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Analysis About Modules and Strings Mismatch Loss in the Photovoltaic Plant

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Abstract: The modules mismatch loss and strings mismatch loss in PV module is theoretically and universally recognized in the PV industry [1]. But for specific projects, how to calculate these losses as well as how to reduce the impact of these losses through external rational wiring was rarely studied. In this paper, the engineering calculation method will be summed up and the relevant formulae suitable for engineering calculation or equipment configuration principles such as cables can finally be obtained by constructing the DC side equivalent circuit model of the photovoltaic power station, and also calculating of modules and strings mismatch loss data based on circuit analysis, which can in turn provide the essential theoretical basis for the accurate efficiency calculation of the photovoltaic power plant system and provide certain theoretical support for engineering drawing optimization design as well.

Keywords: Modules Loss, Strings Loss, String, Serial, Central

1. Introduction

The technology for the building of PV plant is developing which is becoming more necessary in power loss reduction as well as in performance ratio increase. The power loss will lead to bad incoming and power waste [2], so when the design for the PV plant is started, the way to solve these problems should be considered by every design engineers. To find this way, engineers need to analysis the value of power loss and figure out how to plan the routes of cables, how to install the facilities for reduction as well. These needs have to be solved urgently in the stage of project investment analysis, and there must be a simple, practical and accurate method for analysis and calculate loss. Based on this, the thinking of solving this problem has been aroused. Through the analysis, it is considered that the mismatch loss of photovoltaic power station in the solar time interval accounts for the vast majority of its generation time interval. In the solar time interval, the electrical characteristics of photovoltaic power station components are relatively stable, and the output of the power station is relatively idealized, which brings convenience for analysis and simplification of the model. A simple calculation model, the independent DC-side circuit model, can be established by analyzing and calculating the loss data of components in series and parallel connection in solar time. Finally, the approximate calculation formula and configuration principle can be summarized. In this way, loss data can be obtained effectively, which can provide strong theoretical support for the subsequent project, design and construction of photovoltaic power plants.

2. Method

2.1. Modules Loss

Each string of PV power plant is composed of several photovoltaic modules in series. Within each module, its I-V characteristics are different, resulting in modules losses due to different internal resistance, short circuit current and electromotive force. This section focuses on the circuit model, calculation method and avoidance principle of modules loss.

The electrical characteristics of the photovoltaic module during the start time are different from when during the stable operation time. The current keeps constant while the voltage keeps increasing when it starts. The current drops sharply but the voltage keeps unchanged while it stable operates. The circuit characteristics of the photovoltaic module are a kind of non-linear DC source [3]. The following figure is an I-W/V curve of one module, which can illustrate this characteristic:
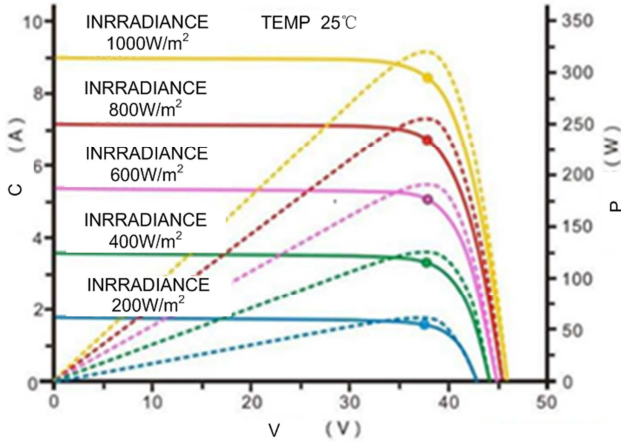
Figure 1. Module I-W/V Curve.

Although the characteristic of photovoltaic module is a non-linear source, the working characteristic of photovoltaic module is close to that of linear source in a short period of time under a specific power condition. Therefore, the equivalent model of constant voltage source can be established by using the method of linear source analysis.
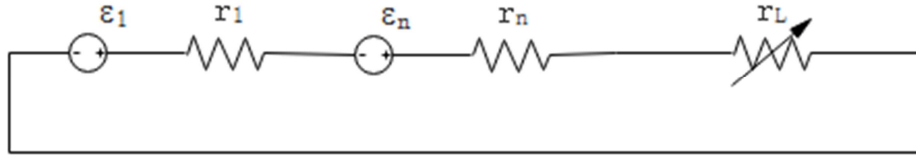

Figure 2. DC-side circuit model of module.

For a string of individual module, the maximum power should work when the load is consistent with the internal resistance [8], which can be expressed by the following formula:

$$P_{max} = \frac{g_1 \times \varepsilon_1^2}{4} = \frac{\varepsilon_1^2}{4r_1} \tag{1}$$

Since the series of photovoltaic units is composed of several modules in string, the following models can be established to simulate the series connection of multiple modules:
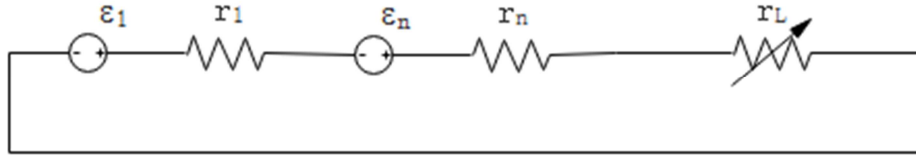

Figure 3. Multi-modules Series Circuit Model.

The maximum output power of the above string of modules shall be:

$$P_{max} = \frac{\left(\sum_{i=1}^{N} \varepsilon_i\right)^2}{4 \sum_{i=1}^{N} r_i} \tag{2}$$

If each module outputs the maximum power separately, the total power is:

$$P_{max} = \sum_{i=1}^{N} \frac{\varepsilon_i^2}{4r_i} \tag{3}$$

By subtracting formula (2) from formula (3), the modules loss value can be obtained.

$$P_L = \sum_{i=1}^{N} \frac{\varepsilon_i^2}{4r_i} - \frac{\left(\sum_{i=1}^{N} \varepsilon_i\right)^2}{4 \sum_{i=1}^{N} r_i} = \frac{1}{4} \cdot \frac{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} r_i r_j (g_i \varepsilon_i - g_j \varepsilon_j)^2}{\sum_{i=1}^{N} r_i} = \frac{1}{4} \cdot \frac{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} r_i r_j (I_{Si} - I_{Sj})^2}{\sum_{i=1}^{N} r_i} \tag{4}$$

Where,

P_L is power modules loss in string,

r_i and r_j are including either the internal series resistance value of modules only or the total series resistance value of the internal strings resistance value plus the total series resistance value of the series connection wire. Which data to be substituted for the calculation should be specific according to the needs of the application scenario.

The formula (4) is suitable for calculating modules losses of a single string of modules consisting of a finite number of modules.

2.2. Strings Loss

The strings of PV power plants are assembled in parallel. Each string is involved in the combiner, its internal I-V characteristics are different and the external cable length is different. But at the combiner point, the combiner's bus will flatten all the voltages. Inverter MPPT needs to ensure maximum power output. Because of the different loop characteristics, the problem is that one of the inverters MPPT is difficult to achieve multi-channel different characteristics. For string inverters, the same MPPT usually does not exceed three strings input, so the strings loss is not obvious. For central inverters, the same MPPT will correspond to more than 20 strings, and the strings loss is more.

For a particular string, its internal characteristics are determined by the open-circuit voltage, short-circuit current, maximum power point voltage and maximum power point current of each module. The series characteristics have been analyzed in above section. The following are the calculation formula, avoidance strategy and design principle of string loss.

For a fixed time, the string is equivalent to a constant

current source or a constant voltage source. For this kind of power supply, the circuit principle analysis shows that the external load loop needs to provide matching resistance to adapt to the internal resistance of the power supply side, so that the maximum power can be obtained. The theoretical value of matching resistance should be the corresponding internal resistance of the power supply at a certain time [4]. Based on this, the equivalent model of parallel connection of modules is established.
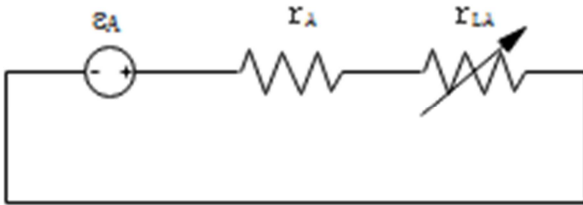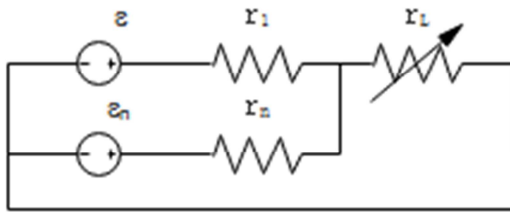

Figure 4. *General circuit model after parallel connection.*

Where

ε_A is always series electromotive force of photovoltaic group,

r_A is always internal resistance plus external line loss,

r_{LA} is always matched resistance of DC side of inverter

When N inverters track each photovoltaic array using independent MPPT, there is theoretically a matching resistance corresponding to each array [5, 13], so the maximum power of N modules is:

$$P_{max} = \frac{\sum_{i=1}^{n} g_i \times \varepsilon_i^2}{4} \qquad (5)$$

For some photovoltaic inverters, such as central inverters, one MPPT will be connected to multi-channel photovoltaic strings, so its electrical schematic will be adjusted, and the results will be quite different.

$\varepsilon_1 \sim \varepsilon_n$ or $I_1 \sim I_n$ is N strings EMF or Short Circuit Current, $r_1 \sim r_n$ is internal resistance value plus external line loss of each strings, r_L is DC-side matched resistance of inverters. Its resistance value varies with the change of internal resistance value of the series. Because there are many power sources and resistors in the circuit, the equivalent circuit diagram is made at first like bellowing:
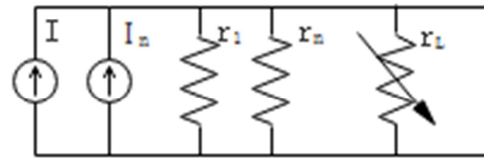

Figure 5. *Simplified model of parallel circuit.*

According to the circuit superposition principle and the Thevenin-Norton equivalence principle [4], the final circuit diagram is equivalent to the circuit Figure 5 above, after that:

$$\varepsilon_A = \frac{\sum_{i=1}^{N} g_i \cdot \varepsilon_i}{\sum_{i=1}^{N} g_i} \qquad (6)$$

$$g_A = \sum_{i=1}^{N} g_i = 1/r_A \qquad (7)$$

In the case of this equivalent circuit, the theoretical maximum power is:

$$P_{max} = \frac{\left(\sum_{i=1}^{N} g_i \cdot \varepsilon_i\right)^2}{4 \cdot \sum_{i=1}^{N} g_i} \qquad (8)$$

By subtracting Formula (8) from Formula (5), it can be concluded that in the case of single MPPT, the modules loss value in string is:

$$P_L = \frac{1}{4} \cdot \frac{\sum_{i=1}^{N} g_i \times \sum_{i=1}^{N} g_i \times \varepsilon_i^2 - \left(\sum_{i=1}^{N} g_i \cdot \varepsilon_i\right)^2}{\sum_{i=1}^{N} g_i} \qquad (9)$$

After the calculation is carried out, it is concluded that:

$$P_L = \frac{1}{4} \cdot \frac{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_i g_j (\varepsilon_i - \varepsilon_j)^2}{\sum_{i=1}^{N} g_i} \qquad (10)$$

Where,

The number of molecular expansion terms should be:

$$P_N^2 = \frac{N \cdot (N-1)}{2} = \frac{N^2 - N}{2} \qquad (11)$$

g_i *and* g_j are including not only the values of strings internal parallel conductance, but also the values of internal parallel conductance and the total parallel conductance of parallel wires. Which data to be substituted for calculation should be specific according to the needs of application scenarios.

2.3. Engineering Example

The former sections has deduced and validated the general formula of modules & strings loss of modules. Engineering calculation can be carried out according to these formulas. This section can basically calculate the modules & strings loss value of corresponding specifications of modules through the calculation of actual engineering cases, and find out the way and method of engineering calculation for each project in the preparatory stage of construction.

Table 1. Electrical data measured in a string.

No.	P_{MAX}	V_{OC}	V_{MPP}	I_{MPP}	I_{SC}	R_I	$TEMP_M$
ACTRUAL-101	167.12	33.85	26.86	6.22	6.83	4.956076	45.50
STC-101	238.63	36.58	28.85	8.27	8.92	4.100897	25.00
102	166.11	33.72	26.65	6.23	6.78	4.973451	46.70
102	236.82	36.62	28.78	8.23	8.80	4.161364	25.00
103	166.19	33.68	26.22	6.34	6.78	4.967552	47.00
103	237.18	36.64	28.80	8.24	8.81	4.15891	25.00
104	178.02	34.08	26.72	6.66	7.17	4.753138	43.60
104	237.39	36.56	28.92	8.21	8.83	4.14043	25.00
105	178.40	34.00	27.15	6.57	7.18	4.735376	44.30
105	239.15	36.55	29.16	8.20	8.82	4.143991	25.00
106	174.49	33.75	26.58	6.57	7.08	4.766949	45.20
106	233.02	36.39	28.67	8.13	8.63	4.216686	25.00
107	174.65	33.72	26.58	6.57	7.10	4.749296	45.10
107	232.81	36.31	29.08	8.01	8.63	4.207416	25.00
108	176.38	33.68	26.79	6.58	7.21	4.67129	45.30
108	234.13	36.33	29.18	8.02	8.75	4.152	25.00
109	176.06	33.65	26.72	6.59	7.19	4.680111	45.40
109	235.10	36.26	28.82	8.16	8.74	4.148741	25.00
110	191.50	34.15	27.08	7.07	7.69	4.440832	46.60
110	241.99	36.82	29.76	8.13	8.83	4.169875	25.00
111	191.50	34.15	27.08	7.07	7.68	4.446615	46.80
111	242.07	36.84	29.78	8.13	8.82	4.176871	25.00
112	189.08	34.09	26.79	7.06	7.63	4.46789	47.40
112	238.67	36.83	29.46	8.10	8.74	4.213959	25.00
113	189.25	34.09	27.22	6.95	7.63	4.46789	47.40
113	238.11	36.82	29.88	7.97	8.73	4.21764	25.00
114	186.59	33.73	26.79	6.96	7.60	4.438158	47.50
114	234.41	36.43	29.54	7.94	8.66	4.206697	25.00
115	186.59	33.75	26.79	6.96	7.61	4.434954	47.40
115	234.73	36.43	29.10	8.07	8.67	4.201845	25.00
116	187.77	33.82	26.72	7.03	7.61	4.444152	40.20
116	226.87	35.68	28.16	8.06	8.59	4.153667	25.00
117	187.79	33.80	26.79	7.01	7.62	4.435696	40.50
117	228.13	35.81	28.27	8.07	8.63	4.149479	25.00
118	191.00	33.88	26.72	7.15	7.75	4.371613	42.20
118	234.08	36.07	28.42	8.24	8.79	4.103527	25.00
119	191.60	33.86	26.79	7.15	7.77	4.357786	42.50
119	234.67	36.03	28.94	8.11	8.80	4.094318	25.00
120	190.07	33.72	26.58	7.15	7.79	4.328626	43.70
120	233.40	36.01	28.44	8.21	8.79	4.096701	25.00

The data in the table above are the electrical data of each photovoltaic module in a string measured by a large-scale ground power plant of a large photovoltaic group company [14]. The calculation is carried out according to the formula (4) in this paper like bellowing:

P_L= (81.59 + 80.59 + 80.68 + 80.71 + 80.67 + 78.45 + 78.29 + 79.51 + 79.2 + 81.28 + 81.17 + 80.55 + 80.31 + 78.81 + 79 + 76.69 + 77.25 + 79.33 + 79.35 + 79.07) - (36.58 + 36.62 + 36.64 + 36.56 + 36.55 + 36.39 + 36.31 + 36.33 + 36.26 + 36.82 + 36.84 + 36.83 + 36.82 + 36.43 + 36.43 + 35.68 + 35.81 + 36.07 + 36.03 + 36.01)^2/4 (4.1 + 4.16 + 4.16 + 4.14 + 4.14 + 4.22 + 4.21 + 4.15 + 4.15 + 4.17 + 4.18 + 4.21 + 4.22 + 4.21 + 4.2 + 4.15 + 4.15 + 4.1 + 4.09 + 4.1) =1592.5-728.01^2/(4×83.21)
=0.15

Under STC condition, the modules loss calculation shows that the modules loss of string consisting of 20 modules is only 0.15W. In this case, the modules loss of 250W module is less than one thousandth of the percentage, so the modules loss of string can be neglected when selecting the same batch of modules.

Table 2. Electrical parameters of strings in a combiner area.

No.	P_{MAX}	V_{OC}	V_{MPP}	I_{MPP}	I_{SC}	G_I	$TEMP_M$
ACTRUAL-1001	4190.52	742.90	583.80	7.18	7.85	0.011	46.40
STC-1001	5161.31	799.40	640.60	8.06	8.82	0.011	25.00
1002	4182.62	742.20	582.70	7.18	7.86	0.011	47.20
1002	5156.30	800.60	631.90	8.16	8.81	0.011	25.00
1003	4180.68	740.60	581.70	7.19	7.87	0.011	48.30
1003	5158.68	801.20	633.20	8.15	8.79	0.011	25.00

No.	P_{MAX}	V_{OC}	V_{MPP}	I_{MPP}	I_{SC}	G_I	$TEMP_M$
1004	4178.11	739.90	581.10	7.19	7.88	0.011	48.50
1004	5158.95	801.20	633.70	8.14	8.79	0.011	25.00
1005	4184.37	741.90	582.70	7.18	7.84	0.011	49.10
1005	5156.41	804.90	645.60	7.99	8.73	0.011	25.00
1006	4187.87	741.70	582.70	7.19	7.85	0.011	49.50
1006	5141.02	804.90	646.10	7.96	8.70	0.011	25.00
1007	4202.78	744.20	583.80	7.20	7.85	0.011	49.80
1007	5181.52	808.90	648.50	7.99	8.72	0.011	25.00
1008	4208.85	743.90	584.40	7.20	7.86	0.011	49.80
1008	5178.07	808.10	648.80	7.98	8.71	0.011	25.00
1009	4175.42	737.60	580.00	7.20	7.92	0.011	49.80
1009	5123.59	801.40	634.50	8.08	8.76	0.011	25.00
1010	4175.30	737.30	579.50	7.21	7.93	0.011	49.90
1010	5127.11	801.10	634.70	8.08	8.77	0.011	25.00
1011	4167.02	736.90	570.20	7.31	7.94	0.011	50.20
1011	5121.10	801.80	634.90	8.07	8.77	0.011	25.00
1012	4169.24	736.40	578.90	7.20	7.94	0.011	50.50
1012	5118.10	801.40	635.00	8.06	8.76	0.011	25.00
1013	4087.33	735.40	568.00	7.20	7.92	0.011	51.10
1013	5028.66	802.10	625.30	8.04	8.72	0.011	25.00
1014	4090.74	735.20	568.00	7.20	7.93	0.011	51.30
1014	5036.44	802.50	625.80	8.05	8.73	0.011	25.00
1015	4190.72	739.00	571.80	7.33	7.94	0.011	51.30
1015	5136.12	805.80	638.90	8.04	8.72	0.011	25.00
1016	4189.34	738.50	580.00	7.22	7.95	0.011	51.30
1016	5135.12	805.30	638.30	8.05	8.73	0.011	25.00

The above table lists 16 groups of strings data of a PV power plant. After substituting the above data with formula (9), the calculation results are as follows:

$$P_L = 0.011 \times [16 \times (639040.36 + 640960.36 + 641921.44 + 641921.44 + 647864.01 + 647864.01 + 654319.21 + 653025.61 + 642241.96 + 641761.21 + 642883.24 + 642241.96 + 643364.41 + 644006.25 + 649313.64 + 648508.09) - (799.4 + 800.6 + 801.2 + 801.2 + 804.9 + 804.9 + 808.9 + 808.1 + 801.4 + 801.1 + 801.8 + 801.4 + 802.1 + 802.5 + 805.8 + 805.3)^2] \div 64 = 0.011 \times [16 \times 10321237.2 - (12850.6)^2] \div 64 = 0.32$$

Under STC condition, the total power of 16 strings is 82118.5W, and the percentage of loss in parallel is very small. Considering the field measurement of this group of data, the measured power data of 16 strings come from the terminals of strings, that is, the conductance of parallels cables is not included, and the strings loss value is understandable because of the low EMF dispersion of the modules. Generally, about 1% of the estim 0ated value is much smaller and normal, which is close to the technical index of serial inverters. At the same time, it can be concluded that the strings loss value of the combiner area mainly comes from the resistance value of the parallels cables under the actual construction conditions.

All tables and formulas are calculated in standard units above.

3. Result

3.1. Several Inferences of Formula (4)

According to formula (4), all modules losses can be calculated accurately. It is very practical for engineering calculation. Its guiding significance is self-evident. From the formula structure, the following inferences can be derived:

Inferences 1: In theory, when the short circuit current of each photovoltaic module is the same, there is no modules loss. At this time, regardless of the EMF and internal resistance of the module, it will only affect other types of losses without modules loss.

Inferences 2: The smaller the dispersion of short-circuit current, the smaller the modules loss. It can also be expressed as the more concentrated the short-circuit current is, the smaller the modules loss is.

Inferences 3: When the short circuit current difference between the two modules is too large, the modules loss can be reduced by choosing two modules with smaller internal resistance instead of two modules with too large electromotive force.

3.2. Several Inferences of Formula (10)

Several effective principles can be concluded from the structure of Formula (10). At the same time, all strings losses can be calculated accurately according to this formula, which conforms to the practical principle of engineering calculation. Several qualitative inferences can be summarized, and quantitative analysis will be introduced in the next section.

Inferences 1: In theory, when the strings EMF of each photovoltaic unit is the same, there is no strings loss. At this time, no matter how the external wiring is, it will only affect the other loss without strings loss.

Inferences 2: The smaller the EMF dispersion of each

photovoltaic string is, the smaller the loss of strings is. It can also be expressed that the more concentrated the EMF of strings is, the smaller the loss of strings is.

Inferences 3: When the difference of EMF between two groups is too large, the strings loss can be reduced by concentrating the wiring length of DC cables in each string.

4. Discussion

In Most Articles for this question, the way to discuss modules loss or strings loss was complex and not suitable for engineering calculations, such us in this one, which abstract is as follows, Variations in the I-V characteristics of photovoltaic modules can lead to significant power loss. This study deals with an analysis of series-string losses. The current parameter of a set of PV modules is considered as a random variable following the Weibull distribution. An analytical expression has been obtained to predict these losses. A preliminary experiment that shown a good agreement with the proposed model is also presented. [16] While in this paper, every formula is simple and practical, therefore it can be used to calculate the losses before the investment for a new PV solar plant.

5. Conclusion

In this paper, the circuit principle of the modules & strings loss of modules is modeled, the calculation formula is deduced, and the engineering case is calculated. Finally, it is concluded that the modules loss accounts for a very small proportion of the total mismatch losses, and the calculation can be neglected. For the strings loss, the formula (9) can be used to calculate which quickly, and the actual parameters of the modules can be obtained from the batch test report provided by the factory of the modules. According to the combination simulation, the suitable group of strings can be obtained. After one calculation being finished, the approximate range of the modules loss of the same specification module can be basically determined, so that provides a fast and accurate way for the theoretical calculation in the design stage.

For engineering construction, when conditions are permitted, priority should be given to ways to reduce the strings loss, such as reducing the open-circuit voltage dispersion rate of each string to avoid large proportion of parallel mismatch, reducing mismatch by adjusting the length of each strings cables to reduce the appropriate dispersion rate of cable length. Hoping it can also play an active role in later engineering applications or computer aided design.

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