Micro-Mismatch Loss Analysis Based on Solar Cell IV Curve

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Abstract—Solar cells are usually connected in series and parallel to meet the voltage and current requirements for application. Shadows on the surface of C-Si (crystalline silicon) solar cell modules lead to the mismatch of current and voltage between the cells, which is one of the main causes of output power loss. In this paper, an approximate calculation method based on IV curve model is introduced. The micro-mismatch is defined as the ratio of current mismatch is less than \((I_{SC} - I_m)/I_{SC}\), usually less than 6%. According to calculation and experiment result, power losses caused by solar cells micro mismatch of \(I_{mp}, P_m, V_m, FF\) in solar module were analyzed. The result shows that the introduced method can simulate the micro mismatch effect of solar cell application. The module power loss is not obvious, when cell matching is less than 1.5%. When the cells current mismatch is 5%, the influence of module power output is less than 1%. When the current mismatch is 5%, the influence of module power output is less than 1%.

1. Introduction
The output power of a single solar cell usually cannot meet the needs of the PV system. Consequently, solar cells must be connected in series or parallel circuits to constitute solar modules and arrays. However, the output of module or array is usually lower than the total power of each cell, since its nonuniform electrical parameters. Bucciarelli (1979), Gonzalez began to notice the mismatch impact on matrix power performance [1]. In 1995, Charlese collected data in a PV system consisting of 192 modules and analyzed the mismatch impact of voltage and current to system output power. Decreasing the power loss caused by mismatch of solar cell and module means a lot to photovoltaic power cost down [2]. PV industry has been continuing the research with scientific institutions in recent years. Karen from Supower Inc. performed covering test on single cell of modules at different ratios in 2006 to simulate the mismatch of cell and performed power test. The result shows that coverage 10% area of a single cell will lead to around 3% power loss for module of 72pcs cells [3]. Piaucult employed Lambert function to theoretically predict the power loss due to mismatch in module matrix in 2010. According to the calculation, an optimized module connection can realize about 4% increment of output power [4]. The experimental study shows that the current mismatch between the top and the bottom modules of the collector is above 5% and the power mismatch between the PV modules is about 4% [5].

Mismatching problems mean that the I-V and P-V curves between the shaded and unshaded parts of PV module are completely different. Under mismatching condition, multiple local peaks can be observed in the PV module characteristics which propose difficulties for the controller to track the maximum point [6,7]. To overcome these problems, Syafaruuddin proposed using a current injection method to compensate the output current of the shaded part. The proposed method is always end up with
a single local maximum point, so that the optimal point of the shaded PV module can easily be identified using a conventional controller [8]. Carlos Olalla et shown that the submodule MPP efficiency of voltage-balancing DPP converters exceeds 98% in the presence of worst-case MPP voltage variations due to irradiance or temperature mismatches [9]. Rhett Evans described a generalised approach to estimating mismatch loss for series connected solar cells, utilising the result that the deviation from maximum power as a function of deviation from maximum power-point-current is a relatively stable relationship for a wide range of solar cell performances [10]. Jianbo Bai presents a simple and accurate method to simulate the characteristic output of a PV system under either partial shading or mismatch conditions [11]. Miodrag Forcan posed gradual approach in the analysis of power losses in PV strings due to mismatches, simulation results have indicated PV string efficiency is significantly reduced due to different combinations of mismatch conditions [12]. Yousef Mahmoud presented a reconfiguration technique that finds the optimal configuration under the shadowed PV module in a reduced computational time [13]. Yutika D. Chaudhari proposed Distributed Module Current Compensation Technique using Flyback Converter (DMCCT-FC) in PV modules. The experimental simulation results show that this technology is conducive to improve the output efficiency of photovoltaic modules under mismatch conditions [14]. Changwoon Han discovered that mismatch loss could be a detrimental factor to the long-term maintenance of solar power plant by comparing the electrical performance of the PV modules before installation and after the exposure of 5.5 years. It is predicted that the PV module power will decline by 4-32% after 25 years [15]. Thus, there is a need for calculating output power reduction of PV modules due to micro-mismatch.

Two points will lead to testing error in evaluating the micro mismatch impact to output power with shadow coverage method: 1) Mismatching uncertainty between cells of the test module; 2) Uneven light distribution of tester. Using theoretical model, like Lambert function, can hardly simulate the difference of parameters like series and shunt resistance etc. Cells of different IV curve, under the same mismatch condition will lead to different output power loss. At present, the influence of mismatch of vast scale on PV modules can be determined in tests, but the impact of micro-mismatch on PV modules is still very difficult to obtain. In this paper, a simple method of calculating the micro-mismatch is introduced—an approximate calculation method based on IV curve model. Compared with the result of experiment and the general calculating method (IV curve superposition), this method is not only simple, but also it could accurately simulate the micro mismatch impact of electrical performance to output power.

2. Model calculation and simulation analysis

2.1. Model Calculations

The relation curve between working current and voltage of solar cell could be measured by sun simulator. As Figure 1 shows, each point on IV curve is a working point which corresponds to different working current and voltage in different load conditions. Power of a single cell could be regarded as its Maximum Power Point (hereinafter referred to as MPP) when the product of working voltage and current is maximum. When a certain amount of cells make up a solar module, the working current (I_{e}) flowing through each cell is the same. When there exists current mismatch at MPP among different cells, each single cell cannot work at its MPP point, and the working point will shift rightwards if one cell has a larger I_{max} that means working voltage increases and working current decreases so that it can match the working current in the series circuit; In reverse, the working point of a cell with a smaller I_{max} will shift leftwards. According to the difference between corresponding working points of power on IV curve and MPP, we can obtain the mismatch loss due to deviation between working power point and MPP. As Figure 1 shows, MPP is 3.90W while working point A is 3.77W, and point B is 3.43W. In solar modules, the sum of power loss of each cell is the mismatch loss. Above method is the IV curve superposition method of mismatch loss. The method is simple and convenient, does not need complicated modeling, only needs a unified calculation formula and basic parameters to accurately simulate the mismatch loss of PV module under different shadow conditions. Different cells have different IV curves. Even within
the same mismatching range, the mismatch loss could still be different. IV curve calculation is able to simulate it correctly. The overall module power could express in below formula:

$$P_{mc} = P_{max_1} + P_{max_2} + \cdots + P_{max_n} = \sum_{n=1}^{n} P_{max_n}$$  \hspace{1cm} (1)

In the formula, $P_{max_1}$, $P_{max_2}$, ..., $P_{max_n}$ is the maximum power of each cell. After cell encapsulated in modules, ignoring the power loss due to reasons like assembly other than performance mismatch, we can express the maximum power as:

$$P_{mm} = (I_1 \times V_1 + I_2 \times V_2 + \cdots + I_n \times V_n)_{max} = \sum_{n=1}^{n} (I_e \times V_n)_{max}$$  \hspace{1cm} (2)

$I_e$ is the operating current, and $V_1$, $V_2$, ..., $V_n$ means working voltage of each cell, while $I_1$, $I_2$, ..., $I_n$ is the working current of each cell. Because cells are in series circuit, working current of each cell equals the module working current $I_e$. Mismatch loss of power $P_{loss}$ could be calculated as:

$$P_{loss} = \frac{(P_{mc} - P_{mm})}{P_{mc}} \times 100\%$$  \hspace{1cm} (3)

IV curve superposition as above could also be calculated in data form. First, we test IV curve of each cell, and take one point as $I_e$ point on the curve every other 0.01A, and working voltage $V_1$, $V_2$, ..., $V_n$ correspond to respective $I_e$ points. The relationship curve between current $I_e$ and $V_1 + V_2 + \cdots + V_n$ is the IV curve of modules. If $I_e \times (V_1 + V_2 + \cdots + V_n)$ reaches MPP, the $I_e$ is then the regarded as MPP current. According to formula (1), (2), (3), we can conclude the theoretic power loss due to mismatch of module current.

When the mismatch of cell is small, a simple method of calculating the Micro-mismatch is introduced in this paper. And $I_e$ on curve is regarded as the average value of all cells maximum power point current, which is:

$$I_e = \frac{1}{n} \times \sum_{n=1}^{n} (I_n)$$  \hspace{1cm} (4)

Power loss of modules equals sum of loss of each cell caused by deviation between $I_e$ point and MPP. We can have the relation curve of current mismatch and power loss according to Figure 1. As Figure 2 shows--approximate calculation of $I_e$ in average value method, when the MPP current of this very cell is smaller than $I_e$ of the whole cell array, it is minus deviation, and positive deviation in reverse. We can see in the figure, when positive deviation is 2.59%, the power loss of the cell is 0.68%; when minus deviation is 5.36%, power loss is 4.97%. Taking 60 cell module as an example, if positive deviation of 45 cells is 2.59%, and minus deviation of 15 cells is 5.36%, we can obtain an approximate power loss caused by current mismatch: $(45 \times 0.68\% + 15 \times 4.97\%) / 60 = 1.75\\%$.

![Figure 1. IV & PV curve of solar cell](image1.png)

![Figure 2. Power loss curve caused by current mismatch](image2.png)
2.2. Equivalent solar cell model

Generally, the maximum power point current of different cells and the voltage under the average current $I_e$ can be obtained by the manufacturer or can be calculated by the following method (four-parameter model).

PV modules are energy converters that directly convert the received solar energy into electrical energy based on the photovoltaic effect of semiconductor P-N junctions under solar irradiation. In our actual application, a typical solar cell model is shown in Figure 3:

![Figure 3. Single diode equivalent model](image)

Current expression:

$$I = I_{ph} - I_D - I_{sh}$$

Which is:

$$I = I_{ph} - I_o\left\{\exp\left[\frac{V + I R_s}{A V_T}\right] - 1\right\} - \frac{V + I R_s}{R_{sh}}$$

Where: $I$ is the operating current of the cell; $I_{ph}$ is the photovoltaic current by the cell; $I_D$ is the dark current of the equivalent diode; $I_o$ is the reverse saturation current of the equivalent diode, its value is related to the temperature of the cell; $V$ is the operating voltage of the cell; $A$ is the ideality factor of the equivalent diode; $q$ is the charge constant, which is usually equal to $1.6 \times 10^{-19}$ C; $T$ is the operating temperature of the cell; $V_T = (k \times T)/q$.

Note: $R_s$ is a series resistor; $R_{sh}$ is a shunt resistor; $I_{sh}$ is the current through parallel resistance ($R_{sh}$).

In a series of cells, the power loss of the module is caused by the different of the photovoltaic current and fill factors ($R_s, R_{sh}$). Figure 4 and figure 5 show the influence of $R_s$ and $R_{sh}$ on the power loss of the module.

![Figure 4. $R_s$ mismatch and power loss simulation curves](image)

![Figure 5. $R_{sh}$ mismatch and power loss simulation curves](image)
As we can see in the Figure 4 and Figure 5, the simulation results show that the smaller the \( R_S \), the greater the power loss under the same current mismatch conditions; However, the change of \( R_{sh} \) has little effect on the power loss, so the effect of shunt resistance is usually ignored in practical application, that is, the \((V + R_S)/R_{sh}\) term of formula (6) is ignored, thus simplifying the equation:

\[
V = AV_T \ln\left(\frac{I_{ph}}{I_0} + 1\right) - IR_S
\]

Thus, in equation (7), we only need to know the photovoltaic current \( I_{ph} \), the reverse saturation current of the equivalent diode \( I_0 \), the ideality factor of the diode \( A \) and the series resistance value \( R_S \) to solve the I-V characteristic curve of the cell. The single diode model (ignores the parallel resistance) has been widely used due to its relatively simple calculation.

2.3 Solving model parameters

When the voltage is 0V, in equation (7), \( I_0 \) \( \exp \left( \frac{R_S I_0}{AV_T} \right) - 1 \) is much less than \( I_{ph} \), so it can be seen as \( I_{ph} \approx I_{sc} \) (8)

When the current is 0 A, in equation (7),

\[
I_0 = \frac{I_{sc}}{\exp \left( \frac{V_{oc}}{AV_T} \right) - 1}
\]

Because \( \exp \left( \frac{V_{oc}}{AV_T} \right) \) is much less than 1, so:

\[
I_0 \approx \frac{I_{sc}}{\exp \left( \frac{V_{oc}}{AV_T} \right)}
\]

(9)

Because \( \exp \left( \frac{V_{oc} + R_S I_{m}}{AV_T} \right) \) is much larger than 1, so at the maximum power point:

\[
R_S = \frac{AV_T \ln (I_{sc} + I_{m}) - I_{m}}{I_{m}}
\]

(10)

Substituting Equation (3.12) into Equation (3.13), there is:

\[
R_S = \frac{AV_T \ln (I_{sc} + I_{m}) + V_{m} - V_{m}}{I_{m}}
\]

(11)

The maximum power point \( \frac{dP}{dV} \) \( m \) = 0, then we can get the following formula:

\[
AV_T = I_0 \cdot \left( \frac{V_{m} + I_{m} R_S}{AV_T} \right) \exp \left( \frac{V_{m} + I_{m} R_S}{AV_T} \right)
\]

(13)

Substituting Equation (10) and (11) into (12), which is:

\[
AV_T = \frac{V_{m} + I_{m} R_S}{I_{m}} \left( I_{sc} - I_{m} \right)
\]

(14)

Simultaneous Equations (9), (12), and (14) can solve the model parameters \( I_0 \), \( R_S \) and \( AV_T \). At this time, in equation (7), only the operating voltage and operating current are unknown. Using the curve superposition method, the operating current is set from 0 to the short-circuit current \( I_{sc} \), the step length is set to 0.001A, and a series of operating voltages are obtained, so the micro-mismatch of cells can be calculated.

2.4 Revision of parameters under different conditions

In practical applications, the solar radiation and the back temperature of PV modules are the two factors that have the greatest impact on the characteristics of PV modules. Under different circumstances, it is necessary to make reasonable revisions according to the actual situation.

The open circuit voltage of PV modules has a significant linear downward trend with increasing temperature; while the irradiation with the open circuit voltage of PV modules is a non-linear relationship, it can be said that under high irradiation, the change of irradiation has almost no effect on the open circuit voltage of PV modules. However, under the low irradiation, the open-circuit voltage of the module has a significant drop; The short-circuit current of the module changes linearly with the
change of the radiation, and the change in temperature has little effect on the short-circuit current. The short-circuit current will increase slightly with increasing temperature, this change is almost negligible.

To sum up the effects of the above irradiation and temperature on the short-circuit current and open-circuit voltage of the module, refer to [16]. This paper uses the following correction formulas for the short-circuit current, open-circuit voltage, maximum power point voltage and maximum power point current of the module in different environments:

\[
I_{sc} = I_{sc, \text{ref}} \cdot \frac{S}{S_{\text{ref}}} \cdot (1 + a\Delta T) \quad (15)
\]

\[
V_{oc} = V_{oc, \text{ref}} \cdot (1 + b\Delta T) + c \cdot \ln\left(\frac{S}{S_{\text{ref}}}\right) \quad (16)
\]

\[
I_m = I_{m, \text{ref}} \cdot \frac{S}{S_{\text{ref}}} \cdot (1 + a\Delta T) \quad (17)
\]

\[
V_m = V_{m, \text{ref}} \cdot (1 + b\Delta T) + c \cdot \ln\left(\frac{S}{S_{\text{ref}}}\right) \quad (18)
\]

Where: \(I_{sc, \text{ref}}\) is short-circuit current of the cell under STC (under standard conditions: irradiation 1000W/m\(^2\) and temperature 25°C); \(S_{\text{ref}}\) is the irradiation under STC, 1000W/m\(^2\); \(V_{oc, \text{ref}}\) is the open circuit voltage under STC; \(a\) is the current temperature coefficient; \(b\) is the voltage temperature coefficient; \(c\) is the fixed coefficient of the cell, equal to \((V_{oc,200} - V_{oc,\text{ref}}) / \ln\left(\frac{S_{200}}{S_{\text{ref}}}\right)\); \(S_{200}\) is 200W/m\(^2\) irradiance;

3. Experiment and date analysis

3.1 Simulation test and calculation of different current.

Choose cells of different current grading A3, B1, B2, B3, B4, and encapsulate them into modules in different combinations as Table 1: take the current of A3 cell as 1, B1, B2, B3, B4 are 97\%, 96\%, 95\%, 94\% separately. Table 1 shows comparison between test results of power loss and approximate calculations in IV curve superposition and average \(I_e\) calculation method. Because connecting resistance and optics match of encapsulation power loss of material optics match vary from cell to cell in module manufacture, the experimental power loss has already excluded other power loss of encapsulation which is concluded from mass production data of the same cell, the same encapsulation material and the same process condition.

Table 1. Power loss caused by different combination of cell mismatch connection.

| Combination Manner of Cell in Module | Module Power \(P_{mc}\) (Wp) | Theoretic \(P_{mm}\) (Wp) | \(I_e\) in average value method of mismatch loss (%) | IV curve superposition method of mismatch loss (%) | Experimental value of mismatch loss (%) |
|-------------------------------------|-------------------------------|--------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------|
| 30B1+ 47B1+ 53B1+ 59B1+ 30A3+ 48A3+ 54A3+ 59A3+ | 233.17 236.32 237.44 237.99 238.04 244.25 246.44 247.54 | 232.94 235.97 237.30 237.96 235.69 242.43 245.28 247.25 | 0.113 0.132 0.126 0.02 0.913 0.726 0.531 0.132 | 0.099 0.149 0.060 0.015 0.987 0.744 0.471 0.117 | 0.010 0.270 -0.170 0.125 0.862 0.786 0.041 0.189 |

According to Table 1, there is no big gap between theoretical calculation in IV curve superposition method and approximate calculation of \(I_e\) in average value method. Experiment result is close to the
calculation for most part except for some part like 53 B1 cells and 7 B4 cells combination whose mismatch loss is a minus value which indicates the power increases while there’s mismatch between cells. This possibly relates to connecting resistance between cells, optics match of encapsulation material and tester errors etc.

3.2. Shadow covering data
Experiments, including large area coverage, small area coverage and simultaneous coverage of several cells, are designed in order to confirm the effect of the shadow or the uneven irradiance to the performance of modules and systems. All testing samples are made of 54pcs 156×156mm2 multicrystalline silicon cells which are all in string connection and a J-Box with 3 bypass diodes. Referring to experiment result in Figure 6 and Figure 7, the module power loss is smaller than 1% when coverage is below 10%. When the coverage increases progressively over 10%, the loss increases linearly. When over 40% of a cell is covered, the loss is above 20%. With the bypass diode assembly, the power tends to be stable after the battery shielding ratio exceeds 50%, and it tends to be stable after the ratio of the non-bypass diode assembly has reached 80%. PVsyst software was used for simulation. The simulation results are shown in Figure 8 and 9. Obtain similar results and prove the accuracy of the experimental results. In Figure 2, when the minus deviation is 10%, the whole cell will be working at its short point and its power is 100% consumed. When cell current mismatch is bigger than 10%, it is hard to simulate its impact on power loss in IV curve superposition method and approximate calculation of Ie in average value method. Simulation of power loss due to mismatch of vast scale is not discussed in this paper.

![Figure 6. Power loss changes with shading ratio](image1)

![Figure 7. Maximum power changes with shading area of cells](image2)

![Figure 8. Power loss changes with shading ratio](image3)

![Figure 9. Maximum power changes with shading area of cells](image4)
4. Conclusion
In this paper, the IV curve superposition method and the approximate calculation of Ie in the mean value method are combined to calculate the power mismatch loss of solar cells. The results are verified by experiments and the following conclusions are drawn:

A) According to the test results and calculation, when the current mismatch is less than 1.5%, the module power consumption is not significant; when the mismatch is 5% (the current difference between unit A3 and unit B3 is 5%), the module power consumption is less than 1%. The effect of FF on power loss will not be further discussed in this paper.

B) For small-scale power loss allocation, the difference between the IV curve superposition method and the Ie approximation in the mean value method is not great. The experimental results are similar to the calculation, but may be caused by the connection of resistance, optics match of encapsulation material and tester error etc.

C) If the current mismatch exceeds 10% in series, the output power will be greatly affected, which should be avoided in practical applications.

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