A Rapid MPPT Algorithm Based on the Research of Solar Cell's Diode Factor and Reverse Saturation Current

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Abstract: - An efficient Maximum Power Point Tracking (MPPT) algorithm is important to increase the output efficiency of a photovoltaic (PV) generate system. The conventional method have some problems in that it is impossible to quickly acquire the generation power at the maximum power (MP) point, i.e., the efficiency of electric power generation is very low, and the amount of electric power generated by solar cell is always changing with weather conditions. Normally, the different solar cells have different diode factor (n) and reverse saturation current (Io). Theoretical and simulative results show that the approximately linear relationship exists between the optimal output current and the short-circuit current, and if the weather conditions are sameness, a piece of solar cell have same photocurrent under different diode factor n and reverse saturation current Io conditions. A new combined perturb and observe (PO) method is described in order to acquire the actual diode factor and reverse saturation current. This paper describes a rapid maximum power point tracking method which is based on the actual n and Io. An expiatory program is applied to acquire the actual maximum power point. The correctness and validity of expiatory coefficients is verified through simulation. The simulation results verified the correctness and validity of MPPT algorithm.

Key-Words: - Maximum Power Point Tracking (MPPT), Renewable energy, Photovoltaic (PV) system, Diode factor, Reverse saturation current, Photocurrent

1 Introduction

Renewable energy sources, such as solar, wind, biomass, etc., are desirable for electrical power generate due to their unlimited existence and environmental friendly nature [1]. PV technology has been developed rapidly over the last two decades from a small-scale, specialist industry supplying the U.S. space program to a broadly based global activity [2]. Studies on PV generate systems are actively being promoted in order to mitigate environmental issues such as the green house effect and air pollution [3-4]. In developing nations, the PV generate system is expected to play an important role in total electrical energy demand, and solar photovoltaic energy has gained a lot of attention because it is renewable, friendly to the environment, and flexible for installation. And more and more specialist of China realized the fundamentality of PV generate systems. A photovoltaic generate system consists of a number of solar cells depending on the required power, voltage and current ratings, and the solar cell price is decreasing. But a photovoltaic generate system still requires expensive initial investments. In order to extract as much energy as possible from a PV system, it is important to have an efficient Maximum Power Point Tracking algorithm.

Many MPPT algorithms and control schemes of PV generate system have been proposed in the literature [1-10], i.e., a cost-effective single-stage control scheme is proposed in the literature[1], it proposes a cost-effective single-stage inverter with maximum power point tracking (MPPT) in combination with one-cycle control (OCC) for photovoltaic power generation. A comparative study of the maximum power point trackers using a switching-frequency modulation scheme (SFMS) for photovoltaic panels is presented [2]. Method of locating the maximum power point (MPP) is based on injecting a small-signal sinusoidal perturbation into the switching frequency of the converter and comparing the ac component and the average value of the panel's terminal voltage. The linearity method is a novel method in order to track the maximum power point [3-4], the proportionality coefficient of the prediction line is automatically corrected using the hill-climbing method when the panel temperature of the solar arrays is changed. The incremental conductance (IC) method is proposed in the literature [5], which is based on the Incremental Conductance method but does not require any current sensing devices. The perturbation and observation (PO) method is well known as the hill-climbing method, it has been widely used because of its simple feedback structure and fewer measured parameters. A digital hill-climbing control strategy combined with a bidirectional current mode power cell is presented which allows getting a regulated bus voltage topology [6]. A simple method which combines a discrete time control and a PI compensator is proposed [7], the object of this paper is to investigate the maximum power tracking algorithms which were often used to compare the tracking efficiencies for the system operating under different controls. The constant voltage (CV) and perturbation and observation (PO) method are very common, a cost-effective two-method MPPT control scheme is proposed in this paper to track the maximum power point (MPP) at both low and high irradiation, by combining a Constant Voltage (CV) method and a modified PO algorithm [8]. The fuzzy methods are described in the literature [9-12] that focus on the nonlinear characteristics of solar cell. A power management system is presented [13], which allows for maximum exploitation of the solar energy. Although, various methods of MPPT control have been proposed in existing literature, but the power generate efficiency is relative low, and the amount of electric power generated by solar arrays is always changing with weather conditions. Different solar panel have different diode factor (n) and reverse saturation current (Io). So they are impossible to quickly acquire the generate power at the maximum power point (MPP). The essential reason is the unknown values of n and Io. The theoretical and simulative results show that not only the optimal output current and short-circuit current have an approximate linear relationship at a constant temperature. But also if the weather conditions are sameness, a piece of solar cell have same photocurrent under different diode factor n and reverse saturation current Io conditions. The conclusion is very important to acquire the actual diode factor and reverse saturation current.

In this paper, first, ttheoretical and simulative results show that a piece of solar cell have same photocurrent under different diode factor n and reverse saturation current Io conditions, and a novel combined perturb and observe (PO) method is described in order to acquire the actual n and Io. Next, the approximately linear relationship exists between the optimal output current and the short-circuit current is described. Finally, an expiatory program is applied to acquire the actual maximum power point, and a rapid maximum power point tracking method is described which is based on the actual n and Io. The simulative results verified the correctness and validity of MPPT algorithm.

2 Principle analyzing and modeling of solar cell

2.1 Solar cell modeling

Various modelling of solar cell have been proposed in the literature [3-10]. The output current I and output voltage V of solar cell is given by (1) and (2) using the symbols in Fig. 1, i.e.,

$$I = Iph - Id - Vd / Rsh \quad (1)$$

$$V = Vd - RsI \quad (2)$$

$$Id = Io[\exp(\frac{qVd}{nkT}) - 1] \quad (3)$$

here Iph is the photocurrent (in amperes), Io is the reverse saturation current (in amperes), Id is the average current through diode (in amperes), n is the diode factor, q is the electron charge (in coulombs), $q = 1.6 \times 10^{-19} C$, k is Boltzmann's constant (in joules per Kelvin), $k = 1.38 \times 10^{-23} J / K$, and T is the solar arrays panel temperature (in Kelvin). Rs is the intrinsic series resistance of the solar cell. Normally, the value of Rs is very small (in milliohm). Rsh is the equivalent shunt resistance of the solar array, and the value is very large (in kilo-ohm). In general, the output current of solar cell is expressed by

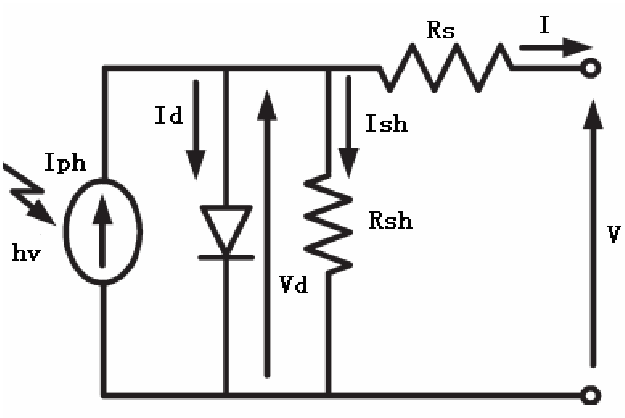


Fig.1, Equivalent circuit for solar cell

$$I = Iph - Io[\exp\{\frac{q}{nkT}(V + RsI)\} - 1] - \frac{V + RsI}{Rsh} \quad (4)$$

Where the resistances Rs and Rsh can generally be neglected, and (4) is simplified to (5).

$$I = Iph - Io[\exp\{\frac{q}{nkT}(V)\} - 1] \quad (5)$$

If the circuit is opened, the output current $I = 0$, and the open-circuit voltage Voc is expressed by

$$Voc = V\max = \frac{nkT}{q} In(\frac{Iph}{Io} + 1) \approx \frac{nkT}{q} In(\frac{Iph}{Io}) \quad (6)$$

If the circuit is shorted, the output voltage $V = 0$, the average current through diode Id is generally be neglected, and the short-circuit current $Isc = I$ is expressed by using (7). The relationship exists between short-circuit current Isc and photocurrent Iph by using (8).

$$I = Iph - \frac{RsI}{Rsh} \quad (7)$$

$$I = Isc = Iph/(1 + \frac{Rs}{Rsh}) \approx Iph \quad (8)$$

Finally, the output power P is expressed by (9)

$$\begin{aligned} P &= IV = (Iph - Id - Vd/Rsh)V = (Iph - Id)V \\ &= (Iph - Io\{\exp[\frac{q}{nkT}(V)] - 1\})V \end{aligned} \quad (9)$$

$$\begin{aligned} P\max = Iph\{&Voc - \frac{nkT}{q} In(1 + \frac{qVmppt}{nkT}) - \frac{Voc}{qVmppt(nkT)} \\ &+ (\frac{nkT}{q})^2 \frac{1}{Vmppt} In(1 + \frac{qVmppt}{nkT})\} \end{aligned} \quad (10)$$

Here P and V are the instantaneous output power and output voltage of solar cell, respectively. The condition of the maximum power point is $\partial P/\partial V = 0$. The maximum power $P\max$ is expressed by (10). Here $P\max$ and $Vmppt$ are the maximum output power and optimal output voltage at the time, respectively.

$$Isc = Isc(25^o C, 1KW/m^2) \times S/1000 \quad (11)$$

$$\begin{aligned} Iph(25^o C, 1KW/m^2) &= Isc(25^o C, 1KW/m^2) \\ &\times (1 + Rs/Rsh) \approx Isc(25^o C, 1KW/m^2) \end{aligned} \quad (12)$$

$$\begin{aligned} Iph &= Iph(25^o C, 1KW/m^2) \times [1 + Ki \times (T - Tr)] \\ &\times (1 + Rs/Rsh) \times Sj/1000 \end{aligned} \quad (13)$$

$$S = \frac{Iph \times 1000}{Iph(25^o C, 1KW/m^2) \times [1 + Ki \times (T - Tr)] \times (1 + Rs/Rsh)} \quad (14)$$

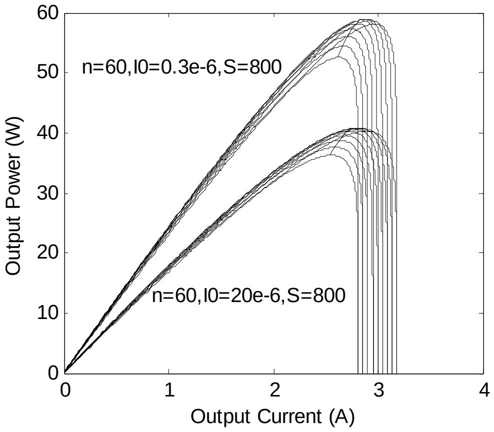
$$\mathrm{Im}\, ppt = Iph[1 - \exp((Vmppt - Voc)\frac{q}{nkT})] \quad (15)$$

Various parameters affect the output power, i.e., two intrinsic resistances, the temperature, the irradiation, the diode factor and the reverse saturation current. Firstly, Rs is very small (mΩ), and Rsh is very large (in kilo-ohm). The effect of two intrinsic resistances is ignored under ideal condition. The values of two intrinsic resistances are the unknown constants. Secondly, the important factors are temperature and irradiation. The short-circuit current Isc and the open-circuit voltage Voc of solar cell are always changing with the temperature and irradiation. If the temperature is changeable, the changing coefficient Kv of Voc is $(-0.37 - -0.4\%)/^o C$ at solar panel temperature $25^o C$, the changing coefficient Ki of Isc is $(+0.09 - +0.1\%)/^o C$ at solar panel temperature $25^o C$, where, Tr are $25^o C$ (in Kelvin). If the irradiation is changeable, the short-circuit current Isc is expressed by using (11) at temperature $25^o C$. Here $Isc(25^o C, 1KW/m^2)$ is the short-circuit current at solar panel temperature $25^o C$, and the irradiation is $1KW/m^2$. The relationship exists between short-circuit current $Isc(25^o C, 1KW/m^2)$ and photocurrent $Iph(25^o C, 1KW/m^2)$ is expressed by using (12) at solar panel temperature $25^o C$, and the irradiation is $1KW/m^2$. The photocurrent Iph is expressed by using (13) with the temperature and irradiation changing. Thus, using (6) and (13), the open-circuit voltage Voc is evaluation. Thirdly, the diode factor n and reverse saturation current Io affect the output power. The n and Io are the unknown constant. Although different solar cells have different n and Io, a piece of solar cell's n and Io is same. Normally, the n exists between 40 and 110, and the Io exists between 0.2 μA and 500 μA. If the value of n and Io are known, the method is easy to acquire a piece of solar cell's maximum output power. The effect of n and Io are analysed in this paper. The irradiation S is expressed (14) as a function of Iph. The optimal output current is given by (15) as a function of the optimal output voltage $Vmppt$ using circuit parameters q, n, k, T.

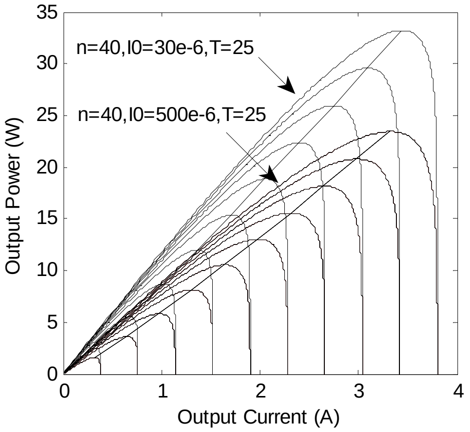
2.2 Relationship of n, Io and Iph

For example, the open-circuit voltage Voc and short-circuit current Isc, which were measured at irradiation $1KW/m^2$ and temperature 25^oC, are $22V$ and $3.8A$, respectively. The changing coefficient Ki of Isc and the changing coefficient Kv of Voc were measured, are 0.001 and -0.004, respectively. Fig. 2 shows P−I characteristics and $P\max$ curve of solar cell, the data are calculated by using above values under the same n and different Io conditions. Fig.2 (a) shows the maximum power curve at same irradiation and different temperature, Fig.2 (b) shows the maximum power curve at same temperature and different irradiation.

If the irradiation is $800W/m^2$, and the temperature is changing from -50^oC to 75^oC, under same diode factor n and different reverse saturation current Io conditions, Fig. 2 (a) shows that the photocurrent Iph is same under same temperature conditions, and the output power is increasing with the Io decreasing from 500 μA to 0.2 μA. If the temperature is 25^oC, and the irradiation is changing from $100W/m^2$ to $1KW/m^2$, under same diode factor n and different reverse saturation current Io conditions, Fig. 2 (b) shows that the photocurrent Iph is same under same irradiation conditions, and the output power is increasing with the Io decreasing from500 μA to 0.2 μA.



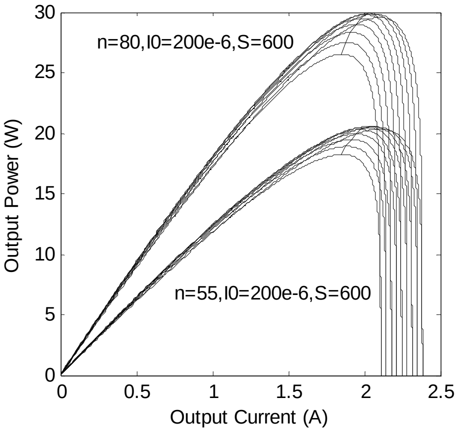
(a)



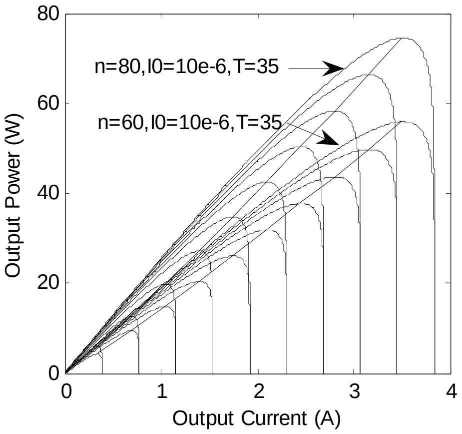
(b)

Fig.2 Calculated P-I characteristics and $P\max$ curve under the same n and different Io conditions. (a) The irradiation S is $800W/m^2$, and the temperature is changing from -50^oC to 75^oC. (b) The irradiation is changing from $100W/m^2$ to $1KW/m^2$ at the temperature 25^oC.

If the irradiation is $600W/m^2$, and the solar panel temperature is changing from -50^oC to 75^oC, under same Io and different n conditions, Fig.3 (a) shows that the photocurrent Iph is same under same temperature conditions and the output power is increasing with the n increasing from 40 to 110. If the irradiation is changing from $100W/m^2$ to $1KW/m^2$ at the temperature 35^oC, Fig.3 (b) shows that the photocurrent Iph is same at same irradiation, and the output power is increasing with the n increasing from 40 to 110.



(a)

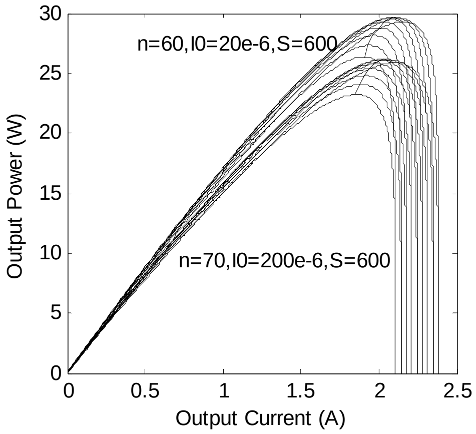


(b)

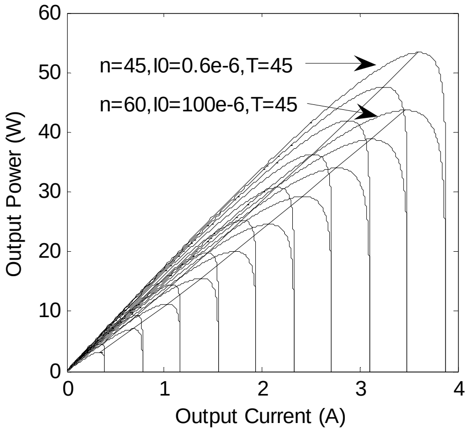
Fig.3 Calculated P-I characteristics and $P\max$ curve under the different n and same Io conditions. (a) The irradiation S is $600W/m^2$, and the temperature is changing from -50^oC to 75^oC. (b) The irradiation is changing from $100W/m^2$ to $1KW/m^2$ at temperature 35^oC.

If the weather conditions are same, Fig. 4 shows that the output photocurrent Iph is same under different diode factor n and different reverse saturation current Io conditions. If the irradiation is $600W/m^2$, and the temperature is increasing from -50^oC to 75^oC, Fig. 4 (a) shows that the photocurrent Iph is same under different diode factor n and different reverse saturation current Io conditions. If the temperature is 45^oC, and the irradiation is increasing from $100W/m^2$ to $1KW/m^2$, Fig.4 (b) shows that the photocurrent Iph is same under different diode factor n and different reverse saturation current Io conditions.

A conclusion is gained in this paper. If the weather conditions are same, a piece of solar cell's output photocurrent Iph is same under different diode factor n and different reverse saturation current Io conditions. The conclusion is very important to acquire the maximum power point of PV system. Based on the conclusion, a novel method was presented to acquire the actual diode factor and reverse saturation current.



(a)



(b)

Fig.4 Calculated P-I characteristics and $P\max$ curve under different n and Io. (a) If the irradiation S is $600W/m^2$, and the temperature is changing from -50^oC to 75^oC. (b) If the irradiation is changing from $100W/m^2$ to $1KW/m^2$ at temperature 45^oC.

2.3 Acquire the actual n and Io

In this case, firstly, the diode factor n and reverse saturation current Io were supposed, are 40 and $500\mu A$, respectively. The output voltage V, the output current I and temperature T of the solar panel, which were detected by using sensors, are the voltage sensor, current sensor and temperature sensor, respectively. The photocurrent Iph is given by using (5), and the assumptive maximum power point was acquired. Fig.5 shows the assumptive maximum power point A of solar cell by using the assumptive n and Io under steady weather conditions. Secondly, Fig.5 shows the actual maximum power point B by using Perturb and Observe method under same weather conditions. The actual optimal output current $\mathrm{Im}ppt$ and optimal output voltage $Vmppt$ is gained by using sensors. As shown in Fig.5, the photocurrent Iph is same under same weather conditions. Finally, the diode factor n is supposed minimum and the reverse saturation current Io is supposed maximum. The actual maximum power is more than the assumptive maximum power. Based on above conclusion, the diode factor n should increase and the reverse saturation current Io should decrease in order to acquire the actual n and Io. Based on the increasing diode factor n and the decreasing reverse saturation current Io, the photocurrent Iph and actual optimal output voltage $Vmppt$ is used to calculate the assumptive optimal output current $\mathrm{Im}\,ppt1$ by using (5). Then, the difference between the actual optimal output current and assumptive optimal output current is $\Delta I \quad (= \mathrm{Im}\,ppt1 - \mathrm{Im}\,ppt)$. If the $\Delta I = 0$, the diode factor n and reverse saturation current Io are actual value. Thus, the actual value of n and Io was saved, and PO method is stopped.

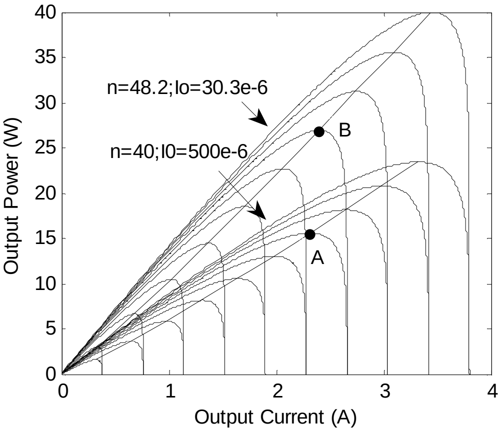


Fig.5 Calculated the actual diode factor n and reverse saturation current Io by using the combined perturb and observe (PO) method.

Next, the process cited above is concretely explained by examples with number obtained based on Fig.5. First, the output voltage and output current were measured at time n1, are $7.0573V$ and $2.1812A$, respectively. In this case, the generated power $P(n1)$ is $15.3934W$. The temperature T of solar penal is 25^oC at time n1. Then, the diode factor n and reverse saturation current Io were supposed, are 40 and $500\mu A$, respectively. The photocurrent $Iph = 2.66A$ is gained by using (5). The irradiation S is $700\,W/m^2$ by using (14). The temperature and irradiation are steady at enough long time. The calculated optimal output current and optimal output voltage were gained, are 2.3089A and 6.7400V, respectively. The calculated optimal output power $P\max'(n1)$ is 15.562W $> \mathrm{P(n1)}$. Second, the PO method is utilized to acquire the actual maximum power point under same weather conditions. The actual optimal output current $\mathrm{Im}\,ppt(n1)$ and optimal output voltage $Vmppt\,(n1)$ were measured, are 2.396A and 11.24V, respectively. Thus, the maximum output power $P\max(n1)$ is 26.9310W, and $(P\max(n1) > P\max'(n1))$. Based on above conclusion, in order to acquire the actual n and Io of a piece of solar cell it is obligatory to increase the diode factor n and decrease the reverse saturation current Io. In this case, the actual optimal output voltage $Vmppt(n1)$ and photocurrent Iph were used to calculate the assumptive optimal output current $\mathrm{Im}\,ppt1$ by using (5). Then, the difference ΔI between the actual optimal output current and assumptive optimal output current is calculated. If $\Delta I = 0$, the actual value of the diode factor n and reverse saturation current Io is gained, are 48.2 and 30.3e-6, respectively. The values of actual n and Io were saved.

3 The proposed MPPT algorithms

For instance, in the case of solar cell, Voc, Isc, Rs, Rsh, Ki, Kv, n, and Io at irradiation $1K/m^2$ and temperature 25^oC, are $22V$, $3.8A$, $8m\Omega$, $10K\Omega$, 0.001, -0.004, 60 and $10\times10^{-6}A$, respectively. Fig. 6 shows V−I characteristics and $P\max$ curve of solar cell are calculated using above values. Fig.6 (a) shows the maximum power curve at different temperature and same irradiation $600W/m^2$, Fig.6 (b) shows the maximum power curve at same temperature 25^oC and different irradiation. It is confirmed through calculating results shown in Fig. 6 that a proportional relationship between the short-circuit current and the optimal output current have been proposed in the literature [3], [4]. The proportionality coefficient using Kx, Kx is $\mathrm{Im}\,ppt(n)/Isc(n)$, which is the coefficient of the optimum output current and the short-circuit current at the time. Normally, it exists between 0.9 and 0.95. The simulative and calculated results verified that an error exists between the maximum power curve and the power curve at $Kx = 0.9 \sim 0.95$. Based on the simulative conclusion, if the irradiation S is more than $150W/m^2$, the coefficient Kx exists between 0.87 and 0.95 under different n and different Io. The irradiation S is less than $150W/m^2$, the coefficient bound is different. Normally, it exists between 0.8 and 0.87 under different n and different Io.