Performance Evaluation of 5kWp grid connected polycrystalline Si-based Photovoltaic Plant

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Abstract — With the increasing penetration of Solar Energy in the distribution grid, it becomes necessary to measure the variability of solar generation output which is affected by factors such as geographic location, Photovoltaic (PV) technology used, and weather conditions. Performance evaluation of such an integrated system will help in the process of designing and maintaining efficient operating conditions for new installations. This paper presents half-year performance analysis of 5kWp grid-interconnected solar power plant installed on the rooftop of a residential location in IIT Kanpur. The site receives good average solar insolation of 4.85 kWh/m²/day with the average temperature varying between 17°C to 35°C in December-January and May-June respectively. Based on IEC-61724 standard, Key Performance Indicators (KPI) such as generated energy, yield, array and inverter efficiencies, performance ratio, and capacitor factor are calculated.

Keywords— Capacity Factor, Grid Connected, Photovoltaic, Performance analysis, Performance Factor

I. INTRODUCTION

Increasing demand for electricity and changing climate caused inclination towards generation from renewable energy sources. The most common renewable sources considered for assisting the traditional generation are solar and wind generation. The location and environmental conditions of India, further support large-scale electricity generation from wind and solar power plants [1].

For the past decade, the generation from solar has grown in parallel with the wind power generation, due to its ease of availability and microgeneration possibility [2]. Under National Solar Mission, an initiative of the Government of India and State Governments to promote solar power, the target capacity was increased from 20GW to 100GW by 2021-22. The cumulative capacity which was 12 GW at the end of the fiscal year 2017, has reached 23GW in April 2018. Approximately, 22GW of grid-connected solar power and 711MW of off-grid solar power is installed at the end of April 2018 [3]. The present concern of the Government of India is to prepare analysis reports of solar power plants installed in India to have the necessary information, which will help in designing and building new solar power plants.

The International Energy Agency has published a report under the photovoltaic power systems programme, which focuses on the analytical assessment of grid-connected photovoltaic plant performance [4]. The report includes 20 different nations and comparative assessment of the performance of different PV plants installed in these nations. A similar document presenting the comparative assessment of solar PV plants installed in India is required to be prepared which will facilitate actual field analysis of PV plants and effectively increase the technical feasibility of the PV installation. It is seen that performance evaluation has affected the parameter selection for PV installations and increasing the PV performance. For example, in [5] it can be seen that the average performance ratio of installations in Germany was improved from 0.66 in 1995 to 0.84 in 2010, with the changes applied after studying the performance analysis reports of International Energy Agency.

In this paper, the performance of 5kWp solar power plant installed in the Indian Institute of Technology (IIT), Kanpur is evaluated based on different key performance indicators described in the literature [4-7]. The solar power plant is part of the 100kWp solar installation, carried under the SmartCity Pilot project awarded to IIT Kanpur. With the proposed target capacity of 100GW in coming years, these performance analysis reports with stated KPI’s will guide the increasing solar PV penetration.

II. DETAILS OF THE INSTALLED SYSTEM

The solar power plant selected for evaluation is one of the 20 installations on different rooftops in the campus of IIT Kanpur. In total, 100 kWp solar PV is connected to IIT Kanpur’s distribution grid. To study the behavior of individual installation, the single 5kWp plant is selected.

20 polycrystalline panels of 250Wp are connected in two parallel strings, to get 5kWp capacity. The panels are mounted on fixed tilted (26.5°) galvanized iron structure, which is fixed on the rooftop of a house with RCC blocks to sustain heavy wind pressure. The two strings of PV panels are connected to a single grid tie inverter. The inverter has two inbuilt MPPTs which track the maximum power in both the strings.

AC output of the inverter is fed to the AC grid of IIT Kanpur at 240V. Voltage range in the Inverter can be defined by the user and is 185-270 V in this case. The details of the PV panel and inverter specifications are provided in [8] and [9] respectively.

III. DATA MONITORING AND LOGGING

Grid tie inverters communicate to the remotely located server over Wi-Fi and data is available on the web portal of grid tie
The rated PV capacity of the system is given as,

\[ P_{PV}(\text{rated}) = V_{PV} \times I_{PV} \]  

where, \( P_{DC} \) is the DC power in watts. \( V_{PV} \) and \( I_{PV} \) are the voltage and current of the PV system.

The rated PV capacity of the system is given as,

\[ P_{PV}(\text{rated}) = V_{PV(SC)} \times I_{PV(SC)} \]  

where, \( P_{PV}(\text{rated}) \) is the rated capacity of the PV plant in watts or kWp and \( V_{PV(SC)} \), \( I_{PV(SC)} \) are the open circuit voltage and short circuit current of the panel respectively.

The total DC energy for a day, month, and a year is calculated as:

\[ E_{DC/\text{day}} = \sum_{i=1}^{n} V_{PV} \times I_{PV} \times (T_n - T_{n-1}) \]  

\[ E_{DC/\text{mon}} = \sum_{i=1}^{N} E_{DC/\text{day},t} \]  

\[ E_{DC/\text{yr}} = \sum_{i=1}^{12} E_{DC/\text{mon},t} \]  

where, \( n \) is the period up to which the data is recorded in a given day and \( T_n - T_{n-1} \) is the minimum time interval for which the power is recorded. \( N \) is the number of plant operation days.

The converted AC power is calculated as,

\[ P_{AC} = V_{AC} \times I_{AC} \]  

where, \( P_{AC} \) is the AC power output; \( V_{AC} \) and \( I_{AC} \) are the AC Voltage and Current at the output of the plant respectively.

The total AC energy \( E_{AC} \) for the day, month, and year is calculated as,

\[ E_{AC/day} = \sum_{i=1}^{n} V_{ACn} \times I_{ACn} \times (T_n - T_{n-1}) \]  

\[ E_{AC/\text{mon}} = \sum_{i=1}^{N} E_{AC/day,t} \]  

\[ E_{AC/\text{yr}} = \sum_{i=1}^{12} E_{AC/\text{mon},t} \]  

2. Yield

a) Array Yield

The total energy output obtained from PV array over a defined period (day, month, or year) per peak rated PV power is considered as array yield. The ratio defines the average hours for which the panel receives rated power for conversion. The daily Array Yield (\( Y_{A,\text{day}} \)) is given as:

\[ Y_{A,\text{day}} = \frac{E_{DC/\text{day}}}{P_{PV(\text{rated})}} \times \frac{P_{PV(\text{rated})}}{P_{PV(\text{rated})}} \]  

Likewise, the monthly (\( Y_{A,\text{mon}} \)) and yearly (\( Y_{A,\text{yr}} \)) Array Yields are:

\[ Y_{A,\text{mon}} = \frac{E_{DC/\text{mon}}}{N \times P_{PV(\text{rated})}} \times \frac{P_{PV(\text{rated})}}{P_{PV(\text{rated})}} \]  

\[ Y_{A,\text{yr}} = \sum_{i=1}^{12} Y_{A,\text{mon}} \]  

b) Field Yield

The total AC energy obtained at the inverter output over a defined period (day, month, or year) per peak rated PV power is defined as the Field Yield. The daily (\( Y_{F,\text{day}} \)), monthly (\( Y_{F,\text{mon}} \)), and yearly (\( Y_{F,\text{yr}} \)) Array Yield are given as:

\[ Y_{F,\text{day}} = \frac{E_{AC/day}}{P_{PV(\text{rated})}} \times \frac{P_{PV(\text{rated})}}{P_{PV(\text{rated})}} \]


\[ Y_{F,\text{mon}} = \frac{E_{AC/\text{mon}}}{N \times P_{PF}} \text{ (hrs.)} \quad (14) \]

\[ Y_{F,\text{yr}} = \sum_{t=1}^{12} Y_{F,\text{mon}} \text{ (hrs.)} \quad (15) \]

c) Reference Yield

Reference Yield \( Y_R \) is the ratio of total in-plane solar irradiance \( (G_t) \) to the array reference irradiance. It represents the energy available under ideal conditions. The reference irradiance is taken as 1kW/m² and the reference yield represents the number of peak sun hours in kWh/m². The monthly average reference yield \( Y_{R,\text{mon}} \) is given as,

\[ Y_{R,\text{mon}} = \frac{G_{i,\text{mon}}}{G_R} \text{ (hrs.)} \quad (16) \]

\( G_{i,\text{mon}} \) is the monthly average irradiance incident on a horizontal surface (kWh/m²/day) and \( G_R \) is the array reference irradiance.

3. Energy Losses

The grid tie power plant experiences energy loss during the process of conversion of energy from radiation energy to DC energy and, then, DC to AC energy. The losses are calculated from the energy data available from the database.

a) Array Capture losses

Losses occurred during conversion of irradiance energy to DC energy due to higher cell temperature, wiring, string diodes, low irradiance, partial shadowing, mismatching, and dust comprise together for Array capture losses. The yearly array capture losses \( L_{Cy,\text{yr}} \) are given as:

\[ L_{Cy,\text{yr}} = Y_R - Y_{A,\text{yr}} \text{ (hrs.)} \quad (17) \]

\[ L_{Cy} = E_{\text{ref}} - E_{\text{DC/yr}} \text{ (kWh)} \quad (18) \]

where,

\[ E_{\text{ref}} = \sum_{t=1}^{N} G_{i,d} \times N_p \times A_m \quad (19) \]

\( G_{i,d} \) is the average irradiance incident on a horizontal surface(kWh/m²/day), \( N_p \) is the number of panels, and \( A_m \) is the area of each panel.

b) System Losses

The losses incurred by the Inverter and passive circuit elements are included in the system losses \( L_s \) and are given as:

\[ L_s = Y_A - Y_E \text{ (hrs.)} \quad (20) \]

The yearly system losses \( L_{s,\text{yr}} \) are given as:

\[ L_{s,\text{yr}} = E_{\text{DC/yr}} - E_{\text{AC/yr}} \text{ (kWh)} \quad (21) \]

4. Conversion Efficiency

a) Instantaneous Array efficiency \( \eta_{PV,\text{inst}} \)

This efficiency represents instantaneous energy generated by the PV array \( P_{array} \) for given instantaneous solar irradiance \( G_{inst} \).

\[ \eta_{PV,\text{inst}} = \frac{P_{array}}{G_{inst} \times A_m} \quad (22) \]

The Daily \( \eta_{PV,\text{daily}} \) and Monthly \( \eta_{PV,\text{mon}} \) average PV Array Efficiency is given as,

\[ \eta_{PV,\text{daily}} = \frac{E_{\text{DC/day}}}{G_{i,d} \times A_m} \quad (23) \]

\[ \eta_{PV,\text{mon}} = \frac{E_{\text{DC/mon}}}{N \times G_{i,\text{mon}} \times A_m} \quad (24) \]

b) Inverter Efficiency \( \eta_{inv} \)

Similar to Array Efficiency, Inverter efficiency can be calculated instantaneously, daily, monthly and yearly. The most effective would be to observe the instantaneous efficiency which helps in the real-time analysis of inverter operation. In general, the monthly inverter efficiency is given as:

\[ \eta_{inv,\text{mon}} = \frac{E_{\text{DC/mon}}}{E_{\text{AC/mon}}} \quad (25) \]

c) System Efficiency

This efficiency defines the operating condition of the entire plant.

\[ \eta_{sys} = \eta_{PV} \times \eta_{inv} \quad (26) \]

5. Performance ratio

The ratio of final yield to the reference yield is called the performance ratio \( (PR) \) of the plant. It shows the effectiveness of the plant by comparing the actual generated energy to the possible maximum energy generation. It includes the effect of different factors such as irradiation, temperature and other weather conditions.

\[ PR = \frac{Y_E}{Y_R} \quad (27) \]
6. Capacity Factor

It is the ratio of energy output to the amount of energy the plant could generate if operated continuously at rated power for the defined number of days. The monthly \( CF_{mon} \) and yearly \( CF_{yr} \) capacity factor is given as:

\[
CF_{mon} = \frac{Y_{F,mon}}{N \times 24} \quad (28)
\]
\[
CF_{yr} = \frac{Y_{F,yr}}{N \times 24} \quad (29)
\]

V. RESULTS AND DISCUSSIONS

Performance analysis is derived for a period of six months and the results are as follows.

A. Irradiance

For comparison, irradiance data is taken from the daily real-time irradiance data, available on the NASA website for the above duration [8]. From Fig. 1 it can be observed that the available irradiance is minimum in December and maximum in September. The average irradiance available is 4.16kwh/m²/day for the selected six months duration. The Irradiance is observed to be increasing from January.

B. Temperature

The temperature data is collected from two different sources i.e. NASA real-time data (Source 1) [8] and the temperature data available from the time and date website (Source 2) [9]. The data from the sources and the deviation error is shown in Fig. 2. For the selected duration, the average temperature is observed to be maximum in September (31\(^{\circ}\)C) and min in January (12\(^{\circ}\)C). Increase in temperature is observed from the month of February. The data available from source 2 is more accurate as compared to the data available from source 1. The maximum deviation of source 1 from source 2, taken as a percentage of source 2, is 34.45% for the month of January and maximum negative deviation of -8.07% for the month of September.

C. Generated Energy

The energy generated by the inverter is calculated for 5 min intervals and summed to calculate total generated DC and AC energy for the selected duration and is plotted in Fig. 3.

The maximum generation of 586.7 units (kWh) DC Energy and 537.29 units (kWh) AC Energy is observed in the month of February. The irradiance for the month of February is less than that for September but the sun hours available are observed more. Hence total generated energy is higher for the month of February. The minimum generation is observed in the month of December which is 425.65 units of DC energy and 390.05 units of AC energy. During the period of observation, average DC energy is 512.73 units/month and average AC energy is 472.47/month.

D. Yield

The reference yield, actual array yield, and actual field yield are calculated for each month and are shown in the Fig. 4. The reference yield varies from a minimum of 3.19 Hrs/day to a maximum of 4.99 Hrs/day in December and September respectively. The monthly average array yield values are ranging from 2.75 to 4.19 Hrs/day or
kWh/kW with a minimum in December and maximum in February.

![Graph](image)

Fig. 4. The variation of monthly average daily yields

The actual average final Yield received is 3.28 Hrs. The maximum final yield is 3.84 Hrs which is observed in the month of February. On an average, total reference yield is 4.56 Hrs/day, total array yield is 3.56 Hrs/day, and total final yield is 3.28 Hrs/day.

E. Energy Losses

Fig. 5. presents the capture losses and system losses observed in the system for the selected duration. The capture losses are observed to be decreasing from 1.18 Hrs. in September to 0.20 Hrs. in February. On the other hand, the system losses depend on the installed panels and inverter. The system losses are almost constant with minimum observed in December of 0.19 Hrs/day.

![Graph](image)

Fig. 5. Monthly average losses observed in the installed system

F. Conversion Efficiency

The solar panel efficiency for each month is shown in Fig. 6. The panel efficiency is 15.40% under standard test conditions of 1000W/m2 and 25°C [10]. The efficiency is calculated by averaging the daily values for each month. The maximum efficiency of 14.78% is observed in the month of February which is 4% less than the standard manufacturer mentioned efficiency. The minimum efficiency of the panels observed is 11.84% which is 23.14% less than standard test condition efficiency in the month of September. The average panel efficiency is observed as 13.23%.

![Graph](image)

Fig. 6. Monthly average PV panel efficiency

![Graph](image)

Fig. 7. Monthly average inverter efficiency

Fig. 7 shows the inverter efficiency calculated for each month. The European efficiency from the datasheet is 97.5% [11] and the efficiency calculated, ranges between 91.49% to 92.80%. The minimum efficiency is observed in the month of February while the maximum efficiency in January. The inverter operates with an average efficiency of 92.22%.

G. Performance ratio

Fig. 8 shows the performance ratio (PR) of the system for each month and the average PR for the duration. The average monthly PR values are ranging from 71.30% to 88.23% and six months average is 79.41%. The performance of the plant is observed to be better than some of the other installations in India [13-15]. This may be the advantage of having a simple grid-tie system and not connecting any storage as an additional subsystem which will reduce the overall efficiency of the plant and hence PR.

![Graph](image)

Fig. 8. Monthly average performance ratio and average performance ratio for six months
H. Capacity Factor

<table>
<thead>
<tr>
<th>Month</th>
<th>Capacity Factor</th>
<th>Average Capacity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep-17</td>
<td>14.64</td>
<td></td>
</tr>
<tr>
<td>Oct-17</td>
<td>15.26</td>
<td></td>
</tr>
<tr>
<td>Nov-17</td>
<td>12.80</td>
<td></td>
</tr>
<tr>
<td>Dec-17</td>
<td>10.65</td>
<td></td>
</tr>
<tr>
<td>Jan-18</td>
<td>12.70</td>
<td></td>
</tr>
<tr>
<td>Feb-18</td>
<td>15.99</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9. Monthly average capacity factor and average capacity factor for six months

The capacitor factor is calculated for the selected duration and is shown in Fig. 9. The average value of capacity utilization factor (CUF) is 13.67% calculated for six months of the monitoring period. It ranges between 10.65% to 15.99%. The capacity factor depends on the climatic conditions. It is within the range observed at other installed locations in India [13-15].

VI. CONCLUSION

The performance parameters for a 5kWp grid-connected PV system are evaluated after six months of monitoring from September 2017 to February 2018. The parameters are calculated for Daily, Monthly, and for whole monitoring period. The average solar irradiation available for generation is 4.16 kWh/m²/day which generated 512.73 kWh of average DC energy and 472.47 kWh of average AC energy per month. The total average reference yield, array yield, and final yield are observed as 4.56 Hrs/day, 3.56 hrs/day and 3.28 Hrs/day, respectively. The average PV array efficiency observed for the monitoring duration is 13.23% when Inverter is operating with an efficiency of 92.22%. The performance ratio and the capacity factor are 0.79 and 0.1367, respectively, observed for the period of monitoring. The capacity factor is calculated assuming that the solar irradiance is constant during the monitoring period. Therefore, the computed capacity factor is less accurate. The analysis provides a reference for future solar installation projects and can be extended to the data compiled for a year which will provide better insight into the performance. Factors such as soiling loss, panel degradation because of temperature, shadow loss, economic analysis, etc., can be further considered for performance evaluation.

REFERENCES


