Research on the optimal capacity ratio of single axis tracking photovoltaic power generation system

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Abstract. Aiming at the current situation of high LCOE (Levelized Cost of Energy) of photovoltaic (PV) power generation system, this paper focused on the calculation of optimal LCOE and capacity ratio of PV arrays to inverters on single axis tracking system in different solar resource areas. The effects of solar resource, system investment, land and finance on the optimal capacity ratio were analyzed, the conclusion was deduced at the end of this paper.

1. Introduction

Recently, domestic and foreign scholars have carried a lot of research work on economic performance of single axis tracking PV power generation system [1-7]. With the development of control technology, the improvement of reliability and cost down, single axis tracking system have been applied in more and more PV plants, which achieved more revenue than fixed installation generation plant. This paper focused on the optimization of capacity ratio of single axis tracking PV power generation system, calculate and analyze the influence of typical data in four solar resource areas, and each parameter to LCOE. Finally, the optimizing principle is deduced in the end.

2. The effects of overloading

2.1. The performance ratio (PR) of PV plant can be calculated as

\[ \eta_{PR} = (1 - \eta_{\text{shield}}) \times (1 - \eta_{\text{Temp}}) \times (1 - \eta_{\text{dispatch}}) \times (1 - \eta_{\text{DC\_Cable}}) \times (1 - \eta_{\text{Inverter}}) \times (1 - \eta_{\text{AC\_Cable}}) \times (1 - \eta_{\text{Trans}}) \]  

(1)

In this paper:

- \( \eta_{\text{shield}} \) (power loss caused by shield and dust) = 7.5%;
- \( \eta_{\text{Temp}} \) (power loss caused by Temp.) = 3.5%;
- \( \eta_{\text{dispatch}} \) (power loss caused by series and parallel) = 2%;
- \( \eta_{\text{DC\_Cable}} \) (DC line loss) = 3%;
- \( \eta_{\text{Inverter}} \) (Inverter loss) = 2.5%;
- \( \eta_{\text{AC\_Cable}} \) (AC line loss) = 1%;
- \( \eta_{\text{Trans}} \) (Transformer loss) = 2%;

Then, the \( \eta_{PR} \) is equal to 80.27%.

2.2. The PR in DC side is as follows
\[ \eta_{(PR, DC)} = (1 - \eta_{\text{shield}}) \times (1 - \eta_{\text{Temp}}) \times (1 - \eta_{\text{dispatch}}) \times (1 - \eta_{\text{DC_Cable}}) = 84.85\% \]  

(2)

The result shows that the maximum input power to inverter can only reach 84.85% of its nominal power, when the capacity ratio is 1:1 and solar insolation is 1000 W/m². Moreover, since the distribution of solar insolation is similar to sine curve, the operation time of the inverter at nominal power is very short (about 1 hour per day). Therefore, under this capacity ratio, the utilization of inverter and its back-end equipment is very low.

2.3. Analysis of the influence to PV plant in terms of overloading

As shown in figure 1:

- P_{max} > P'_{max}, the operation time of inverter at nominal power is longer, which can enhance the utilization of inverter and its back-end equipment effectively.
- T_2-T'_1 > T'_2-T'_1, the operation time per day is longer, that is because the inverter can only be started when the DC input power is larger than its threshold. Under the same solar insolation, the overloaded PV plant can output more power, especially in the morning and evening period, so more revenue can be acquired.
- The distribution of the output power of inverter is turned from sine to trapezoid when overloaded, which makes the output power of PV plant more stable than before. Furthermore, it is convenient for grid to control the active power.
- The devices can work safely since the inverter will not exceed its maximum allowed power even when overloaded.

Based on the analysis above, PV plant overloading is beneficial to the enhancement of revenue, utilization of devices and the stabilization of output power. The capacity ratio should be well considered because there is a balance point between the generation revenue and investment of PV plant. This paper selected the optimal LCOE as target function to study the ideal capacity ratio in different solar resource areas.

3. Simulation and calculation

3.1. Insolation data in typical areas
In order to study the optimized principle conveniently, the distribution trend of annual hours insolation data in Suzhou, Yangquan, Lhasa and Golmud is plotted separately as follows:

**Figure 2.** (a) Average hourly irradiation distribution per month in Yangquan, (b) Average hourly irradiation distribution per month in Suzhou, (c) Average hourly irradiation distribution per month in Golmud and (d) Average hourly irradiation distribution per month in Lhasa.

From figure 2 above:
- The distribution of solar insolation is similar to sine curve, the higher the monthly solar insolation, the better the solar resource in that month.
- The solar resource in Lhasa and Golmud is better than Suzhou and Yangquan, the highest average solar insolation and the average insolation per month of the former are both better than the latter.
- The distribution of solar resource in different regions in similar longitude is also different significantly. For instance, Golmud (N36°24′, E94°53′) has the highest average hourly insolation on May. The highest insolation of Lhasa (N29°30′, E91°15′) is distributed in 640~810 W/m², while 480~880 W/m² in Golmud. The difference between each month in Golmud is greater than Lhasa.

### 3.2. Calculation of LCOE
In this paper, the nominal capacity PV generation system is 3.5 kW, the range of capacity ratio is 1:1~1.8:1 (interval 0.05), and the nominal power of inverter is 3.5 kW. The degradation of PV module is 2.5% in the first year, 0.7% every year thereafter, the life of PV plant is 25 years. By importing the insolation data of four areas to PVSYST6.5, the total quantity of four areas in 25 years is listed in table
LCOE is the key parameter for evaluating the economic performance of PV plant. In order to realize PV parity as soon as possible, a lot of researches on LCOE of PV plant have been carried out [8-11]. The calculation method of LCOE is given out in literature [12]. In this paper, the formula of LCOE is:

\[
LCOE = \frac{(I_0 \times P_0 + I_{\Delta} \times P_{\Delta}) + \sum_{n=1}^{25} \frac{(P_0 + P_{\Delta}) \times (O + M)}{(1+i)^n} + \sum_{n=1}^{25} \frac{(P_0 + P_{\Delta}) \times F}{(1+i)^n}}{\sum_{n=1}^{25} \frac{Q_n}{(1+i)^n}}
\]

\(I_0\) — Installation cost per watt on capacity ratio 1:1, ¥/Wp;
\(I_{\Delta}\) — Installation cost per watt of overloaded part, ¥/Wp;
\(P_0\) — Capacity on capacity ratio 1:1, W;
\(P_{\Delta}\) — Capacity of overload part, W;
\(F\) — Field cost, ¥/Wp;
\(i\) — interest rate;
\(O\) — Operation cost per watt, ¥/Wp;
\(M\) — Maintenance cost per watt, ¥/Wp;
\(Q_n\) — Average quantity per year, kWh/year;
\(n\) — life of PV plant, year.

The parameters above are setting as table 2 below:

**Table 2. Parameters of LCOE.**

| \(I_0\) (¥/Wp) | \(I_{\Delta}\) (¥/Wp) | \(F\) (¥/Wp) | \(O + M\) (¥/Wp) | \(i\) | \(n\) (Year) |
|----------------|----------------|-------------|-----------------|-----|------------|
| 6              | 4.35           | 0.032       | 0.02            | 0.08| 25         |

The result of calculation of LCOE is shown in table 3:
Table 3. LCOE in four areas.

| Capacity ratio | Suzhou (¥/kWh) | Golmud (¥/kWh) | Yangquan (¥/kWh) | Lhasa (¥/kWh) |
|----------------|----------------|----------------|------------------|---------------|
| 1.00:1         | 0.5436         | 0.2975         | 0.4471           | 0.3132        |
| 1.05:1         | 0.5376         | 0.2943         | 0.4422           | 0.3098        |
| 1.10:1         | 0.5321         | 0.2914         | 0.4378           | 0.3068        |
| 1.15:1         | 0.5271         | 0.2888         | 0.4337           | 0.3040        |
| 1.20:1         | 0.5225         | 0.2864         | 0.4300           | 0.3015        |
| 1.25:1         | 0.5183         | 0.2842         | 0.4266           | 0.2995        |
| 1.30:1         | 0.5145         | 0.2825         | 0.4235           | 0.2982        |
| 1.35:1         | 0.5109         | 0.2813         | 0.4206           | 0.2977        |
| 1.40:1         | 0.5076         | 0.2807         | 0.4179           | 0.2979        |
| 1.45:1         | 0.5046         | 0.2809         | 0.4156           | 0.2988        |
| 1.50:1         | 0.5018         | 0.2817         | 0.4137           | 0.3002        |
| 1.55:1         | 0.4995         | 0.2832         | 0.4123           | 0.3021        |
| 1.60:1         | 0.4975         | 0.2852         | 0.4114           | 0.3044        |
| 1.65:1         | 0.4961         | 0.2877         | 0.4111           | 0.3070        |
| 1.70:1         | 0.4951         | 0.2906         | 0.4112           | 0.3098        |
| 1.75:1         | 0.4946         | 0.2938         | 0.4119           | 0.3129        |
| 1.80:1         | 0.4948         | 0.2973         | 0.4130           | 0.3163        |

*——Italic thickening part corresponding to the best LCOE of four areas

3.3. Calculation of annual utilization hours

Since the increment of capacity ratio will lead to power limitation when the solar insolation is greater than 1000 W/m², which will cause the decline of annual utilization hours. This paper calculated the annual utilization hours under different capacity ratio in Suzhou and showed the relationship between the reduction of LCOE and the decline of annual utilization hours.

Table 4. Relationship between LCOE, capacity ratio and annual utilization hours in Suzhou.

| Capacity ratio | 1:1  | 1.1:1 | 1.2:1 | 1.3:1 | 1.4:1 | 1.5:1 | 1.6:1 | 1.7:1 | 1.75:1 |
|----------------|------|-------|-------|-------|-------|-------|-------|-------|--------|
| Annual utilization hours | 1290 | 1290  | 1290  | 1290  | 1288  | 1282  | 1272  | 1266  |
| Hours decline | 0%   | 0%    | 0%    | 0%    | 0%    | 2%    | 8%    | 18%   | 24%    |
| Percentage of hours decline |       |       |       |       |       | 0.16% | 0.62% | 1.39% | 1.86% |
| LCOE(¥/kWh)     | 0.5436 | 0.5321 | 0.5225 | 0.5145 | 0.5076 | 0.5018 | 0.4975 | 0.4951 | 0.4946 |
| Percentage of LCOE reduction | 0% | 2.12% | 3.88% | 5.35% | 6.62% | 7.69% | 8.48% | 8.92% | 9.01% |

*The data above is the first operation year, with the increase of operating time, the difference of annual utilization hours and the power degradation of PV modules each year is getting smaller, finally tends to zero.

From table 4, it can be seen that:

- In Suzhou, when capacity ratio is less than 1.5:1, there would no limitation for output power.
- On the contrary, annual utilization hours will decrease with the increment of capacity ratio.
- LCOE is reducing when the annual utilization hour is declining. There is only 1.86% decrease in annual utilization hours while 9.01% decrease in LCOE. It means that the significant reduction of LCOE can be acquired by decreasing annual utilization hours slightly.
3.4. Analysis of calculation results
The following conclusions are obtained by calculating the capacity ratio in four areas:

- When the longitude is basically the same, the area with better average monthly irradiation has lower LCOE and capacity ratio, but the difference is not obvious. For example, the optimal capacity ratio is 1.35:1 in Lhasa while 1.4:1 in Golmud.

- When the latitude is basically the same, the LCOE in western China is much better than that in eastern because of the abundant solar resources. Also, the capacity ratio in the western region is much smaller than that in the East. For example, the optimal capacity ratio in Golmud (N 36°24', E 94° 53') is 1.4:1 while 1.65:1 in Yangquan (N37 °56', E113°33').

- Suzhou has the poorest solar resource in four areas. Therefore, the optimal capacity ratio is 1.75:1, the largest in four areas.

![Graphs](a)(b)(c)(d)(e)

**Figure 3.** $I_0-$LCOE, (b) $I_\Delta-$LCOE, (c) $i-$LCOE, (d) $(O + M)-$LCOE and (e) F-LCOE.
4. Analysis of the impact of parameter variation on LCOE and capacity ratio

Because of the different project conditions, the cost of land, construction, material, financing, operating and maintenance is totally different, according to the parameters listed in Table 2, the parameters in 0.9–1.1 (interval 0.05) range, trend of the LCOE and the optimal capacity ratio in Golmud is calculated, the result is shown below:

From Figure 3, it can be seen that:

- LCOE and capacity ratio will increase with the increment of \( I_0 \). This is due to the increase in the installation cost will not bring more power generation benefits. Therefore, in order to get better LCOE, the capacity ratio must be increased.
- LCOE will increase with the increment of \( I_\Delta \), and the optimal capacity ratio will decrease with the increment of \( I_\Delta \). This is due to the fact that the higher installation cost of the overloaded part has achieved a balance with the power generation. Therefore, more revenue can be acquired when the \( I_\Delta \) is lower.
- As the part of the whole system cost, \( i, (O+M) \) and \( F \) is little, the influence of which to capacity ratio is slight and ignorable. LCOE will monotonically increase with the three parameters increment.

5. Conclusions and perspective

5.1. Conclusions

By calculating the LCOE under different capacity ratio of single axis tracking system in four different solar resources areas, the optimal capacity ratio is given out, and the influence of investment cost on capacity ratio is analyzed.

- The distribution trend of monthly average irradiation hour of solar resources has a significant impact on capacity ratio. The area with higher monthly irradiation resource and smaller irradiation difference, has smaller capacity ratio.
- Since the solar resources in western China is abundant, the capacity ratio is obviously lower than that in eastern region. If the capacity ratio is same, the revenue in western China is better than eastern.
- The relationship between the capacity ratio and non-overloaded part cost per watt will increase monotonously, in order to reduce the capacity ratio, the cost of non-overloaded part should be reduced as lower as possible.
- The relationship between the capacity ratio and overloaded part cost per watt will decrease monotonously. The decline of the optimal capacity ratio will lead to the ascent of LCOE. Therefore, the cost of overloaded PV plant should be reduced as much as possible.
- Although the overloading will lead to the loss of power generation in some periods, the loss is completely acceptable compared with the cost down of LCOE significantly.
- Despite the impact of interest rate, operation and maintenance cost and the cost of land on the optimum capacity ratio can be ignored, the impact on LCOE is remarkable, therefore the three costs should be reduced as far as possible.
- In the construction of PV plant, constricted by land area, declare installation capacity and other factors, in order to make the project be constructed with the best capacity ratio, the declare of land area should be referred to the optimal capacity ratio.

5.2. Perspectives

Limited by length, this paper has carried the study on single axis tracking PV power system in four areas only. In the future, the research range can be extended to more solar resource areas and types of support bracket, which makes the results more representative and general.

Furthermore, IRR (Internal Rate of Return), investment payback period and other economic index can be researched to evaluate the comprehensive economy of PV power plant.
References
[1] Jiang H Q, Tian J K, Jiang Z J and Gu J F 2009 Impact of using auto-tracking system on electricity tariff for PV station Electr. Power Construction 30 76-8
[2] Wang H B 2012 Economic analysis on increasing single axis tracking device of photovoltaic power system Energy Eng. 2012 62-5
[3] Liu Q C and Shen H 2011 Solar tracing system and application Guangdong Electric Power 24 66-9
[4] Dousoky G M, El-Sayed A H M and Shoyama M 2011 Maximizing energy-efficiency in single-axis solar trackers for photovoltaic panels IEEE International Conference on Power Electronics & Ecce Asia (Jeju, Korea) pp 1458-63
[5] Dolara A, Grimaccia F, Leva S, Mussetta M and Faranda R 2012 Performance analysis of a single-axis tracking PV system IEEE J. Photovolt. 2 524-31
[6] Maatallah T, Aliim S E and Nassrallah S B 2011 Performance modeling and investigation of fixed, single and dual-axis tracking photovoltaic panel in Monastir city, Tunisia Renew. Sustain. Energ. Rev. 15 4053-66
[7] Bahrami A, Okoye C O and Atikol U 2017 Technical and economic assessment of fixed, single and dual-axis tracking PV panels in low latitude countries Renewable Energ 113 563-79
[8] Delfanti M, Olivieri V, Erkut B and Turturro G A 2013 Reaching PV grid parity: LCOE analysis for the Italian framework International Conference & Exhibition on Electricity Distribution (Stockholm, Sweden) pp 1-4
[9] Said M, El-Shimy M and Abdelraheem M A 2015 Photovoltaics energy: Improved modeling and analysis of the levelized cost of energy (LCOE) and grid parity – Egypt case study Sustain. Energ. Technol. Assessments 9 37-48
[10] De Sabata A, Margineanu D, Jovanovic D and I Luminosu 2014 Economics of a small-scale, grid-connected PV system in Western Romania: An LCoE analysis International Symposium on Electronics & Telecommunication (Timisoara, Romania) pp 1-4
[11] Talavera D L, Muñoz-Cerón E, Casa J D L, Ortega M J and Almonacid G 2011 Energy and economic analysis for large-scale integration of small photovoltaic systems in buildings: The case of a public location in Southern Spain Renew. Sustain. Energ. Rev. 15 4310-9
[12] Hernández-Moro J and Martínez-Duart J M 2013 Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution Renew. Sustain. Energ. Rev. 20 119-32