Efficiency diagnosis and optimization in distributed solar plants

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Abstract

Distributed solar plants are widely used in the power supply of the factories and the residences. To increase the power generation, it is inevitable to model the efficiency of the distributed solar plant and diagnose its efficiency performance. In this paper, a practical 3 MW distributed solar plant is taken as an example. The data analysis reveals the performance ratio (PR) of the plant is around 59%, which is much lower than the recommend value 75%. The efficiency diagnosis also shows that the conventional design method, which is used to determine the module quantity in a photovoltaic (PV) array, has its limitation. This method may lead to the voltage mismatch between the desired operation point of the PV array and the connected inverter, which degrades the performance of maximum power point tracking (MPPT) of the PV system. In the conventional design, the tilted angle of the PV modules is chosen based on the maximum irradiation that the modules can reach. However, the maximum irradiation on PV modules does not necessarily means the maximum electricity yield. Therefore, a new design methodology that optimizes the module quantity and the tilted angle of PV modules in the solar plant is proposed in this paper. Simulation results verify the effectiveness of the proposed method.

Key Words: Distributed solar plant; Performance ratio; Efficiency diagnosis; Optimal design

1. Introduction

Distributed solar plants have been going through a rapid development in recent years (Wang, 2020). According to National Energy Administration of China, new installed capacity of solar plants is up to 30GW in 2019, among which distributed solar plants reaches 12GW, accounting for 40% of the total installation. Normally, distributed solar plants are located on the rooftop of factories. Generally, due to the complex working environment, the performance ratio (PR) of distributed solar plants is much lower than that of the concentrated plants on the ground.

Analysis and optimization of distributed PV stations have been carried out in some literature. However, they mainly focus on kW-level systems (Al-Badi, 2018); (Tato and Brito, 2019); (Shyu, 2013), rather than the MW-level PV systems. Besides, in (Chandrasekaran et al., 2020); (Zhu et al., 2019); (Ma et al., 2019), the efficiency of the PV system is increased by improving the performance of the converter. From the point of view of the PV plant designer, the approach is not appropriate in practice. The optimization from the PV system configuration is worth researching. Furthermore, based on the efficiency analysis with PVsyst software, the annual PR of a distributed PV station reaches 0.89 (Yoo et al., 2016), which is very ideal. In fact, PR values of some existing distributed PV stations are much lower than 0.75 recommended by International Energy Agency (IEA) (Kymakis et al., 2009); (Emziane and Al Ali, 2015); (Rodrigues et al., 2016). Therefore, a practical procedure of efficiency diagnosis for the distributed solar plant is needed urgently.

The existing design procedure for module quantity in a PV array only considers the effect of the module temperature (Berwal et al., 2017). The procedure easily leads to voltage mismatch between the desired operation point of the PV array and the connected inverter under the low light, which degrades the MPPT performance of the PV system. Therefore, the design procedure of the module quality is required to be optimized urgently. In addition,

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the tilted angle of PV modules is determined based on the maximum irradiation that modules can reach (Jamil et al., 2016); (Ramli and Bouchekara, 2018). However, this tilted angle does not necessarily mean the maximum electricity yield because of the effect of the temperature.

In this paper, a practical 3 MW distributed solar plant is taken as an example. The data analysis reveals the performance ratio (PR) of the plant is around 59%, which is much lower than the recommend value 75%. An efficiency model is constructed based on the efficiency of grid-connected inverter, PV module, and PV array. The model confirms that the existing design procedure for module quantity of a PV array has its limitation on MPPT performance under the low irradiation. From the PV system configuration, a design procedure of the module quantity is proposed, which takes the effect of irradiation into account. Simulation results based on the new procedure indicate that the PR increases by 4.55%.

In addition, it reveals that the traditional design method of the tilt angle is unreasonable without considering the temperature. Thus, a novel method is proposed to optimize the tilt design by maximizing the annual power generation. Simulation results verify the effectiveness of the proposed method. The research carried out in this paper provides the accurate guidance to the efficiency diagnosis and the optimal design for distributed solar plants. And it is also conducive to accurate estimation of power generation capacity of a given distributed solar plant.

2. Experimental platform

In this paper, a 3 MW distributed solar plant has been installed on the rooftop of a factory to analyze the performance on a system-level basis. While a module-level platform has been established to analyze the module efficiency in the outdoor environment.

2.1. System-level experimental platform

The 3 MW solar plant has been installed at 32° N and 119° E since 2015, with a fixed tilt of 3° and an azimuth of 180° (towards the south). The system is divided into 3 subsystems with the capacities of 1.41 MW, 1.06 MW and 0.53 MW respectively. The total number of the 255 W polysilicon PV modules is 11814, and the number of modules in series is 22. Then there are 5 centralized grid-connected inverters, among which the rated output power of 01 inverter and 02 inverter are 630 kW and others are 500 kW. The system was monitored from May 2015 to April 2016. The structure of the PV system is shown in Fig. 1.

2.2. Module-level experimental platform

The performance of the PV module has a direct impact on the power generation of a solar plant, as the PV module is a direct unit for the photoelectric conversion. The module-level platform has been installed at 31° N and 121° E, with a fixed tilt of 3° and an azimuth of 180° (towards the south), as shown in Fig. 2(a). This type of the PV module is the same as that used in the solar plant. A meteorograph is installed to monitor the meteorological data, such as solar irradiance, ambient temperature, module temperature, wind speed, wind direction and humidity. A tester of I-V curve characteristic (Model IVT-20-200) is used, as shown in Fig. 2 (b), to obtain the output characteristic of PV modules, such as maximum power, MPPT voltage, MPPT current, open circuit voltage, short circuit current, I-V curve and so on.

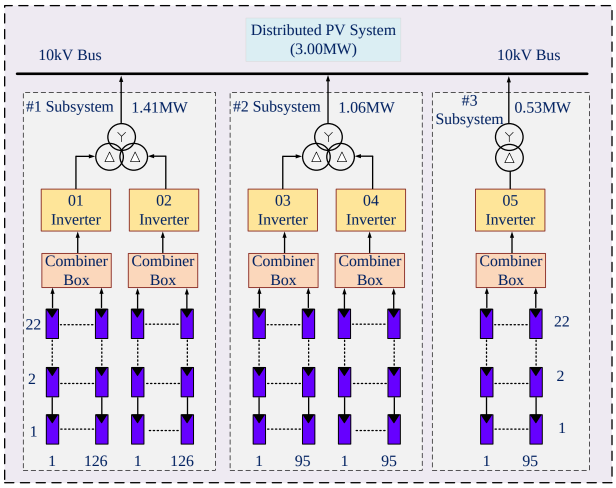
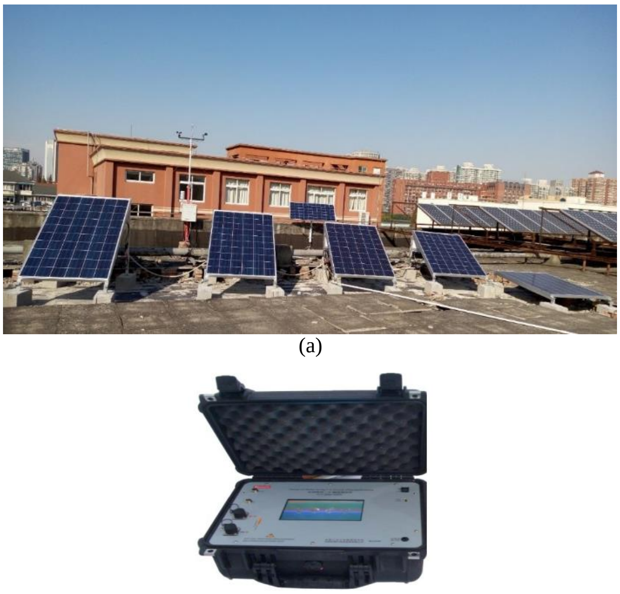


Fig. 1. System-level experimental platform.



(a)

(b)

Fig. 2. Module-level experimental platform. (a) hardware setup, (b) tester of I-V curve characteristic.

2.3. Definition of the efficiency

Several variables are defined to characterize the inputs and outputs of the PV system in this section. The PV module efficiency (η_m) can be determined by (1):

$$\eta_m = \frac{I_{mp}V_{mp}}{SA} \tag{1}$$

where I_{mp} and V_{mp} are the current and the voltage of the maximum power point respectively, S is the irradiance on the surface of PV modules in W/m^2, and A is the total surface area of PV modules in m^2.

The PV array efficiency (η_A) describes the ratio of the output power of the PV array to the irradiance received by the PV array, and reflects the loss of the PV array in operation. It can be calculated by (2) (Yoo et al., 2016):

$$\eta_A = \frac{P_{DC}}{SA} \tag{2}$$

where P_{DC} is the output power of the PV array in W. The inverter conversion efficiency (η_{inv}) can be determined by (3):

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \tag{3}$$

where P_{AC} is the power output from the inverter in W.

The performance ratio (PR) describes the ratio of the total alternating current (AC) energy output from the system to the theoretical generating capacity, and reflects the total loss of the PV system, including the PV array, the inverter conversion, the AC link, the troubleshooting and so on. It can be calculated by (4) (Ferrada et al., 2015):

$$PR = \frac{E_{AC}}{H_T A \eta_0} \tag{4}$$

where E_{AC} is the energy output from the system in kWh, H_T is the irradiation received by the PV array per unit area over a period of time in kWh/m^2, η_0 is the PV module efficiency at standard testing conditions (STC).

3. Efficiency analysis

3.1. System-level efficiency analysis

The PR value of the investigated PV system from May 2015 to April 2016 is just 59%, which is much lower than the recommended value (75%) by IEA. In order to increase the power generation capacity, it is necessary to analyze the causes for the low PR value. With the definition in (4), Fig. 3 shows the distribution of the monthly PR and the monthly average daily irradiation of the PV system.

From the analysis of Fig. 3, the irradiation values in winter (November, December and January) are much lower than that from other months. Also, the PR in winter is also lower than that of other months. Therefore, the annual PR decreases.

Fig. 4 shows the distribution of the daily PR and the daily irradiation. The daily PR model of the PV system is a quadratic function dependent on the daily irradiation by using the statistical software SPSS, and the function is described as (5):

$$PR = 0.051 + 0.153H_T - 0.007H_T^{\ 2} \tag{5}$$

The goodness of fit of (5) is 0.797 (the closer to 1, the better). And the effect of irradiation on the PR has been considered in (5), so the PR model can be used to predict the power generation capacity with similar configurations.

Based on the analysis of Fig. 3 and Fig. 4, the daily PR value of the system is significantly affected by the irradiation, and is mostly distributed in the range of 40%~70%. The average value of the PR is about 75% when the irradiation ranges from 5 kWh/m^2 to 8 kWh/m^2. When the irradiation ranges from 2 kWh/m^2 to 5 kWh/m^2, the average value of the PR is about 45%. Moreover, when the irradiation is 1~2 kWh/m^2, the average PR value is just only 25%.

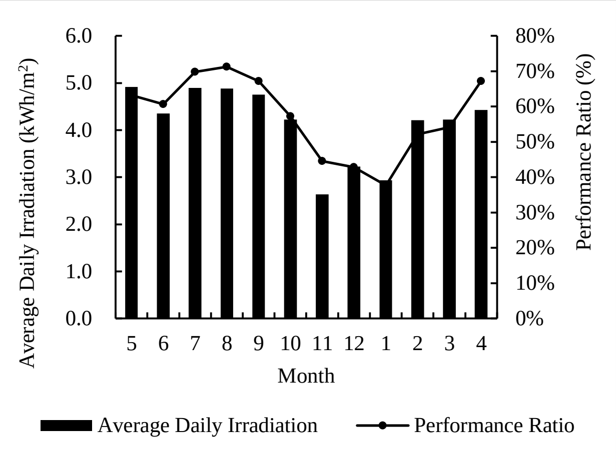


Fig. 3. Distribution of the monthly average daily irradiation and the monthly performance ratio.

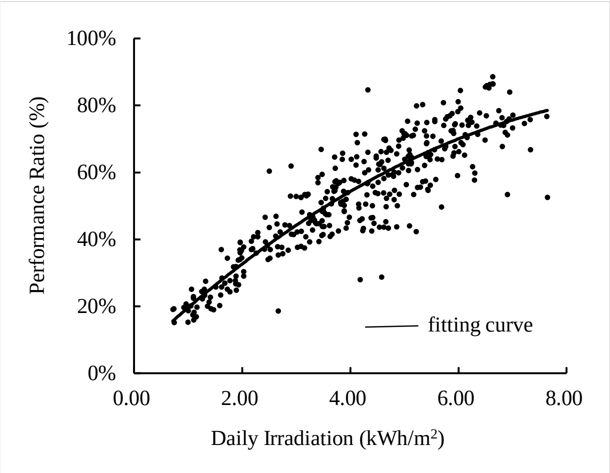


Fig. 4. Daily performance ratio varies with the daily irradiation.

It can be obviously concluded that the PR decreases severely in the winter or on cloudy days, resulting in that the annual PR is far lower than the recommended value. Therefore, it is necessary to analyze the mechanism of the efficiency attenuation in priority and then improve the conversion efficiency.

With the definition of the PR in (4), the factors affecting the performance ratio include the PV array, the inverter conversion, the AC link, the troubleshooting, the shading, and so on. The effect of the shading is not considered, because the space between PV arrays is large enough to avoid the shading in the 3 MW station. Meanwhile, the conversion efficiency of the PV array and the inverter is significantly affected by the irradiation. Therefore, the research scope can be narrowed to explore the relationship between the meteorological factors, the conversion efficiency of the inverter, and the PV array.

3.2. Inverter-level efficiency analysis

In the construction of the distributed PV system, the generation efficiency of the power station is mainly determined by the performance of the inverter. Generally, only the European efficiency or the maximum efficiency of the inverter has been offered in the datasheet. However, the conversion efficiency of the inverter is affected by the input power to the inverter (Rodrigo et al., 2016), and indirectly affected by the irradiance. Based on the data of the meteorograph and No. 05 inverter, Fig. 5 shows the distribution of the inverter efficiency vs the irradiance, taking the data in May as an example.

The efficiency model of the inverter is approximately an exponential function dependent on the irradiance (Michal, 2016); (Tseng et al., 2018), and the function is described as (6). The goodness of fit reaches 0.799, which performs great.

$$\eta_{\mathrm{inv}} = 0.963 - 0.593\,\mathrm{e}^{-0.008S} \tag{6}$$

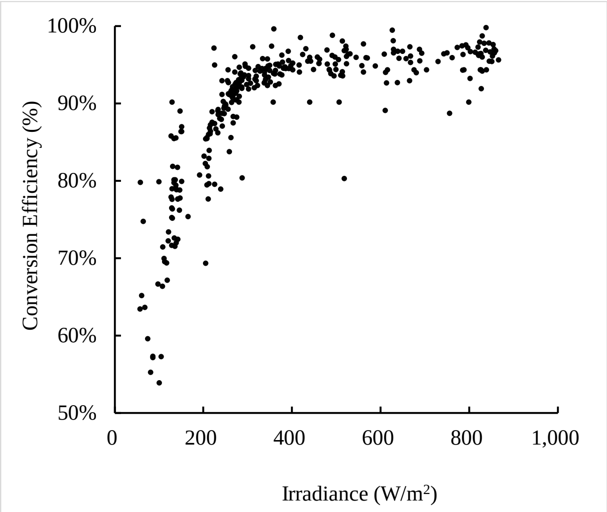


Fig. 5. Conversion efficiency of No. 5 inverter.

According to Fig. 5 and (6), the conversion efficiency of the inverter is stable at 96% with the gradual increase of the irradiance. In addition, the average value of the conversion efficiency is about 90% when the irradiance ranges from 200 W/m^2 to 400 W/m^2 (in the early morning, the evening or on cloudy days).

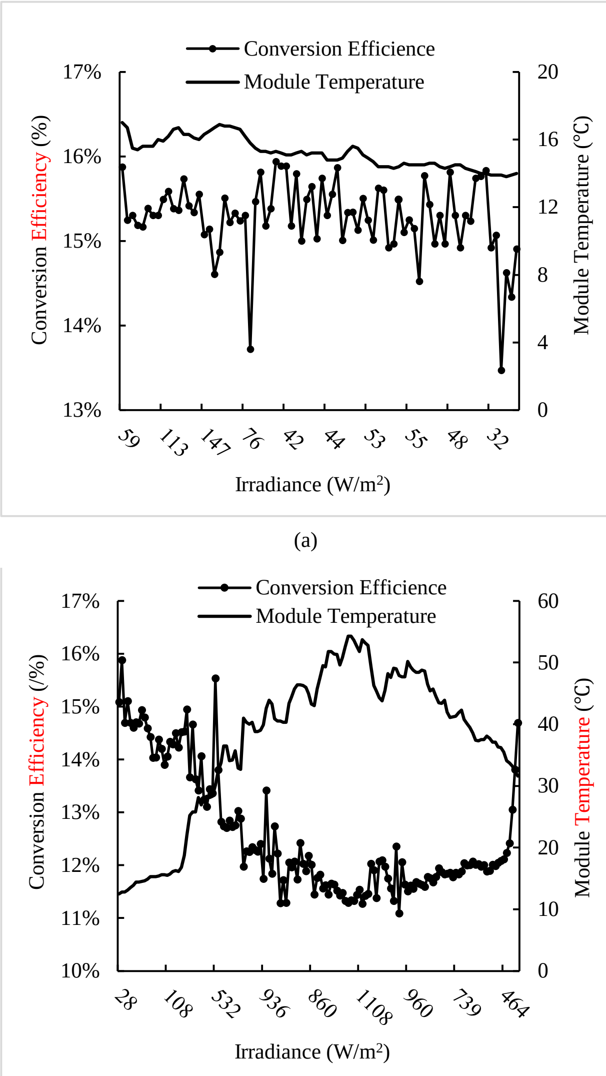
Although Fig. 4 shows the daily irradiation values and Fig. 5 shows the instantaneous values respectively, they both show the relationships between the PV system efficiency, the inverter efficiency and the low light. In detail, PV system efficiency is about 30% on cloudy days in Fig. 4, which presents that PV system efficiency decreases severely under the low light. However, the inverter efficiency is about 70% under the low light in Fig. 5, which presents that the inverter efficiency decreases slightly under the low light. Therefore, the attenuation of inverter efficiency under the low light is not the main reason which leads to the severe drop in the PV system efficiency.

3.3. Module-level efficiency analysis

PV arrays are composed of PV modules in series and in parallel, and a PV module is a direct unit of photoelectric conversion. Before analyzing a PV array, the study of a single PV module is necessary.

Major meteorological factors that affect the output power of the PV module include the irradiance, the ambient temperature, the wind speed, the wind direction, the humidity, etc. According to some research, the conversion efficiency of the module is determined by the irradiance and the module temperature under ideal conditions (no shelter, no dust, etc.).

In order to quantify the effect of the irradiance and the module temperature on the conversion efficiency of the module, the output power and the meteorological data was measured on April 23 (the average temperature is 15.00°C) and on April 18 (the average temperature is 39.47°C) based on the module-level platform. According to (1), the conversion efficiency of the module varying with the irradiance and the module temperature is shown in Fig. 6 (the x-axis showing the varying of the irradiance in one day).



(b)

Fig. 6. Conversion efficiency and temperature of the module. (a) on a cloudy day, (b) on a sunny day.

From Fig. 6(a), the conversion efficiency of the module varies from 15% to 16%, and the module temperature varies from 13°C to 16°C on the cloudy day. Fig. 6(b) shows that the conversion efficiency varies from 12% to 15%, and the module temperature varies from 20°C to 60°C on the sunny day.

The module efficiency is affected by the temperature rather than the irradiance. According to Fig. 6(a) and Fig. 6(b), the module efficiency on the cloudy day (with lower temperature) is greater than that on the sunny day. This is because the module efficiency is greater when the temperature is lower. Thus, the low annual PR under the low irradiance does not result from the attenuation of the module efficiency.

3.4. Conversion efficiency of the photovoltaic array

In addition to the effect of the irradiation and the module temperature on the conversion efficiency of PV modules, the attenuation of MPPT performance also affects the conversion efficiency of the PV array. In order to analyze the impact of the irradiation on the array efficiency on cloudy days and sunny days, two closer dates are selected, which are May 2 (PR is 39.16%) and May 21 (PR is 76.82%).

Taking No. 03 inverter of the PV system as an example, the output voltage of the PV sub-array (i.e., DC side voltage of 03 inverter) and the conversion efficiency of the PV array are obtained. In Fig. 7, the x-axis shows the varying irradiance in one day, and the theoretical voltage of the PV sub-array can be obtained by (7) (Wu et al., 2009):

$$
\begin{aligned}
V_{\mathrm{Am}} &= NV_{\mathrm{mp}}^{*}(1+\mathrm{c}\,\Delta T)\ln(e+\mathrm{b}\,\Delta S) \\
V_{\mathrm{Ao}} &= NV_{\mathrm{oc}}^{*}(1+\mathrm{c}\,\Delta T)\ln(e+\mathrm{b}\,\Delta S)
\end{aligned} \tag{7}
$$

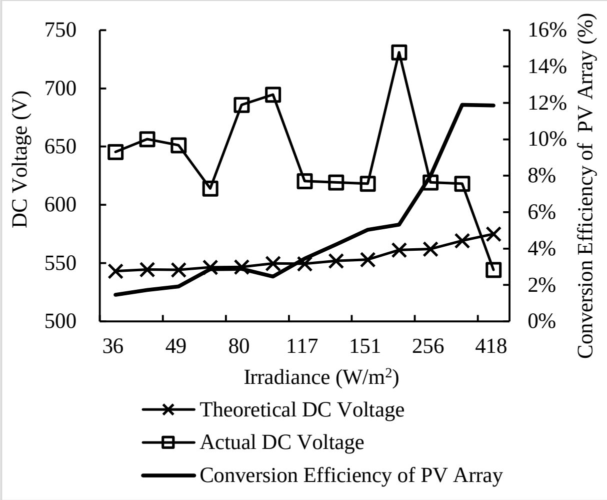
where V_{Am} and V_{mp}^{*} represent the MPPT voltage of the PV array and PV module, V_{Ao} and V_{oc}^{*} represent the open circuit voltage of the PV array and PV module, N is the module number in series of the PV array, c = -0.288%/°C, b = 0.5, $\Delta T = T_{\mathrm{m}}$-25, $\Delta S = S/S_{\mathrm{ref}} - 1$, T_{m} is the module temperature, S_{ref}=1000 W/m^2.

In Fig. 7, the average conversion efficiency of the PV array on May 2 (a cloudy day) is only 4.85%, and the average conversion efficiency on May 21 (a sunny day) reaches 11.66%. It is shown that the actual operating voltage of the PV sub-array is close to the theoretical MPPT voltage when the irradiance is greater than 400 W/m^2. At the same time, the array conversion efficiency is about 13%. When the irradiance is lower than 400 W/m^2, the actual operating voltage of the sub-array is much higher than the theoretical voltage of MPPT, and the array efficiency decreases dramatically with the drop of the irradiance.

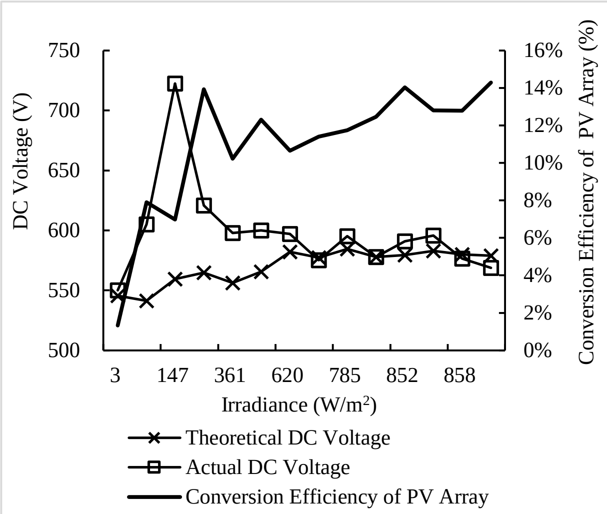
3.5. Results of efficiency diagnosis

The MPPT control scheme of the inverter is disabled, when the MPPT voltage of PV array is lower than the MPPT range (550V-950V) of the inverter. The absence of the MPPT control often happens on the cloudy day because of the low irradiance as shown in Fig. 7(a). Therefore, the PV array efficiency decreases severely under the low irradiance. On the contrary, the MPPT control can operate well on the sunny day as shown in Fig. 7(b), and the PV array can always operate at the maximum power point.

Therefore, the voltage mismatch of the desired operation point of the PV array and the MPPT range of the inverter leads to the low PV array efficiency under low irradiance, which is the main reason causing the low PV system efficiency.



(a)



(b)

Fig. 7. Distribution of the working voltage of inverter DC side and PV array conversion efficiency. (a) on a cloudy day, (b) on a sunny day.

4. Optimization of the module quantity in series

Based on the efficiency diagnosis of the solar plant above, the traditional design for the number of PV modules in series has the limitation, which easily leads to the voltage mismatch between the PV array and the inverter. By optimizing the module quantity in series, the voltage of the PV array can be increased to meet the MPPT range of the inverter under the low light.

4.1. Limitation of the traditional method

The module quantity N in series of the solar plant is 22, based on the traditional design method (Berwal et al., 2017):

$$N \le \frac{V_{\mathrm{dc\,max}}}{V_{\mathrm{oc}}^{*}\times[1+(t-t_0)\times K_{\mathrm{v}}]} \tag{8}$$

$$\frac{V_{\mathrm{mppt\,min}}}{V_{\mathrm{mp}}^{*}\times[1+(t'-t_0)\times K_{\mathrm{v}}]} \le N \le \frac{V_{\mathrm{mppt\,max}}}{V_{\mathrm{mp}}^{*}\times[1+(t'-t_0)\times K_{\mathrm{v}}]} \tag{9}$$

where K_{v} is the voltage temperature coefficient of the PV module in %/°C, and the value of the plant is -0.3%. t and t' are the lowest temperature and the highest temperature of the PV module, t_0 is the module temperature under the standard test environment. In the plant, t and t' are -12°C and 70°C, t_0 is 25°C. $V_{dc\ max}$ represents the maximum DC voltage allowed by the inverter, which is 1000V. V_{oc}^* and V_{mp}^* are the open circuit voltage and MPPT voltage of the PV module under standard test condition, and the values are 37.82V and 30.29V respectively; $V_{mppt\ min}$ and $V_{mppt\ max}$ are the lower limit and the upper limit of the MPPT range of the inverter, which are 550V and 950V respectively.

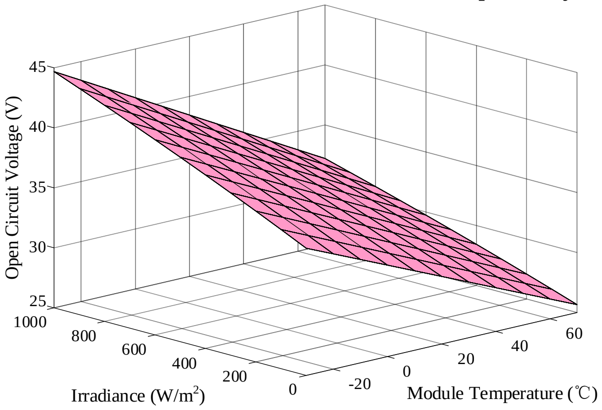


Fig. 8. Three-dimensional diagram of the open circuit voltage of the PV module.

In the design of the module quantity N, the upper limit of N is determined by the open circuit voltage of the PV module in (8), and the low limit is determined by the voltage at the maximum power point of the module in (9). The key to calculating the upper limit of N is to obtain the maximum open circuit voltage of the module throughout the year, which is in the denominator of the right side of (8). The calculation of the maximum open circuit voltage in (8) is unreasonable, which only considering the lowest temperature of the PV module. When the module temperature reaches the lowest value, the open circuit voltage is not necessarily the maximum value.

The open circuit voltage of the PV module is affected by the module temperature and the irradiance. Based on (7), the three-dimensional diagram of the open circuit voltage is obtained. As shown in Fig. 8, the open circuit voltage increases not only with the decrease of the module temperature, but also with the increase of the irradiance. Theoretically, when the irradiance reaches the higher value of 1000 W/m^2 and the module temperature reaches the lowest value, the open circuit voltage is the maximum value. In this case, the maximum open circuit voltages calculated by (7) and (8) are same. However, when the lowest temperature is reached, the irradiance cannot reach 1000 W/m^2 in practice. Hence, the maximum of N designed by the traditional method is unreasonable.

4.2. Optimization of the method

In order to obtain the optimal value of N, the maximum open circuit voltage of the PV module throughout the year needs to be obtained in priority. Based on the data of the solar plant and (8), the distribution of the open circuit voltage can be obtained. The monthly maximum voltage, the corresponding irradiance and the module temperature are shown in Table I.

Table I

Distribution of the maximum open circuit voltage in the plant through the year

Month	5	6	7	8	9	10
$V_{oc\ max}$(V)	35.7	34.2	34.5	32.9	34.5	35.3
S(W/m^2)	784	492	793	691	727	832
T_m(°C)	29.3	24.3	40.8	48.1	36.7	35.7
Month	11	12	1	2	3	4
$V_{oc\ max}$(V)	35.5	35.1	35.6	38.8	35.8	34.4
S(W/m^2)	398	560	593	757	701	763
T_m(°C)	28.4	21.3	18.7	2.7	24.2	49.0

According to Table I, the maximum open circuit voltage appears in February; the voltage is 38.8V and the module temperature is 2.7°C. Based on the data of the plant, the lowest module temperature is -12°C, which appears on January 24. As the irradiance was just 2 W/m^2, the open circuit voltage is not the maximum value under the lowest module temperature. Therefore, the traditional design method of N is not reasonable. The module temperature and the irradiance need to be considered, when designing the number of PV modules in series.

Because the maximum DC voltage ($V_{dc\ max}$) of the inverter is 1000V, N can be calculated by N=1000/38.8=25.8. For the convenience of array wiring, the number of modules in series is usually even, and thus N can be set as 24, which is 2 more than the value of traditional design.

By the optimization of the number of PV modules in series, the MPPT voltage of the PV array increases. The MPPT voltage can be kept within the MPPT range even in low irradiance cases, which is conducive to solving the voltage mismatch between the PV array and the inverter. That finding is applicable to all PV arrays and inverters.

4.3. Optimization results

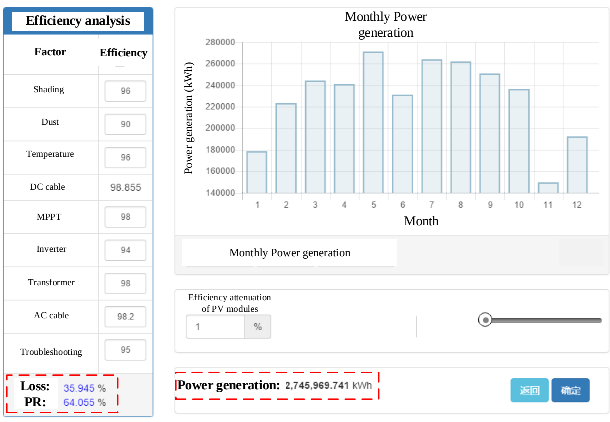


Fig. 9. Simulation results of optimization.

Taking the 3 MW solar plant as an example, the annual PR value is 59.45%, and the annual power generation is 2633 MWh. By optimizing the module number in series, the poor efficiency of PV array under low irradiance can be solved. To verify the optimized PV station, we develop a software, and the optimization results of the proposed strategy are obtained as Fig. 9. After optimization, the PR value is 64% and annual power generation is 2746 MWh, which implies a 4.55% increase in annual PR and an increase of 113 MW in annual power generation.

Based on the above analysis, in the regions with similar climate, the number of PV modules in series can be increased by 2 on the traditional design results. It is beneficial to improve the efficiency of the solar plant.

5. Optimization of the tilted angle of PV array

In the above section, the PV system has been optimized from the perspective of the system configuration. When the building roof meets the requirement of installing PV brackets, the annual power generation can be increased by optimizing the installation inclination of the PV array.

5.1. Traditional design method

For completeness, the traditional design method of the tilted angle is briefly presented here, which is based on obtaining the maximum annual irradiation. Fig. 10 is the flow chart of the traditional method, where β is the inclination of the PV array to the ground; H_m is the maximum annual irradiation received by the PV array in kWh; H_a is the annual irradiation in kWh; H_{Tn} is the daily irradiation received by the PV array on the nth day of the year in kWh; β_m is the optimal tilt angle of the maximum irradiation (H_m).

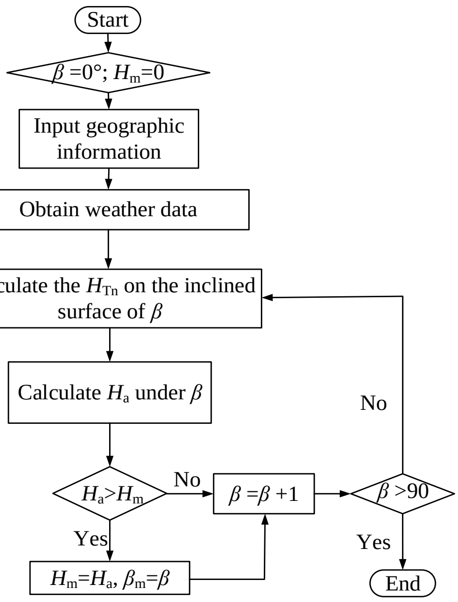


Fig. 10. Flow chart of the traditional method for tilt angle.

As the daily irradiation (H_T) at each tilt angle is difficult to obtain, it is necessary to convert the horizontal irradiation obtained from NASA database or the weather station into the irradiation at each tilt angle. In the conversion model of the horizontal irradiation, Hay model is more concise and practical, so it is more applicable in the engineering (Ulgen, 2006). In Hay model, when the PV module is at an angle of β to the ground, the formula for estimating the daily irradiation received is shown in (10):

$$H_T = H_b R_b + H_d \left[\frac{R_b H_b}{H_0} + 0.5\left(1 - \frac{H_b}{H_0}\right)(1+\cos\beta) \right] + 0.5\rho H (1-\cos\beta) \qquad (10)$$

where H_b is the daily direct irradiation of the horizontal plane in kWh; H_d is the daily horizontal diffuse irradiation in kWh; H_0 is the daily extraterrestrial irradiation on a horizontal surface in kWh; ρ is the surface reflectance, and generally takes 0.2; H is the total horizontal irradiation in kWh; R_b is the ratio of the direct irradiation of the inclined plane to that of the horizontal plane.

In (10), the direct irradiation H_b and the diffuse irradiation H_d need to be known for calculating the total irradiation H_T. Due to the limitation of measurement conditions, the daily H_b and H_d are often not available from the weather station. Therefore, the "direct-diffuse separation" model is used to separate the daily H_b and H_b from the daily horizontal irradiation H.

Considering the applicability to the region, this paper uses the "direct-diffuse separation" model proposed by Liu & Jordan (Khorasanizadeh and Mohammadi, 2016). By inputting the daily H, H_b and H_d can be estimated. In any area, by combining the "direct-diffuse separation" model and Hay model, the annual irradiation H_a received by the PV array at any inclination can be obtained.

Clearly, the irradiance in summer is strongest. However, the energy loss due to the temperature arise also reaches the maximum. Therefore, the power generation is not the largest when the irradiation is maximum.

5.2. Optimization of the design method

Based on the data from the module-level experimental platform, experimental results about the correlation between the meteorological factors and the power of PV modules are shown in Table II by SPSS software. In specific, the correlation is strong when the value nears 1.

Clearly, the power of PV modules is affected by the solar irradiance S, the module temperature T_m, the ambient temperature T, the wind speed W_s and the wind direction W_d. The correlation between the wind speed and the power of PV modules is weak. We did not consider the wind speed when determining the optimal tilt, because the effect of wind speed on PV system efficiency is weak.

Table II
Correlation between meteorological factors and the power of PV modules

Factor	S	T	T_m	W_s	W_d
Correlation	0.989	0.518	0.793	0.107	0.064

In this paper, the effects of the irradiance and the module temperature on the PV system are considered comprehensively. And the proposed method is based on the maximum annual output power of PV modules:

$$E_a = \sum_{n=1}^{365} (H_{Tn} * \eta_{mn}) \qquad (11)$$

where E_a is the annual power generation per unit area in kWh; η_{mn} is the daily average conversion efficiency of the module on the n-th day of the year.

5.2.1 Model of the module efficiency

According to (11), the module conversion efficiency η_m needs to be obtained before optimizing the tilt. However, there is still no simple or practical calculation method of η_m, which requires further modelling.

The main factors affecting the conversion efficiency of the PV module are the irradiance and the module temperature. As researched in (Wu et al., 2009), the optimized current and voltage of the module are as follows:

$$I_{mp} = I_{mp}^* S(1+a\Delta T)/S_{ref}$$
$$V_{mp} = V_{mp}^* (1+c\Delta T)\ln(e+b\Delta S) \quad (12)$$
$$\Delta T = T_m\text{-}25; \quad \Delta S = S/S_{ref} - 1$$

where, I_{mp}^* and V_{mp}^* are the current and the voltage at the maximum power point under STC condition; a, b and c are engineering coefficients: a = 0.25%/°C, b = 0.5, c = -0.288%/°C; T_m is the module temperature, S_{ref} =1000 W/m^2.

Combining (1) and (12), the conversion efficiency of the PV module can be derived as (13):

$$\begin{aligned}\eta_m &= \frac{I_{mp}V_{mp}}{AH_T} \\ &= \frac{I_{mp}^* \frac{S}{S_{ref}}(1+a\Delta T)V_{mp}^*(1+c\Delta T)\ln(e+b\Delta S)}{AS} \\ &= \eta_m^*[1+(a+c)\Delta T]\ln(e+b\Delta S)\end{aligned} \quad (13)$$

where η_m^* is the module conversion efficiency under STC.

In order to improve the accuracy of the model, SPSS software is used to fit (13) nonlinearly. It can be found that (a+c) is close to the temperature coefficient of the PV module, so the value of (a+c) is -0.41%/°C from the datasheet. The value of b is 0.093 after fitting. The corrected value is introduced into (13) to obtain the modified model.

It can be seen that the module efficiency decays at a rate of 0.41%/°C with the increasing of the module temperature. And the module efficiency increases exponentially as the irradiance increases. The efficiency model proposed in this paper considers the irradiation and the module temperature, which is simple and practical.

5.2.2 Calculation process of the proposed method

Based on the η_m model and (11), the traversing method is used to select the optimal tilt angle, and the flow chart is shown in Fig. 11. The β_m of the maximum power generation (E_m) is the optimal tilt angle.

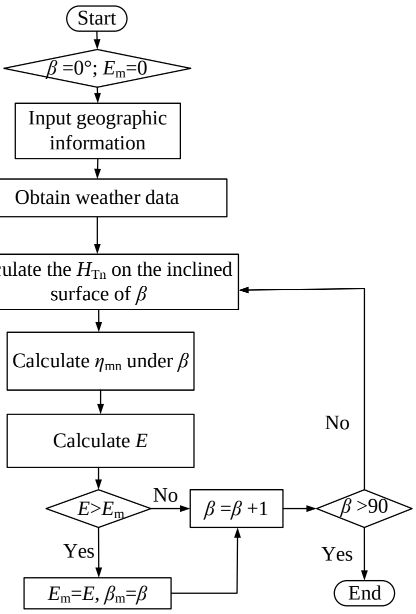


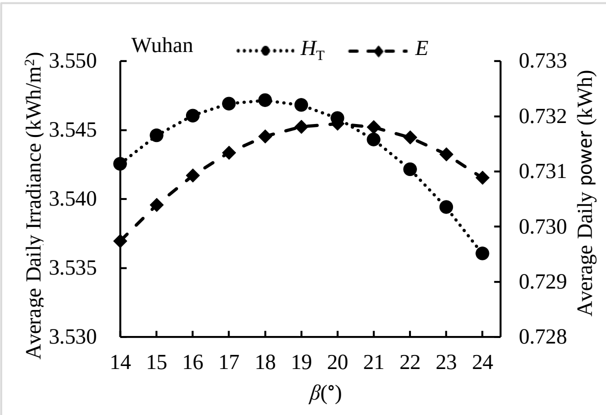
Fig. 11. Flow chart for designing the optimal tilt angle.

5.3. Simulation results of the proposed method

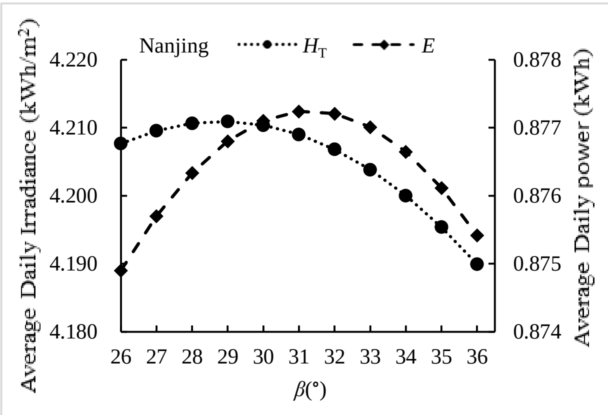
In order to verify the performance of the proposed method for the tilt angle, the meteorological data of Beijing, Nanjing and Wuhan are selected. The tilt angles are calculated according to the traditional method and the optimized method respectively. In Fig. 12, H_T and E are represented, varying with the tilt angles, where the abscissa is the tilt angle, the left ordinate is the average daily irradiance H_T; the right ordinate is the average daily power generation E of the module.

In Fig. 12, optimal tilt angles from two methods are different. Optimal angles in Wuhan are 18 degrees and 20 degrees respectively; optimal angles in Nanjing are 29 degrees and 31 degrees respectively; optimal angles in Beijing are 43 degrees and 45 degrees respectively. Based on the simulation results, it can be concluded that optimal angles of three regions are 2 degrees higher than those of the traditional method. The difference is due to the new method proposed in this paper that takes the module efficiency into consideration.

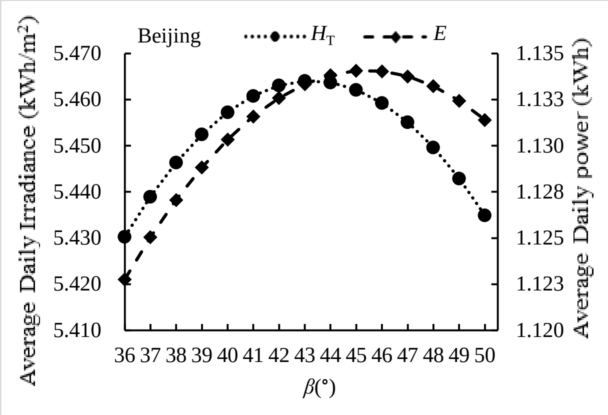
Taking the proposed 3 MW solar plant as an example, the tilt angles designed by two methods are 32 degrees and 34 degrees respectively. It is estimated to increase the power generation by 1450kWh in one year.



(a)



(b)



(c)

Fig.12. Curves of H_T and E under different angles. (a) in Wuhan, (b) in Nanjing, (c) in Beijing.

6. Conclusion

The annual PR of the proposed distributed solar plant is only 59%, which is much lower than the recommended value 75%. Based on the efficiency diagnosis, it is revealed that the traditional design for the module quantity in series of a PV array has the limitation, which easily leads to voltage mismatch between the PV array and the inverter. In order to deal with the voltage mismatch, it is proposed that the effect of the irradiation needs to be considered in the design of the module quantity in series. Simulation results show that the annual PR of the solar plant can be increased by 4.55%.

Furthermore, it is revealed that the traditional design of the tilt angle is unreasonable without considering the temperature. Meanwhile, a novel method is proposed to optimize the tilt of PV modules by maximizing the annual power generation. Simulation results verify the effectiveness of the proposed method.

Above research results provide guidance for the efficiency diagnosis and the optimal design for distributed solar plants. Besides, it is also conducive to accurate estimation of the power generation capacity of a given distributed solar plant.

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