V_k)\| \leq \epsilon \), then calculation is stopped, the optimal voltage \( V \) is \( V_k \), else executing step 4;
4) Start from \( V_k \), doing 1-dimensional searching along the direction of the gradient, and solve the best step \( (\alpha_k) \);
5) Solving \( V_{k+1} = V_k + \alpha_k \nabla P(V_k) \);
6) If \( P(V_{k+1}) - P(V_k) \leq \eta \), then calculation is stopped, the optimal voltage \( V = V_{k+1} \), else \( k = k+1 \), return to step 2.
IV. SIMULATION OF THE MPPT BASED ON OPTIMAL
GRADIENT METHOD

In order to verify the optimal gradient method proposed in this paper, simulation has been performed in Matlab/Simulink software. When the solar illumination changes from 400W/m² to 1000W/m², MPP of CVT is constant, and MPPs of the P&O method are shown in Fig. 6, and MPPs of the optimal gradient method are shown in Fig. 7. All kinds of MPPT methods’ power-voltage curves shown in can be seen in Fig. 8.

Fig. 6 shows that there is a vibration between two MPP points by using P&O method, this kind of swing can’t realize MPPT because two points swing lead to power’s swing and can’t stop at MPP when the solar illumination is unchangeable. Fig. 7 shows that the optimal gradient can achieve MPP and spends a few steps when the solar illumination changes. Compare with the Fig. 6 and Fig. 7, the optimal gradient method can fast reach MPP. In Fig. 8, it shows that the output power of PV with the optimal gradient method is more than that of PV with the P&O and the CVT. The CVT can’t track MPP while ambient circumstance changes because its MPP is constant.

V. CONCLUSION

The optimal gradient algorithm is used for tracking of the maximum power point in PV systems is proposed in this paper. The simulation results show the new algorithm brings the operating point very close to the actual MPP with a few iterations compared with conventional tracking methods such as P&O. The CVT method needs to adjust MPP to track the real MPP. Compared with conventional methods, the new algorithm proposed in this paper is quite efficient during the transient tracking phase, and is especially suitable for fast changing environmental conditions. The scheme is quite robust and can be implemented on any fast controller such as the DSP.

REFERENCES