

Estimating the Performance Ratio and Degradation Factor of Rooftop Solar PV Plant

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Abstract: This paper investigates the effect of degradation on the grid connected rooftop solar plant. The effect of degradation and plant performance are evaluated and analyzed for 20kWp SPV plant on rooftop of EEE Block in CVR College of Engineering for the year 2015 and 2016. The above analysis is done manually from the plant data extracted from web-interface. The degradation of the plant is analyzed by first calculating the performance ratio of the plant for two successive years. Later the percentage change in the plant Performance Ratio's are calculated. This investigation reveals that degradation of the plant performance is high in summer season because of increased ambient temperature. The degradation is more during the month of May and less during the month of February. The reasons for this kind of performance are analyzed. After analyzing the results, it is recommended that plant should be maintained and inspected at regular interval for the improved performance.

Keywords: Degradation factor, Grid Connected Solar PV Plant, Panel degradation, Performance Metrics, Performance Ratio (PR), System Performance.

I. INTRODUCTION

One of the best ways to generate electrical energy from the solar radiation is by Photo-Voltaic effect. In this process the solar radiation is directly converted into DC electrical energy using the Solar Cell. One solar cell can generate only small amount of electrical power. Hence, to generate moderate power, large number of solar cells are connected either in series or parallel to form a Solar array to get the required electrical power from solar energy.

Grid connected PV systems are widely being used because of their own advantages. Power production from these Solar PV plants to be monitored properly for better utilization of plant and available resources [1-4]. The performance of these plants cannot be judged easily by considering the quantity of energy generated from the plant every day. The output of solar plant depends upon the amount of solar irradiation that falls on effective surface area of Solar PV array. This solar radiation is not the same throughout the year and every location. It is good in summer, adequate in winter and moderate in monsoon season. Hence, justifying the performance of the plant based on the amount of electrical energy generated by the plant is not hypothetical. Therefore, to analyze the performance of PV plants, few metrics are essential. Performance Ratio (PR) is the most important metric that is adopted by the

solar industry experts to analyze the performance of the plant.

Climatic conditions like high temperature and high humidity have negative influence on performance and consistency of the SPV modules. Besides the module performance, inverter efficiency is also a significant factor which greatly impacts the overall performance of the system and behavior. Besides temperature, many factors that influence the performance of SPV plants are solar insolation, shading effect, effect of climate, wind speed, electrical load matching, dust on panels, accuracy of MPPT operation and various losses that are occurring in the system like array capture losses, soil losses, inverter losses, etc. The solar industry experts need to understand every influencing parameter and its effect on the performance of plant. [5-6].

Performance of the PV module decreases at faster rate compared to other equipment, as modules are exposed to direct weather conditions. The degradation rate is normally high in the first year upon initial exposure to the solar light. Later it stabilizes. Factors affecting the degree of degradation include, quality of the material used in manufacturing, packing of solar cells, process of manufacturing modules and solar cell technology.

Factors for degradation are high winds, soil, dust, snow, fog, discoloration, lamination defects, mechanical stress and cell contact breakdown. Another important factor is breakage of Ethylene Vinyl Acetate (EVA) encapsulation, which is used as a back sheet of the PV module by UV light.

One of the important factors to be considered is that, all the modules will not degrade at same rate. Their degradation rate is different from one module to another module. Proper maintenance and inspection should be done at the site in regular intervals for better performance of the plant over a long time.

In this paper, Section II describes the location of the plant and capacities of the sub-plants located in the site. Section III, clearly discusses the performance analysis of Grid connected plant using Performance Ratio and Degradation Factor in detail. Section IV, systematically analyzes the results and discussion on Plant performance using these parameters followed by conclusion and references.

II. SPECIFICATIONS OF GRID CONNECTED SPV PLANT

Specifications and design of every grid connected SPV plant depends upon many factors like weather conditions, local load requirements, nature of the loads, maximum demand etc. The geographical coordinates of site/plant determine the seasonal tilt angle of the solar modules.

A. Location of the plant

The grid connected SPV plant for this investigation is located on the rooftop of the CVR College of Engineering, Hyderabad, Telangana state. The global coordinates of the site are Latitude: 17.20° N, Longitude: 78.60° E. This site location is at an altitude of 545 m. above the sea level.

B. Capacities Of Photo Voltaic Plant

The maximum capacities of various grid connected SPV sub plants on the rooftops of different independent buildings in CVR College of Engineering are tabulated in Table I including the commercial dates of operation of each sub plant with their full name plate ratings.

TABLE I.
DETAILS OF SUB PLANTS, THEIR CAPACITIES AND DATE OF COMMENCEMENT OF PLANT

Name of the Sub Plant	Location of the Plant	Installed Power	Date of Commencement of Plant
CVR PG Block	EEE Block	120 kWp	03-03-2014
Single Axis Tracking	Main Block	40 kWp	18-01-2015
Library	Library Block	20 kWp	23-10-2014
Single Axis Polar Tracking	Main Block	40 kWp	11-03-2015
CVR CS Block	CSE Block	60 kWp	22-10-2015
CVR New	First Year Block	80 kWp	03-03-2016
Overall Plant Capacity		360 kWp	---

The important electrical apparatus that are required for the grid interactive SPV plants are: Solar PV Modules (Array), DC Solar Cables, Grid tied String Inverters, AC Cables, Junction Boxes, Switchgear Equipment, Net-Metering facility (Bi-directional energy meter), Lighting Arrestors and electrical earthing's at appropriate locations. All the apparatus, components and devices used in this SPV sub-plants are according to the IEC 61724 standards as per the guidelines given by MNRE [7].

String inverter is the power electronic device that converts the DC electricity generated by the Solar Array from incident solar radiation into 3-phase AC electrical energy at PCC. Fig. 1 shows the 20kW grid tied REFU_{sol}/008K-020K string inverter used in this 20kW grid connected solar PV plant. Its maximum efficiency is 98.2% at STC conditions. For every 20kW array one independent string inverter is commissioned. Table II. shows the other important inverter data as given by the manufacturer.

The term solar PV array is defined as the interconnection of different solar modules either in series/ parallel

depending upon system design, rating and configuration. The modules used in this rooftop SPV plant are supplied by Kohima Energy Pvt. Ltd. The model number of the module is KE-60-M250, with peak DC electrical power rating of 250Wp at STC conditions (25°C ambient temperature, 1000 W/m² Insolation, Air mass ratio is 1.5). The other Specifications of Solar Module -KE-60-M250 are given in Table III. [8].

TABLE II.
DETAILS OF GRID INTEGRATED REFUSOL 020K SOLAR STRING INVERTER

	REFU _{sol} 020K
DC DATA	
Recommended Max. PV Power, kWp	21.6
MPPT Range	480 V-850 V
DC Start Voltage	350 V
Max. DC Voltage	1000 V
Max. DC Current	41 A
MPP Trackers	1
AC DATA	
Rated AC Power	19.2 kVA
Max. AC Active Power	19.2 kW
Rated Power factor	1
Max. AC current	3 X 29
Distortion factor THD	<1.8 %
Max. efficiency	98.20%
European efficiency	97.80%

REFU_{sol}/008K-020K
For medium-sized to megawatt installations



- Light & compact
- Highest efficiency (98.2%)
- Easy installation
- Outdoor (IP65)
- Maintenance free

Figure 1. String Inverter used in SPV plant on rooftop of EEE Block

As per this design, there are 80 such KE-60-M250 solar modules. These 80 modules are further connected in 4 parallel strings. Each string consists of 20 modules in series. Fig.2 shows the onsite photograph of a 20kW rooftop grid connected plant commissioned on the Library block. Present investigation on performance ratio and degradation factor was performed on the 20kWp grid connected SPV plant commissioned on the rooftop of the library block.



Figure 2. 20kWp Solar PV Plant on EEE Block of CVR College of Engineering

TABLE III.
SPECIFICATIONS OF SOLAR MODULE KOHIMA ENERGY PVT. LTD.

STC–Irradiance of 1000 W/Sq. m at 25°C	KE-60-M250
Maximum Power (P_{max})	250 W
Maximum Power Voltage(V_{mp})	31.44 V
Maximum Power Current(I_{mp})	7.95 A
Open circuit Voltage(V_{oc})	37.86 V
Short Circuit Current(I_{sc})	8.69 A
Fill Factor	75.98%
Module Efficiency(%)	15.40%
Nominal Operating Cell Temperature (NOCT)	45+2
Temperature Coefficient of I_{sc} (α)	0.04 /°C
Temperature Coefficient of V_{oc} (β)	-0.32 /°C
Temperature Coefficient of P_{max} (γ)	-0.45 /°C
Cells per module	60
Cell type	Multi - Crystalline Silicon
Cell Dimensions	156 m.m X 156 m.m

III. PERFORMANCE ANALYSIS (PR & DEGRADATION)

A. Performance Ratio (PR)

Performance Ratio is one of the most significant metrics that is used for evaluating grid connected SPV plants. The empirical formula to evaluate the PR is as follows.

$$PR = \frac{\text{Actual AC Energy generated by plant}}{\text{Nominal Energy}}$$

$$\text{Where Nominal Energy} = \text{GHI (in kWh/m}^2\text{)} \times \text{Rated module efficiency} \times \text{Total Active PV area (in m}^2\text{)} \quad (1)$$

The Performance Ratio is generally evaluated for a year to get a complete idea about the plant. PR also can be evaluated on daily, weekly, or monthly basis. Depending on the period of evaluation, corresponding parameters are chosen. In the above empirical formula, the denominator expression consists of GHI, Module efficiency and Active PV area. The value of the Module efficiency is picked from nameplate ratings given by the panel manufacturer. Active area is strictly the area covered by polycrystalline solar cells alone in the entire solar array. Whereas GHI of site or plant location depends upon several factors like ambient temperature, temperature of the cell, soil and losses due to dust, partial shading, weather conditions, etc. Hence calculation of PR takes all the above factors into

consideration. Consequently, the influence of all the above parameters will be replicated in the Performance Ratio evaluation. If the evaluated PR value is near 100 %, one can conclude that PV plant is in excellent operating condition.

The manual procedure to evaluate the PR of the SPV plant is as follows:

- Determine the time of analysis (Optimum period is one calendar year).
- Active PV area of the solar array has to be computed by number of modules used in PV array.
- Collect the information about PV module efficiency from the datasheets.
- AC electrical energy output of the Plant from the inverter data.
- By using the irradiance sensor (Pyranometer) gather the values of the measured solar insolation values.

PR is the appropriate performance metric to compare the performance of various SPV plants at different locations independent of weather and climate conditions. Deviations from the expected PR indicate either a fault in the system or a problem within the PV plant itself.

PR is the most accepted global standard to measure the performance of a SPV plant. Periodically few stakeholders and Independent Power Producers (IPP) are very keen to evaluate and compare the PR's of the dissimilar rated solar plants across the globe, which are located at different geographical locations [9-16].

B. Degradation Factor

Degradation is an industry term that is used to describe the decrease in the power output of the solar PV plant over a period of time. The degradation mainly happens in solar modules, inverters and Cables used in the PV plant. All components definitely degrade, but degradation rate is not uniform for all the equipment used in the system. High attention must be paid towards module degradation. Because, solar modules are the critical devices that collect the solar energy from the sun and convert it into DC electricity. If the panels/modules degrade at faster rate, the output power from the modules will decrease day by day resulting in poor energy yield of the plant for life time. Factors affecting the degree of degradation include, quality of the material used in manufacturing, packing of solar cells, and solar cell technology. Other important factor is breakage of Ethylene Vinyl Acetate (EVA) encapsulation, which is used as a back sheet of the PV module by UV light.

IV. RESULTS & DISCUSSIONS

Solar Radiation values of the site are gathered from the data available by the NASA at the nearest location. The table IV demonstrates the monthly solar radiation values at the site for the year 2015 and 2016. Fig.3 shows the graphical representation of the same for the years 2015 and 2016 of the 20kWp SPV plant on rooftop of Library Block.

TABLE IV.
MONTH WISE SOLAR RADIATION VALUES FOR THE YEARS 2016 AND 2015 OF 20KW SPV PLANT

Month & Year	Solar Radiation 2016	Solar Radiation 2015
January	158.4	154.7
February	169.6	169.9
March	178.9	184.9
April	188.3	197.8
May	201.1	201.7
June	153.2	151.4
July	140.4	169.3
August	150.4	152.4
September	111.6	149.5
October	148.6	155.5
November	139.7	153.2
December	143.2	149.7
Average	156.95	165.83

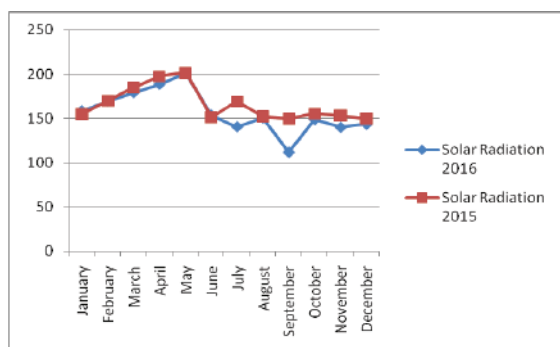


Figure 3. Monthly Solar radiation values for the years 2015&2016 of 20kW_p SPV plant on rooftop of Library Block

A. Calculation of Performance Ratios (at STC)

Table V and Table VI show the calculated monthly nominal Performance Ratios of the plant at STC conditions for the year 2015 & 2016 respectively. All the PR values are calculated by looking at the name plate details of STC conditions (STC conditions are 25° C of ambient temperature, Solar radiation of 1000 W/m² and Air-mass ratio of 1.5). The calculated Performance Ratio's at STC conditions are also called as Nominal Performance Ratios. Temperature corrected Performance ratio is getting popular nowadays for better analysis. However, Nominal Performance ratios are used in this work for the analysis of plant performance.

These monthly calculated PR's are compared and analyzed to estimate the degradation of the plant output. The important fact to be understood here is, plant output is always dependent upon solar radiation input to the modules. If the radiation is high, energy output will be high and vice versa. Estimating the degradation rate only using energy output will not give feasible results. For instance, from the Fig. 3, during the months of July and September, solar radiation values are less in the year 2016 compared to 2015. However, corresponding PR's are higher in the year 2015 than in 2016. Hence, it is always better to compare the

Performance Ratio's of the plant than comparing the energy output.

TABLE V.
MONTH-WISE AVERAGE ACTUAL AC ENERGY GENERATED, AVERAGE THEORETICAL DC ENERGY COULD GENERATED AT 25°C AND NOMINAL PR OF 20KW SPV PLANT FOR THE YEAR 2015

Month & Year	AC Energy Produced Year 2015	Theoretical DC Energy 2015	PR2015
January	2611.85	2782.92	93.85
February	2787.53	3056.36	91.20
March	2988.03	3326.20	89.83
April	2929.68	3558.26	82.33
May	2973.22	3628.42	81.94
June	2262.63	2723.56	83.08
July	2567.97	3045.57	84.32
August	2365.32	2741.55	86.28
September	2351.52	2689.38	87.44
October	2588.20	2797.32	92.52
November	2581.72	2755.94	93.68
December	2518.12	2692.98	93.51
Average	2627.15	2983.20	88.06

TABLE VI.
MONTH-WISE AVERAGE ACTUAL AC ENERGY GENERATED, AVERAGE THEORETICAL DC ENERGY COULD GENERATED AT 25°C AND NOMINAL PR OF 20KW SPV PLANT FOR THE YEAR 2016

Month & Year	AC Energy Produced Year 2016	Theoretical DC Energy 2016	PR2016
January	2606.70	2849.48	91.48
February	2744.10	3050.96	89.94
March	2791.40	3218.26	86.74
April	2720.00	3387.36	80.30
May	2788.50	3617.62	77.08
June	2207.40	2755.94	80.10
July	2063.50	2525.68	81.70
August	2283.10	2705.57	84.39
September	1720.40	2007.59	85.69
October	2429.60	2673.19	90.89
November	2314.10	2513.09	92.08
December	2355.90	2576.05	91.45
Average	2418.72	2823.40	85.67

B. Calculation of Degradation Factor

Table VII compares the amount of AC energy generated by the plant in the year 2015 & 2016. Fig. 4 shows the graphical comparison of the same. Similarly, Table VIII shows the comparison of the Performance Ratio's of the plant for the year 2015 & 2016. Fig.5 represents the graphical comparison of the same data. From the graphs, it is observed that, the Performance Ratio's of the plant for the year 2015 is slightly higher than the performance Ratio's for the year 2016. This drop in the performance ratio is due to degradation in various components used in the system. If the degradation factor is even 1% per a year, it may result in high payback period. Fig. 6 shows the graphical representation of the month-wise percentage degradation values [17].

TABL VII.
MONTH WISE AC ENERGY PRODUCED FOR THE YEARS 2016 AND 2015 AF 20KW SPV PLANT

Month & Year	AC Energy Produced in Year 2016	AC Energy Produced in Year 2015
January	2606.70	2611.85
February	2744.10	2787.53
March	2791.40	2988.03
April	2720.00	2929.68
May	2788.50	2973.22
June	2207.40	2262.63
July	2063.50	2567.97
August	2283.10	2365.32
September	1720.40	2351.52
October	2429.60	2588.20
November	2314.10	2581.72
December	2355.90	2518.12
Average	2418.72	2627.15

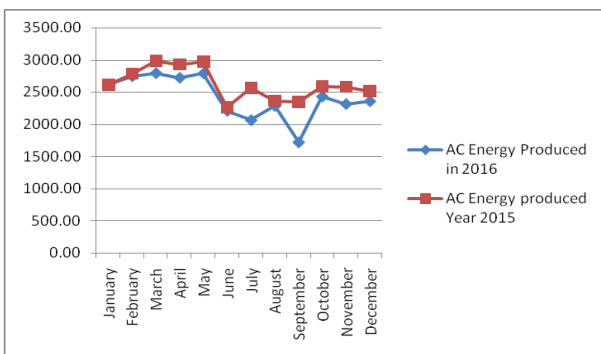


Figure 4. Monthly AC energies produced by the plant for the years 2015&2016 of 20kW_p SPV plant on rooftop of Library Block

TABLE VIII.
MONTH WISE PERFORMANCE RATIO VALUES FOR THE YEARS 2016 AND 2015 OF 20KW SPV PLANT

Month & Year	PR 2016	PR 2015	% Degradation
January	91.48	93.85	2.53
February	89.94	91.20	1.38
March	86.74	89.83	3.45
April	80.30	82.33	2.47
May	77.08	81.94	5.93
June	80.10	83.08	3.59
July	81.70	84.32	3.10
August	84.39	86.28	2.19
September	85.69	87.44	1.99
October	90.89	92.52	1.77
November	92.08	93.68	1.70
December	91.45	93.51	2.20
Average	85.67	88.06	2.72

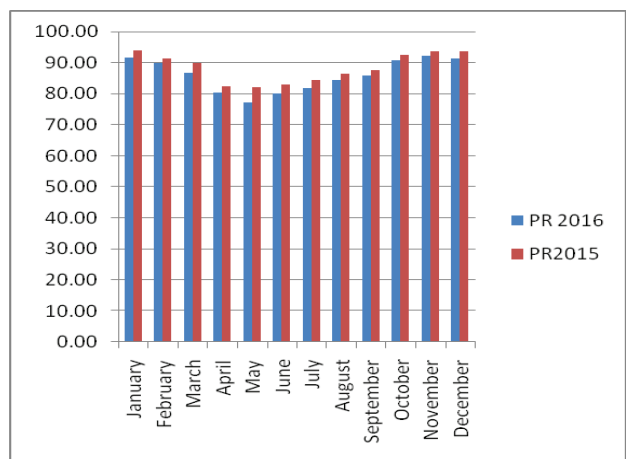


Figure 5. Monthly Performance Ratios of the plant for the years 2015&2016 of 20kW_p SPV plant on rooftop of Library Block

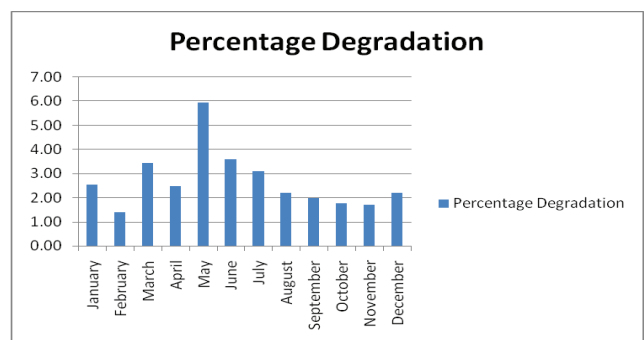


Figure 6. Monthly percentage degradation of 20kW_p SPV plant on rooftop of Library Block from 2015 and 2016 PR data

V. CONCLUSIONS

In this research, the effect of degradation on the Performance of 20kW_p grid connected SPV plant on rooftop of Library block was analysed from 2015&2016. During the period March to June, the degradation values are significantly more because of increase in ambient temperature causing more power losses at module level. The

calculated degradation factors were found to be a little higher than expected values. These values should be minimised by taking proper measures for better performance of the solar plant in terms of degradation. It is recommended that modules must be cleaned at regular intervals either before sunrise or after sunset as the main reason for degradation is observed to be dust and soiling. The maximum value of the performance ratio is observed in the month of Jan 2015 with 93.85% and minimum value is observed to be in the month of May 2016 with 77.08%. After comparing the PR's of plant for successive years, the maximum degradation is observed to be in the month of May'16 because of high ambient temperature and minimum in the month of February'16 because of clear sky conditions. It is also observed that the overall plant performance is satisfactory as per industry standards.

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