Real time performance assessment of utility grid interfaced solar photovoltaic plant

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ABSTRACT

Continuous monitoring of large-scale solar photovoltaic (PV) installations is necessary to check the deterioration and monitor the performance of the PV plant. Fault diagnosis is crucial to ensure the PV plant operates safely and reliably. This paper presents a diagnosis methodology based on current-voltage (I-V) and PV characteristics to monitor and assess the behavior of solar PV. In this paper, I-V curve characterization using an I-V curve tracer is used to check the deterioration and diagnosis of the PV panels. The real-time performance of the 50.4 kWp rooftop solar grid interfaced PV plant is investigated and analyzed using I-V and PV curve tracers in real-time conditions. The overall performance of solar PV is assessed on a real-time test system in different scenarios such as variable climatic conditions, partial shading conditions, aging of solar panels, short circuit conditions, and dust decomposition. Furthermore, the performance assessment of solar PV is evaluated using performance indicators such as open circuit voltage index, short circuit current index, fill factor, and performance ratio.

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1. INTRODUCTION

As the concern over the energy crisis and global warming has grown in recent years, the world is turning towards alternate energy sources [1]–[3]. Solar power is one of the accessible alternative energy resources that has been expanding quickly and gaining a lot of attention. Nevertheless, owing to variable climate change, the photovoltaic (PV) modules witness deterioration, affecting the lifespan, power reduction, overall efficiency, reliability, and return on the PV investment [4], [5]. Hence, PV plants must be monitored and preserved to ensure continuous operation and to know its current status [6]. The efficacy of PV plant is measured with the help of current-voltage (I-V) and PV curves. The I-V and PV curves provides information about PV plant and timely identification of failure of modules and allows us to replace the modules. I-V curve tracing delivers a quick and precise approach for determining real-time module monitoring of Solar PV modules. This type of tracing method is beneficial for verifying and meeting the PV product's specifications while validating and testing solar installations. In this context, several I-V curve extraction techniques that use transistors, electronic loads, direct current to direct current (DC-DC) converters, variable resistive loads, and capacitive loads have been documented in the literature [7]. Characterization of PV modules using variable resistances is reported in [8]–[10]. This approach needs various ranges of variable resistors for various PV module ratings. This technique is hence appropriate for low-power PV production applications. The I-V curves created using this method are not accurate or uniform. Moreover, this method's regular human involvement needs likely to result in lower accuracy. Characterization of PV panels using multiple resistors has been reported in [11] to analyze the performance of solar PV plants. However, this method requires a manual change of resistors and is time-consuming. Hence, solar irradiance and thermal conditions change during measurement. The capacitive type of tracer is realized in [12]–[14] to monitor performance of PV modules. This technique is inexpensive, and the measurement period is small. Nevertheless, this method needs significant amount of capacitance, particularly for big PV arrays. Another primary tool to extract I-V curves is the variable electronic load with linear MOSFET, and drain resistance is reported in [15]. This method is easier and less expensive than capacitive loads for low voltages. The change of resistance is easily possible by changing gate voltage. This approach uses a transistor instead of a resistor to consume the energy generated by the PV generator. As a result, a heat sink could be required to keep the working junction temperature within the advised ranges. The heat sink adds weight and thickness to the device when required, restricting its use. Bidirectional DC-DC converters are implemented in [16]–[19] to produce I-V curves that accurately depict the behavior of operating PV generators. These methods demand significant effort and extra circuitry parts, though. The disadvantage of this approach is that the transistor uses up all the power, which might lead to device temperatures that are too high. The device can be made bulky and heavy by adding a heat sink to help with heat release. The PV panels are subjected to degradation and failure under different environmental conditions over some time. These state-of-the-art devices enable real-time, high-resolution measurements of the electrical characteristics of individual PV modules and strings, providing invaluable insights into the overall health and efficiency of the entire solar plant. The I-V curve-based diagnosis is an important tool for diagnosing the performance of PV panels in various scenarios. This work uses a standard I-V curve tracer of rating 500 W and 1500 V, to assess the condition of the panels/strings during starting and yearly plant servicing. The performance of grid interfaced PV plant is performed using I-V curve tracer at the string level on a 50.4 kWp solar plant located on the rooftop of Shri Vishnu Engineering College for Women, Bhimavaram. The key contributions of the manuscript are addressed as follows in the revise manuscript.

- The foremost contribution of the present paper is to track and estimate the performance of real-time solar PV plant in various abnormal cases such as partial shading, dust deposit, cell cracking, variable weather condition, and short circuit condition.
- The real time data is compared with module manufacturer's reference data sheet in various abnormal scenarios
- The performance assessment of solar PV is calculated using performance indicators for instance open circuit voltage index, short circuit current index, fill factor, and Performance ratio
- The real time results of grid connected solar PV plant in various situations are compared with the published work. The results so obtained are in alignment with the results of the earlier work

The structure of the manuscript is given here. Section 2 discusses the mathematical modeling of solar PV cell. Section 3 deliberates about the grid-interfaced solar PV plant. The results are articulated in section 4. Conclusions are provided in section 5.

2. MATHEMATICAL MODELING OF PV CELL

The equivalent model as shown in Figure 1 is essentially described to estimate the I–V curve in various scenarios and to understand and analyze the behavior of PV panels. The popular PV model is single diode model since it is simpler to use and has a fewer variable. The mathematical model includes a diode and a current source linked in parallel. The series resistance accounts for losses produced internally and voltage drop due to photo voltaic current. The shunt resistance characterizes the leakage current flowing to ground when the diode operates in reverse bias condition.

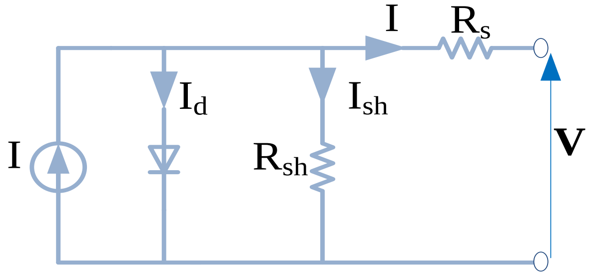

Figure 1. Equivalent circuit of solar PV

The basic diode equation of solar cell as shown by (1) [20].

$$I = I_s - I_d - I_{sh} = I_s - I_0\left[e^{\frac{q(v+IR_s)}{\eta KTN_s}} - 1\right] - \left(\frac{V+IR_s}{R_{sh}}\right) \quad (1)$$

where I is total current delivered by PV generator; R_s is series resistance; R_{sh} is the shunt resistance; I_0 is the reverse-bias current of the diode; q is charge of an electron (1.6 X 10-19 C); K denotes Boltzmann constant (1.380649×10-23) J/K; T is PV temperature of solar cell in degree kelvins; and η is diode ideality factor. Where I_d is voltage dependent current given by recombination.

$$I_d = I_0\left[\exp\left(\frac{(V_T + IR_s)}{\eta V_T}\right) - 1\right] \quad (2)$$

Where Thermal voltage is given by (3).

$$V_T = \frac{kT_c}{q} \quad (3)$$

Where I_{sh} represents shunt branch current.

$$I_{sh} = \frac{V+IR_s}{R_{sh}} \quad (4)$$

For a given photovoltaic array N_s represents number of cells connected in series under standard test conditions (STC) conditions. Then

$$I_{module} = I_{cell} \quad (5)$$

$$V_{module} = N_s * V_{cell} \quad (6)$$

The module current is represented by (7).

$$I_M = I_L - I_0\left[exp\left(\frac{(V_M + I_M N_s R_s)}{\eta N_s V_T}\right) - 1\right] - \frac{V_M + I_M N_s R_s}{N_s R_{sh}} \quad (7)$$

Where I_L denotes light current; I_0 denotes diode reverse saturation current; I_M and V_M are the array current and voltage; The thermal voltage V_T, η represents ideality factor; where 'a' represents modified ideality factor for array

$$a = \frac{N_s \eta k T_c}{q} \quad (8)$$

3. GRID INTERFACED SOLAR PV PLANT

The grid interfaced solar PV plant and its line diagram is revealed in Figures 2 and 3. A grid-interfaced 50.4 kWp PV system consists of 160 solar panels of 315 Wp rating which are connected to 8 strings. Each string consists of 20 modules arranged in tandem. The 8 strings are joined to the DC junction box through cable.

Figure 2. 50.4 kWp grid tied rooftop solar plant

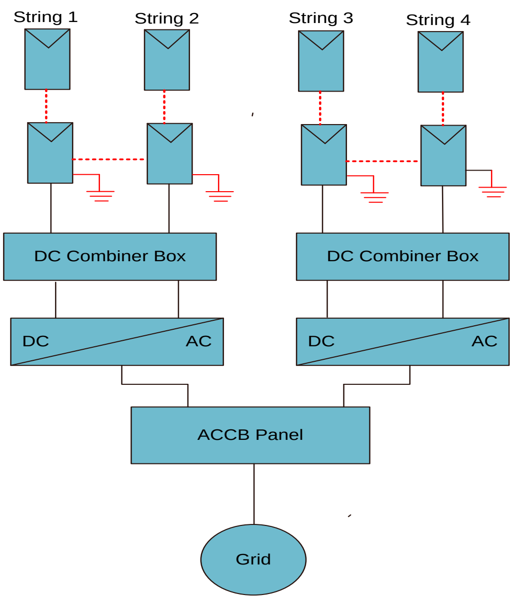

Figure 3. Single line diagram of 50 kWp grid interfaced solar PV plant

The plant consists of two inverters of rating 25 kVA and each inverter is connected to 4 strings. The output of two inverters is connected to AC combiner junction box through a connecting cable. The output of AC combiner box (ACCB) is connected to cross-linked polyethylene (XLPE) cable to the distribution grid.

4. RESULTS AND DISCUSSION

Experimental framework of grid connected PV solar using I-V curve tracer is displayed in Figure 4. The real-time experimental results are performed under various working conditions to analyze the 50.4 kWp solar-configured PV plant performances using an I-V curve tracer. The electrical parameters of PV module and technical specifications of I-V curve tracer are given in Tables 1 and 2. During experimentation, the following case studies are considered.

Case 1: Characterization of PV system under variable environmental conditions
Case 2: Performance analysis in partial shading condition
Case 3: Performance analysis under dust accumulation on solar panels
Case 4: Performance analysis under aging condition
Case 5: Performance analysis short circuit condition.

Figure 4. Experimental framework of grid connected PV solar using I-V curve tracer

Table 1. Technical specifications of HT I-V curve tracer

Description	Range
Wattage	500 W
Voltage	0-1000 V
Current	0-15 A

Table 2. Specifications of PV module

Electrical parameter	Value
Module capacity	315 wp
No of cells (Polycrystalline)	72
Open circuit voltage	46.15 V
Short circuit current	8.91 A
Voltage at peak power	36.92 V
Current at peak power	8.55 A
Inverter rating	25 kVA
efficiency	16.26
Series resistance R_{se}	1 Ohm
Cell temperature coefficients	
Open circuit voltage (α)	-0.3 % / 0C
Short circuit current (β)	+0.05 % / 0C
Nominal power (γ)	-0.40 % / 0C

4.1. Case 1: Under variable environmental conditions

I-V and PV curves display information about the cell's state and directly depend on temperature and irradiance levels. Figure 5 illustrates the real-time I-V and PV characteristics measured using an I-V curve tracer when the PV module operates under variable weather conditions. Insolation and temperature are two environmental variables influencing a PV module's performance. The increase in solar irradiance raises the short circuit current generated by solar photovoltaic with little increase in open circuit voltage. The electrical parameters of solar PV at the string level at constant temperature and at different irradiances are tabulated Table 3.

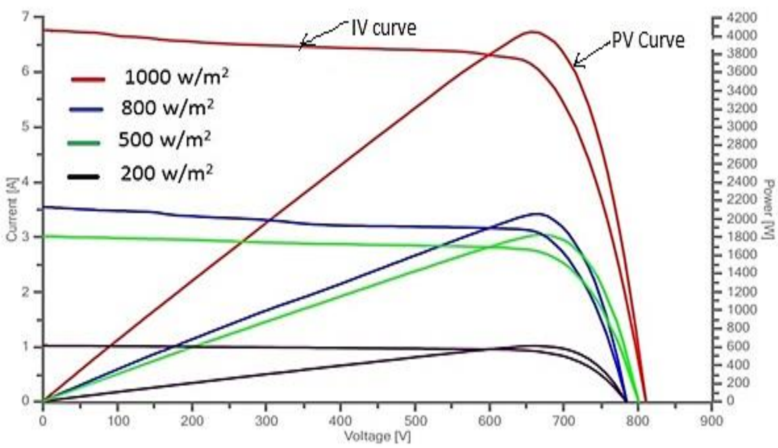

Figure 5. Real time I-V and PV curves of poly crystalline PV at various insolation and constant temperature

Table 3. Real time results under constant temperature and variable irradiance condition

Temperature	Insolation	Isc(A)	Voc(V)	Vmp(V)	Imp(A)	Pm(W)
	200	1.1	780	680	0.9	600
	500	3.0	790	685	2.9	1600
25	800	3.5	795	690	3.4	2000
	1000	6.8	1000	700	6.7	3900

4.2. Case 2: Partial shading conditions

Three different scenarios have been artificially created to study the impact of partial shading (PS) conditions by placing objects on the PV panels, as presented in Figure 6. The performance of solar PV is analyzed in the presence of different partial shading environments. The experimental results of solar PV under different partial shading regions are shown in Figure 7. The PS conditions are experimented under 20%, 30%, and 40% PS conditions and are tested at STC (1,000 w/m2 and 25c) conditions. As the panel shading rises, the PV module's peak power point drops. The maximum power point (MPP) of a PV string array with 20% shade is 3800 W. The MPP of the PV string array drops to 3,400 W and 3,200 W, respectively, as the shade is increased to 30% and 40%, respectively. Figure 7 shows that the partial condition's effect reduces the maximum power generated by PV as well as the efficiency of solar PV.

Figure 6. Solar panels under partial shading condition

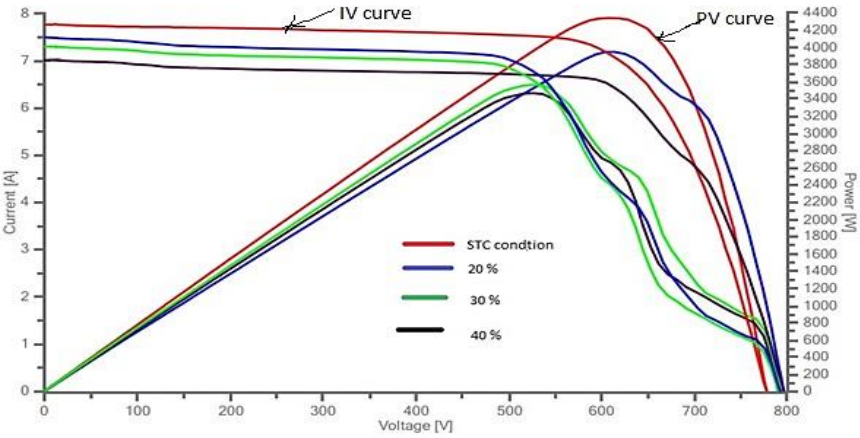

Figure 7. I-V and PV curves under 20%, 30%, and 40 % partial shading condition

4.3. Case 3: Performance of Solar PV under dust accumulation

The impact of dust on solar panels is investigated under STC conditions. The dust accumulation prevents reaching irradiance from the sun on solar PV modules, which causes a diminishing of open circuit voltage, and short circuit current as noticed in Figure 8. Hence, the peak power of the solar array is decreased, as displayed in Figure 8. The I-V and PV curve measurement got from dusty solar panel is compared with normal condition with a clean solar panel.

4.4. Case 4: Performance of solar PV under aging condition

Figure 9 shows the I-V and PV curves in aging conditions. The aging condition is created by choosing different PV panel array series resistance using an HT 500W I-V curve tracer. Due to aging of solar PV panels, the series resistance of solar cells decreases. Figure 9 illustrates a dip in voltage and current in I-V and PV curves. Also, as seen in Figure 9, the peak power output delivered from solar panels declines under aging conditions. The results show that the power output diminishes with a rise in series resistance which will affect the efficiency of the solar PV plant.

4.5. Case 5: Short circuit condition

The PV and I-V curves in short circuit condition are displayed in Figure 10. The maximum power extraction and short circuit current from solar PV slightly decreases due to short circuit condition when compared to normal condition. Under a short-circuit condition, the voltage across the PV array drops to nearly zero. This is far from the optimal voltage range for power production, and as a result, the system cannot extract maximum power. Power output decreases significantly.

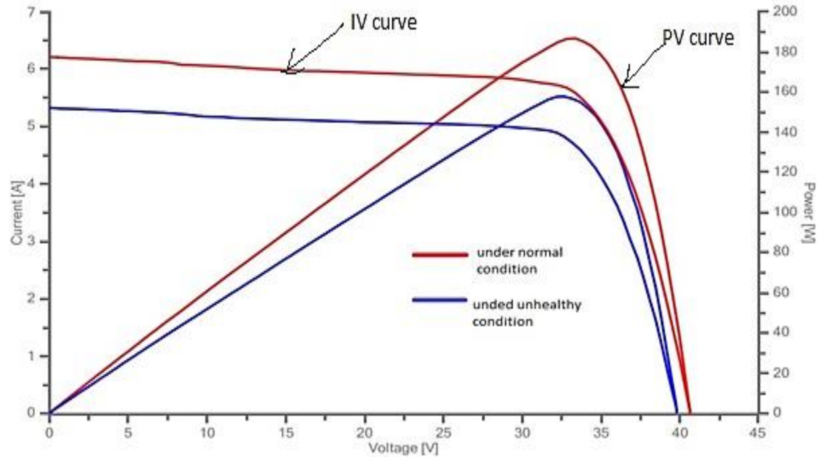

Figure 8. I-V and PV curves under dust accumulation condition

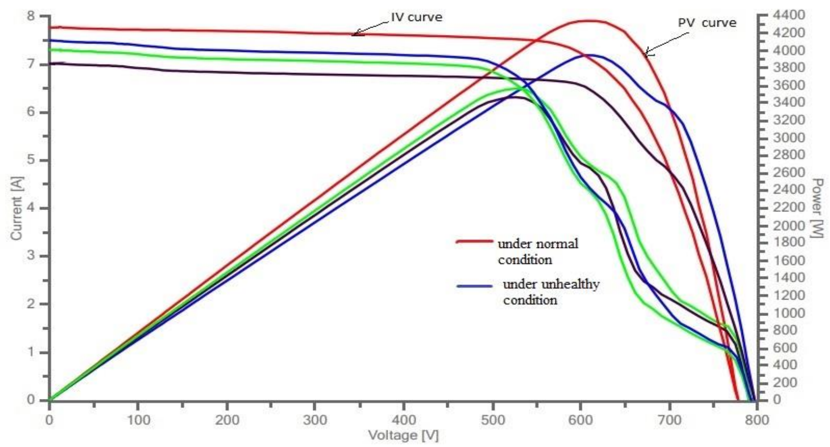

Figure 9. I-V and PV curves under dust aging condition

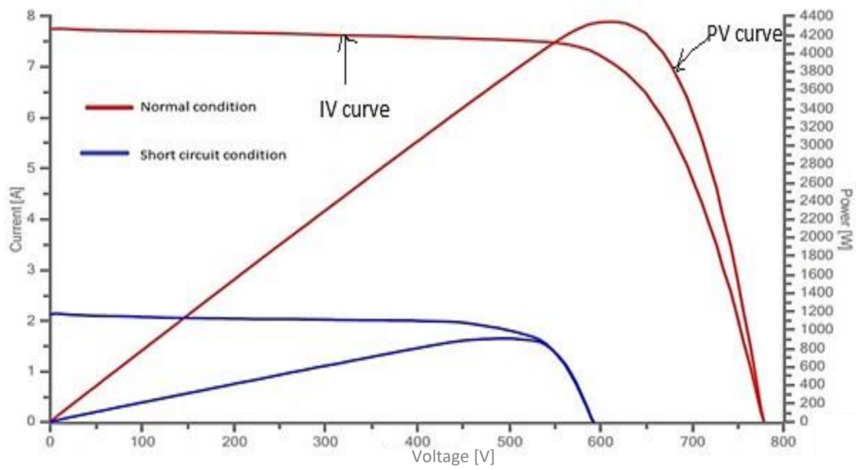

Figure 10. I-V and PV curves under short circuit condition

4.6. Performance assessment of PV solar plant

The abnormal conditions change the PV plant performance by reducing open circuit voltage, the power extracted from PV panels, short circuit current, and decrease in efficiency and fill factors. The following matrices, such as fill factor, performance ratio, open circuit voltage deviation index Doc, and short circuit current deviation index (Dsc), are recommended to investigate the PV solar power plant performance.

4.6.1. Open circuit voltage index (Doc)

The open circuit voltage deviation indices Doc represents how accurately the I-V curve tracer traces in measuring open circuit voltage This parameter is crucial for assessing the overall health and functionality of a solar PV system, as it provides insights into the voltage potential that the system can generate under optimal conditions.

$$D_{\mathrm{oc}} = \sqrt{\left(\frac{\hat{v}_{\mathrm{oc}}}{v_{\mathrm{oc}}}\text{-}1\right)^2} \tag{9}$$

where $\hat{v}_{oc}$ and v_{oc} are voltage under open circuit in real time and normal condition.

4.6.2. Short circuit current index (Dsc)

The short circuit current deviation index (Dsc) represents how precisely the I-V curve tracer traces short circuit current. The short circuit current index is a measure of the robustness and safety of the solar PV system in the event of a short circuit, and it helps engineers and installers ensure that the system can handle such scenarios without compromising its integrity.

$$D_{\mathrm{sc}} = \sqrt{\left(\frac{\hat{I}_{\mathrm{sc}}}{I_{\mathrm{sc}}}\text{-}1\right)^2} \tag{10}$$

where $\hat{I}_{sc}$ and I_{sc} denote current under short circuit condition in real time and normal condition.

4.6.3. Fill factor

Fill factor is given as ratio of product of peak voltage and current to open circuit voltage under real time condition and short circuit current under normal condition. The fill factor is an important measure to know how efficiently a solar cell converts sunlight into electrical power. It is influenced by various factors, such as the quality of the materials used in the solar cell, the design of the cell, and the operating conditions.

$$\mathrm{FF} = \frac{V_{\mathrm{mp}} * \mathrm{I}_{\mathrm{mp}}}{V_{\mathrm{oc}} * \mathrm{I}_{\mathrm{sc}}} \tag{11}$$

4.6.4. Performance ratio

The performance ratio (PR) is used to evaluate the deviance between peak power under real time and maximum power under normal condition. The PR is a crucial metric in the field of solar photovoltaic (PV) systems, serving as a key indicator of the overall efficiency and effectiveness of a solar installation. A higher performance ratio indicates a more efficient and effective system, while a lower ratio suggests potential issues or losses in energy generation.

$$\mathrm{PR} = \frac{P_{m(\mathrm{actual})}}{P_{m(\mathrm{normal})}} \tag{12}$$

The comparative performance index analysis under various working conditions is shown in Table 4. Table 4 illustrates that there is a dip in performance indicators under abnormal conditions from its ideal value. The performance indicators such as open circuit voltage, short circuit current deviation index, and performance ratio are deviated from its ideal value of 1 when the panels are exposed to dust, partial shading, aging, insolation changes and aging condition. Moreover, the fill factor also decreases due to reduction in power delivered from solar plant under these abnormal scenarios from its ideal value of 100%. The statistical analysis of performance indicators is revealed in Figure 11. From Figure 11 it is perceived that PR value is reduced drastically under short circuit condition when compared to all other abnormal scenarios.

As demonstrated in Table 5, the results of this investigation are in accordance with earlier studies. This research helps in understanding how PV plants in coastal locations operate for investors and researchers. The comparative analysis of performance indicators such as performance ratio (PR) and fill factor (FF) of various roof top solar PV plants in India is made with respect to existing published literature.

Table 4. Comparative performance index analysis under various working conditions

Conditions	Open circuit voltage deviation index	Short-circuit current deviation index	% Fill factor	Performance ratio
Variable insolation	0.268	0.086	74.0	0.80
Partial Shading	0.1824	0.212	72.0	0.733
Dust accumulation	0.156	0.230	72.0	0.69
Aging condition	0.138	0.292	74.0	0.67
Short circuit condition	0.5439	2.81	72.0	0.152

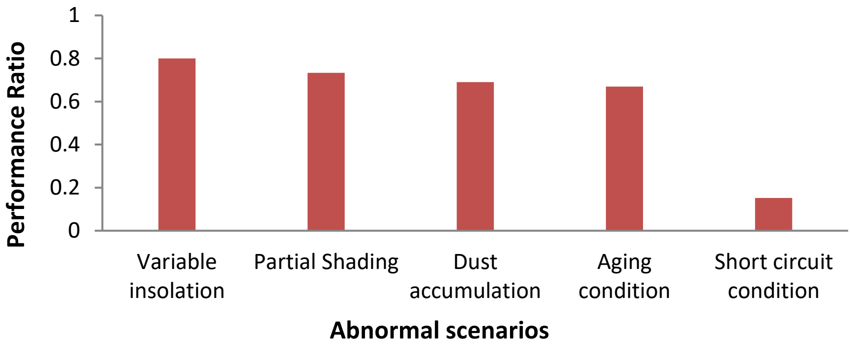

Figure 11. Statistical analysis of performance ratio under abnormal conditions

Table 5. Comparative analysis of performance indicators roof-top PV plants with existing literature

Location	Solar plant capacity	PR (%)	Fill factor	References
Hyderabad	100 kWp	80	73.2	Dubey *et al.* (2016) [21]
Chandigarh	200 kWp	77.3	74	Kumar *et al.* (2018) [22]
Ahmedabad	150 kWp	75.1–82.5	75	Vasita *et al.* (2017) [23]
Bhubaneswar	100 kWp	78	75.2	Sharma *et al.* (2017) [24]
Haryana	50 kWp	87	72.3	Berwal *et al.* (2017) [25]
Gujarat	25 MWp	80.1	73.4	Bhullar *et al.* (2018) [26]
Odisha	100 kWp	80	71	Mohanty (2020) [27]
Tamil Nadu	5.00 kWp	76.83	78	Duraivelu *et al.* (2021) [28]
Vishakhapatnam	1.00 MWp	87.9	74	Navothna *et al.* (2022) [29]
Bhimavaram	50.4 kWp	80	74	Present study

5. CONCLUSION

In this paper, a comprehensive approach for real-time performance assessment of utility grid-interfaced solar PV plant using I-V curve tracer has been presented. The results obtained through real-time experimentation were used to envisage the performance of the PV plant. The performance of PV plants in various abnormal scenarios such as variable insolation condition, partial shading condition, aging condition, dust deposition and short circuit condition has been investigated and tested using an I-V and PV curves using curve tracer. Finally, performance assessment of solar PV using the performance indicators is evaluated. Real-time assessment helps identify and address issues affecting the efficiency of solar PV systems promptly. It also maximizes the utilization of renewable energy resources, leading to higher energy yields. Real-time data collection and analysis become increasingly important, creating opportunities for data-driven decision-making and predictive maintenance. The evaluation of performance indicators such as open circuit voltage index, short circuit index, performance ration, fill factor are utilized to predict the longevity of solar PV plant and to make the proper remedial measures. The performance of solar PV in partial condition has been tested. It was found that the peak power extraction and open circuit voltage and short circuit current reduces. From the results and discussions, it was perceived that performance ratio and fill factor were severely affected due to short circuit condition and aging condition. The real-time performance assessment of utility grid-interfaced solar PV plants is a multifaceted endeavor with far-reaching ramifications, encompassing economic, environmental, and societal benefits that contribute to a sustainable and resilient energy future.

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