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IMPACT OF SOLAR PV ON POWER QUALITY

Ms. Mukta Singh D

B.Tech Madhav Institute of Technology and Science

Gwalior, Madhya Pradesh

ABSTRACT

We live in a time where conventional energy resources are deteriorating at a faster rate and we have little left in our reserves. So, we are searching for alternatives; which are renewable energy resources. Among all the renewable resources, solar has the vast potential especially for a Torrid and Temperate country like India where Tropic of Cancer passes from the middle. Government is taking lots of initiative to promote solar power's production and usage. Also, at the COP26 at Glasgow, India committed to produce 500GW through renewable energy resources by 2030 and to limit its CO_2 emissions to net 0 by 2070. And solar energy is going to play a large part in withstanding this pledge. Now while we install a solar pv system at the rooftop there are some factors like harmonic distortion and power factor which are impacted by it, which in turn reduces the efficiency of the system. We are going to test and mathematically model these impacts in the climate of Ghaziabad,Uttar Pradesh state of India on a 100kW_p solar panel in the months of May and December. The tests will help us to determine that for what pv inverter's power, the power factor is above 0.9 and at what power total harmonic distortion in current increases beyond the recommended value. A relation between total harmonic distortion in current and power factor is also obtained.

CONTENTS

1. INTRODUCTION

Nowadays, Grid connected photo voltaic system (GCPVS) are widely used all around the world and since 1997 their market has grown continuously[1]. In developed and some developing countries, new renewables represent 2.4% with a rapid growth[2]. Among all the renewable energy resources in this research work we are going to focus on solar energy. India receives 5000 trillion kWh of solar energy in a year and 2300-3200 hours annually. Also, in India most part receives 4-7 kWh of solar radiation per square meter per day and having 250-300 sunny days per year. With this much energy, solar photovoltaic and solar thermal energy India can generate 35 MW per square kilometer[3]. This shows us the potential of solar energy in India.

Year 2020 was record breaking for the solar PV market with new installations of an estimated value of 139 GW_{DC}, summing up the global total at an estimated 760 GW_{DC} with both on grid and off-grid capacity. Demand for solar PV is increasing and expanding since it is becoming the most suitable option for electricity generation not only in households but also in industries. Solar pv power along with the wind power helped the renewable powersector to hike in the second half of the 2020 year and assisted in prevailing over the Covid-19 pandemic. Solar pv accomplished the largest amount of increase ever seen in the capacity in a year[4]. In the year 2030 there will be an increase of 1.5% annually in the worldwide energy demand from 12000 Mtoe to 16800 Mtoe and the developing countries of Asia will lead this growth with 40% increase[5]. At the global level, sustainable development is prevailing with solar technology along with other renewable energy technologies. To existing energy systems, these technologies can give small increasing capacity additions with short lead times[6].

In a grid connected solar pv system inverter is an important component since it converts the generated dc power into ac power in order to match the grid frequency and voltage alsoan inverter is significant for the safety and reliable integration of the grid[7][8]. At the Point of Common Coupling (PCC) when the inverter is connected to the grid, the power quality shouldn't deteriorate[9]. As a result, the impacts of an inverter with bad power quality should be taken seriously[10]. Appropriate power quality can be produced by using current controlled VSI (Voltage Source Inverter)[11]. Regulations applied by grid codes[12] or international standard requirements like IEC standards[13] and IEEE standards[14] says that THD should be less than 5%[10]of fundamental current for current and less than 2% for voltage according to standard IEC 61727 [15] and power factor greater than 0.9[10]. We already know the relation between power factor and total harmonic distortion for a load, through the paper on "Harmonics and How They Relate to Power Factor" by W. Mack Grady and Robert J. Gilleskie, which is, if the total harmonic distortion increases then power factor decreases; a relation of inverse proportionality[16].We will find the relation for the power factor and harmonic distortion for the PV system.

Several studies have been conducted in the past on the power quality aspects of PV inverter. Like the paper on "Assessment and mathematical modeling of energy quality parameters of grid connected photovoltaic inverters"[17] which shows test results of 3 different pv inverters and also talks about power factor's and current THD's mathematical models. In theresearch on "Assessment of Harmonic Distortion in small grid-connected photovoltaic systems"[18] shows that based on the capacity and the demand profile the power factor can change. In another paper on"Electric energy accounting and power quality in electric networks with photovoltaic power stations"[19] effect of pv energy quality aspects on the accuracy of the energy meters are presented.

Along with discussing many new control techniques, to increase the power quality using compensation technique in micro grid various devices are proposed. Also, how to suppress harmonics and reactive power compensation in the micro grid deploying the droop control were talked about in the paper on "Harmonic compensation in distributed generation based micro-grid using droop control technique"[20]. Kourtesi et al., propose ways to reduce harmonic value in power[21].

2. SYSTEM UNDER STUDY

This research work is based on testing in Ghaziabad, Uttar Pradesh, India on a 100kWp grid integratedSRTPV system (grid connected solar rooftop pv system), NITCampus, India. Data is collected in the months of May and December.As shown in the Figure 1. this PV system consists the PV array that converts the solay energy into the electrical energy. Here the pv array consists of 338 modules with P_{max} =320 W that are opaque type polycrystalline. For receiving maximum sunlight/ radiation from the sun, the array is set at an inclination of 28.7℃ in the south faced direction. The PV array is connected to a charge controller which is inbuilt in this system that is further connected to an inverter of 100kWwhich converts DC power into AC for feeding the AC load.Solar photovoltaic modulehasopen circuit voltage 46V, rated voltage of 37.7V, short circuit current of 9.03A with rated current at 8.50A. Fill Factor of the module is 77.04% with efficiency at 16.67%, dimension of 1955 × 982 × 36 mm and nominal cell temperature being 44 ± 2 °C. The solar pv system is integrated with a Kirloskar's 63kVA, 3 phase delta (HV side) – 3 phase-star (LV side) connected three phase distribution transformer (TPDT) with oil natural air cooling (ONAN) having HV side voltage as 11 kV and LV side voltage as 433 V.For recording the data regarding the power factor and harmonic distortion in current a power analyzer is employed in parallel to the main connection. The point of common coupling receives power from both PV system and the grid. Point of common coupling is connected to the AC load.

Through mathematical modelling of the data acquired from the testing we'll analyze the impact of solar pv system (actually the inverter) on the power quality parameters like power factor and total harmonic distortion.

3. POWER QAULITY PARAMETERS OF INVERTER AND THEIR MATHEMATICAL MODELLING

A pv solar energy system often works alongside the grid in order to provide better service. A pv solar system accommodates pv array, inverter, charge controller and other equipment to connect to grid. A pv array is made up of solar cells connected in series and parallel which converts the solar energy into the electrical

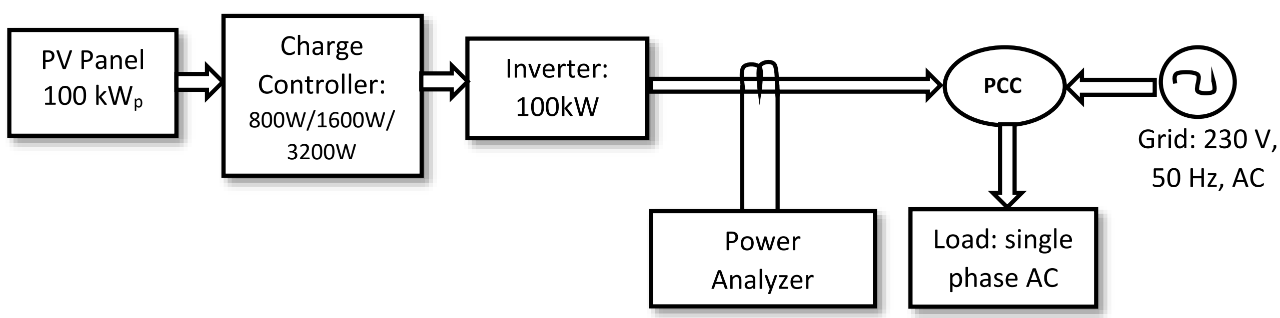

Fig 1. Schematic diagram of PV grid connected system

energy. An inverter converts that generated DC power into the AC power as only AC is accepted by the grid. A charge controller is employed for the safety of the battery which stores the electricity after conversion from the inverter.

Checking the quality of the power before feeding it to the grid is important to save the system from disruptions. Any complication with the power quality is usually the disturbances in voltage, current or frequency which produce impairment in the operations of the equipment. The pv system shouldn't get damaged due to any defects in the grid. In the same way, the failure in the pv system shouldn't harm the grid and effect the consumers[17].

3.1. Power factor

Power factor is the ratio of working power measured in kilowatts(kw) to apparent power measured in kilovolt amperes (kVA). Harmonic distortions are generated in current and voltage waveforms in non-linear or switching devices.

This happens when there is a reactive load since there is a phase difference between current and voltage waveform.

$$PF = \frac{P}{S} = \frac{\frac{1}{T}\int V_i(t).I_i(t).dt}{V_{RMS}.I_{RMS}}$$

where Vi and Ii are the voltage and current at time t, $VRMS$ and $IRMS$are the root mean square of voltage and current and T is the periodof thewaveform which correlate to the integration time used to calculate the power[17].

3.2. Total Harmonic Distortion

Total harmonic distortion is the ratio of RMS value of harmonic components in the current to the RMS value of fundamental component of the current. Same is for the total harmonic distortion in voltage.

$$THDv = \frac{\sum_{n=2}^{\infty} V_n^2}{V_1}$$

$$THD_I = \frac{\sum_{n=2}^{\infty} I_n^2}{I_1}$$

where THD_I is the total harmonic distortion in current, I_n is the currentcomponent of the nth harmonic, I_1 is the fundamental component ofcurrent, THD_v is the total harmonic distortion in voltage, V_n is thecomponent of the voltage of the nth harmonic and V_1 is thefundamental component of the voltage [17].

In this work the mathematical modelling is done based on the test results obtained by testing and storing data through a power analyzer and it is done as a function of relative power which is the ratio of $P_{AC}$and P_{RATED} in case of this work.

On this data curve plotting and fitting is done. Then the coefficients are obtained and equations that best suit the results and data from the test are chosen.

In a research work by Cardona and Carretero[22], mathematical modelling for the total harmonic distortion in the inverter is shown through the equation,

$$THD_i = A.\left(\left(\frac{P_{AC}}{P_{RATED}}\right)^{-B}\right)$$

where A and B are fitting parameters.P_{AC} is the inverter's output power andP_{RATED} is the inverter's rated power.

Three approximation methods validated with three functions was presented by Hernandez and Jay for representing the inverter with grid support functions in HIL simulation to create an inverter model [23].According to the paper by A. Rampinelli the mathematical model used for calculating the power factor as a function of inverter's relative power is

$$PF = \frac{C_0.C_1 + \left(C_2.\left(\frac{P_{AC}}{P_{RATED}}\right)^{C_3}\right)}{C_1 + \left(\frac{P_{AC}}{P_{RATED}}\right)^{C_3}},$$

where C_0, C_1, C_2, C_3 are coefficients of the model, P_{AC} output power of the inverter and $P_{RATED}$is the rated power of the inverter[17].

Paper by A. Rampinelli and the other cowriters also mathematically modeled the total harmonic distortion in current and presented the equation as

$$THD_i = T_0.exp\left(-T_1.\left(\frac{P_{AC}}{P_{RATED}}\right)\right) + T_2.exp\left(-T_3.\left(\frac{P_{AC}}{P_{RATED}}\right)\right)$$

where T_0, T_1, T_2 and T_3 are coefficients that came after fitting the curves[17].

4. DATA ANALYZATIONANDRESULTS

4.1. Results of data obtained in the month of May.

The data is recorded from 6:30 am in the morning till 6 pm in the evening.

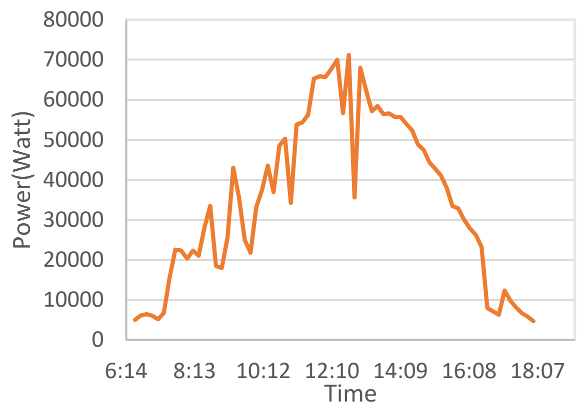

Fig2. Variation of power with time (May)

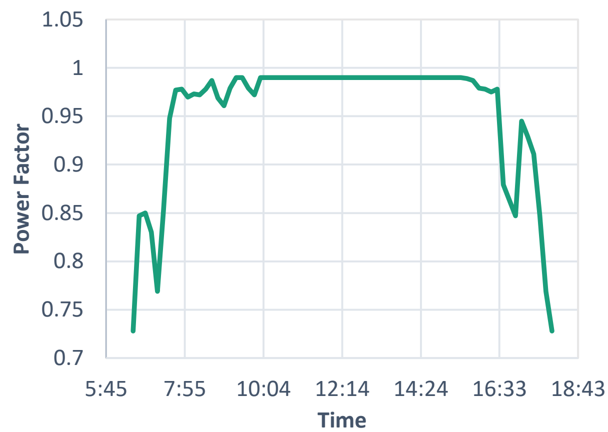

Fig4. Variation of power factor with time (May)

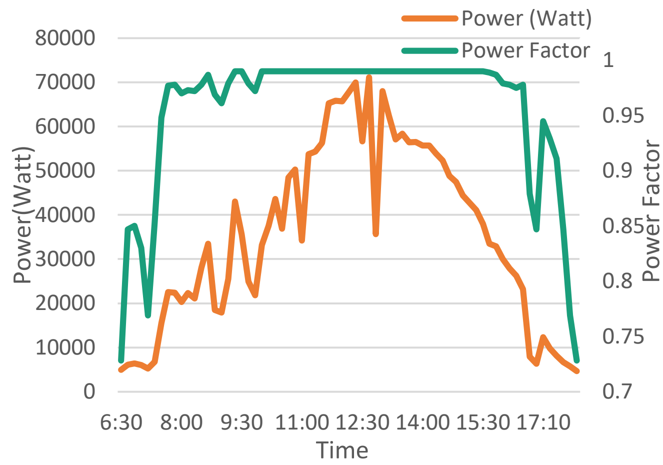

Fig6. Variation of power and power factor with time (May)

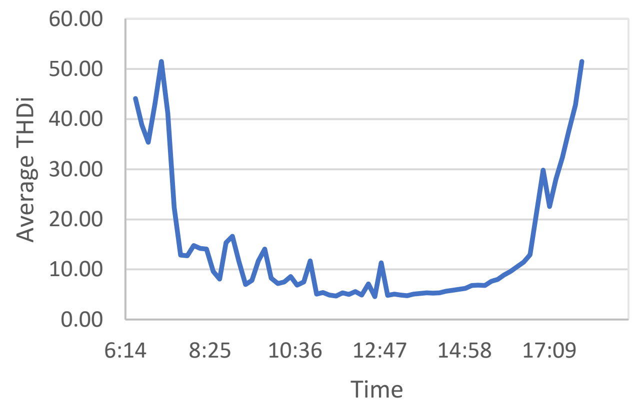

Fig3. Variation of Average THDi with time (May).

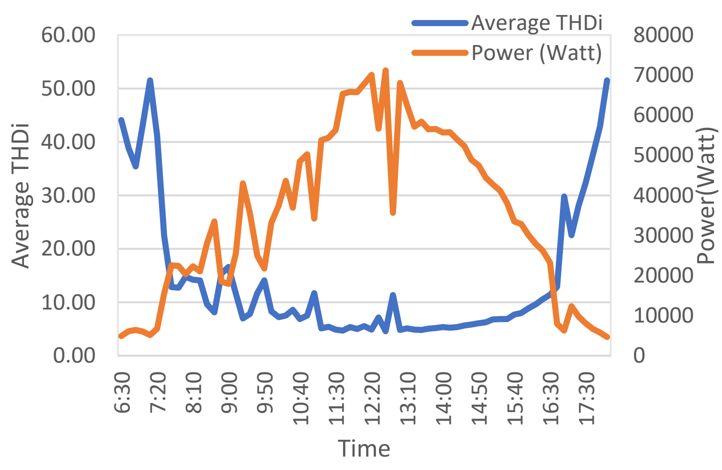

Fig5. Variation of Average THDi and power with time (May).

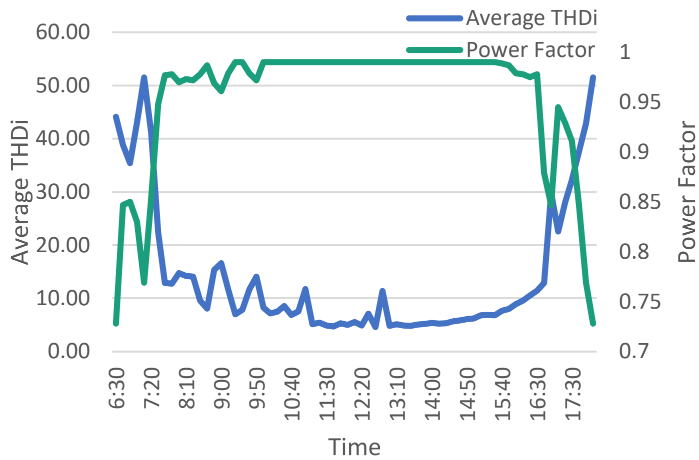

Fig7. Variation of Average THDi and Power Factor with time (May).

As shown in Figure 2 highest power is produced at the afternoon time and it decreases in the morning and evening.Figure 3 shows that the harmonic distortion in current is lowest in the afternoon time and higher in the morning and evening. Figure 4 depicts that the power factor value is highest in the afternoon and lesser at other times. Figure 5 shows that when power produced is highest the THDi is lowest and likewise Figure 6 shows that Power factor value is highest when the power is highest. Figure 7 focuses on the relation between power factor and current harmonic distortion and it says that when power factor is more, THDi is less and vice-versa.

4.2. Results of data obtained in the month of December.

The data is recorded from 9 am in the morning till 4:30pm in the evening.

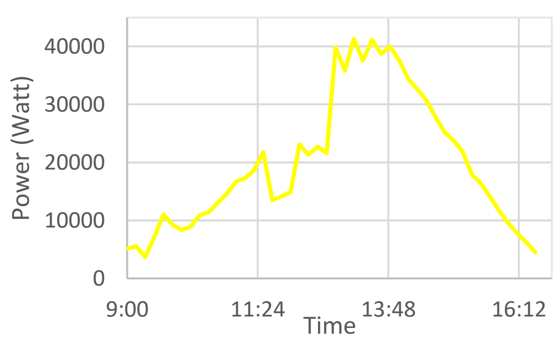

Fig8. Variation of power with time (Dec).

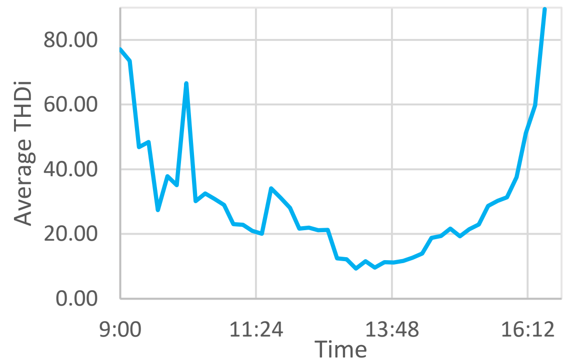

Fig9. Variation of THDi with time (Dec).

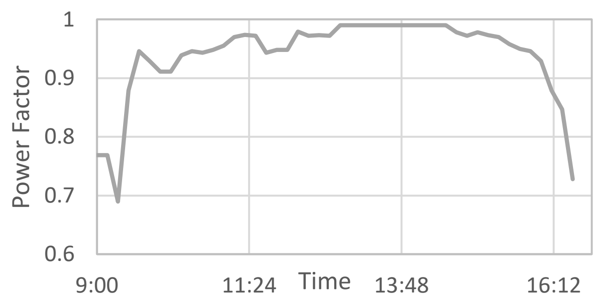

Fig10. Variation of power factor with time (Dec).

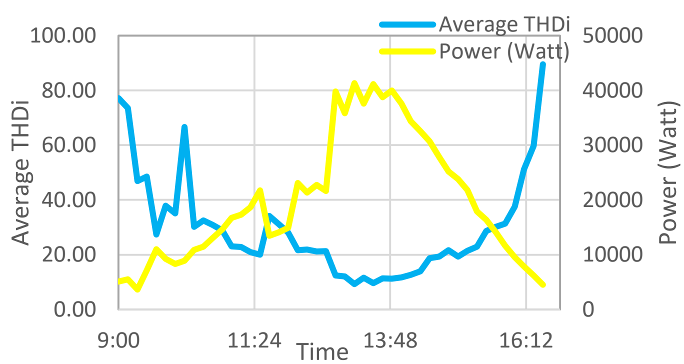

Fig11. Variation of THDi and power with time.

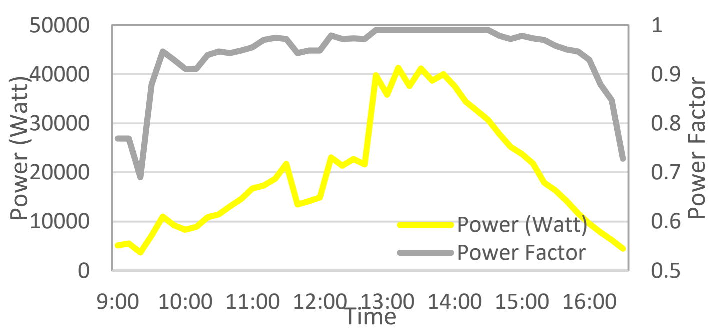

Fig12. Variation of power and Power factor with time (Dec).

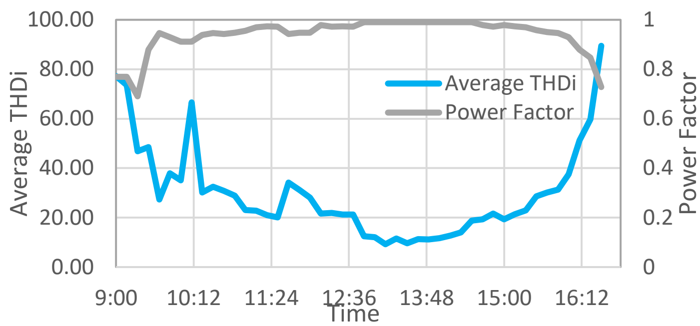

Fig13. Variation of THDi and power factor with time (Dec).

As shown in Figure 8 highest power is produced at the afternoon time and it decreases in the morning and evening. Figure 9 shows that the harmonic distortion in current is lowest in the afternoon time and higher in the morning and evening. Figure 10 depicts that the power factor value is highest in the afternoon and lesser at other times. Figure 11 shows that when power produced is highest the THDi is lowest and likewise Figure 12 shows that Power factor value is highest when the power is highest. Figure 13 focuses on the relation between power factor and current harmonic distortion and it says that when power factor is more, THDi is less and vice-versa.

4.3. Comparing the data obtained in May and December

The data collected for both seasons is at different timings because of the fact that sun rises early in summer and also sets late whereas in winter the sun rises late and also sets early. Due to this in the month of May PV plants are able to work for longer hours than in December.

Through the graphs plotted it can be clearly seen that although the power quality values follow the same pattern in both the months but they differ in the time period that they provide that result in. As we can refer to Figure 14 to see that in May power factor with values above 0.9 is for a much longer time than in December.

Likewise, it can also be seen in Figure 15 that the values of THDi below the recommended value are obtained for a much shorter time in December than in May.

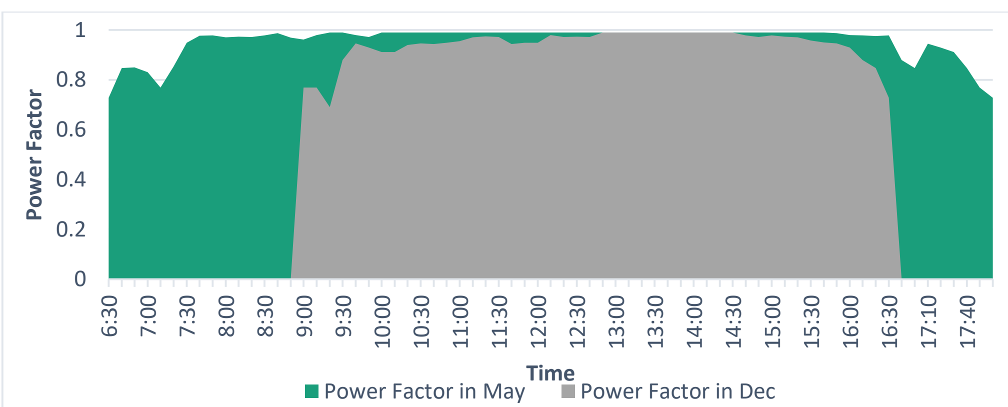

Fig14. Comparison of Power Factor values obtained in the months of May and December.

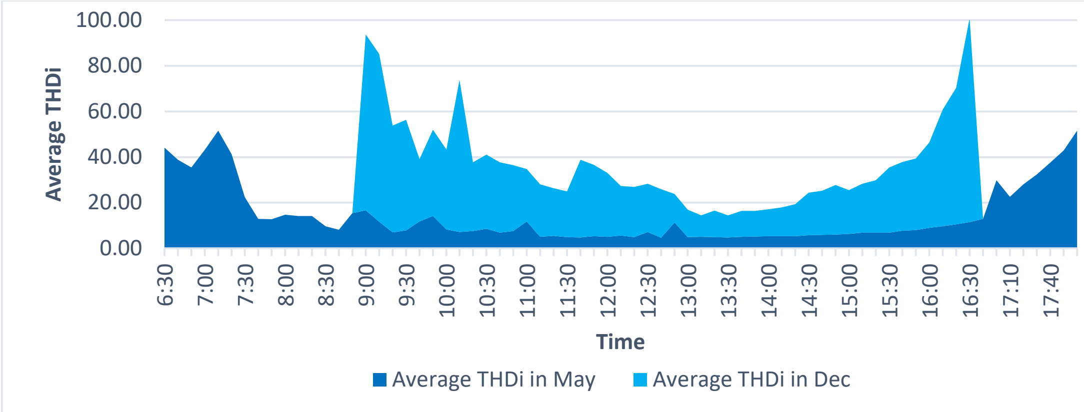

Fig15. Comparison of Average THDi values obtained in the months of May and December.

4.4. Power factor curve and Analyzing the data

Power factor depends on the relative power of the inverter. Figure 16 shows the curve of the power factor with relative power. Relative power and power factor are directly proportional. Similar trend can be seen in Figure 18 in the month of December.

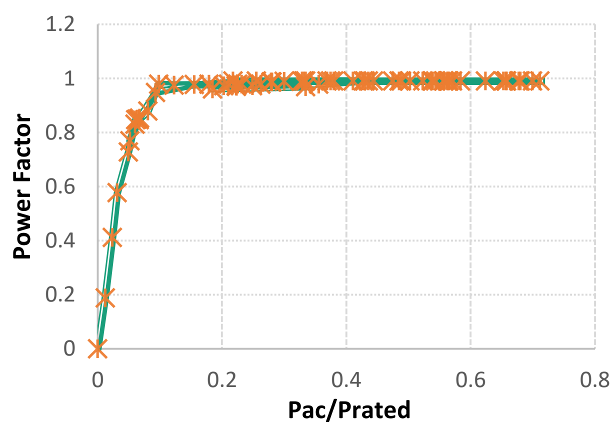

Fig16. Power factor as the function of relative power in May.

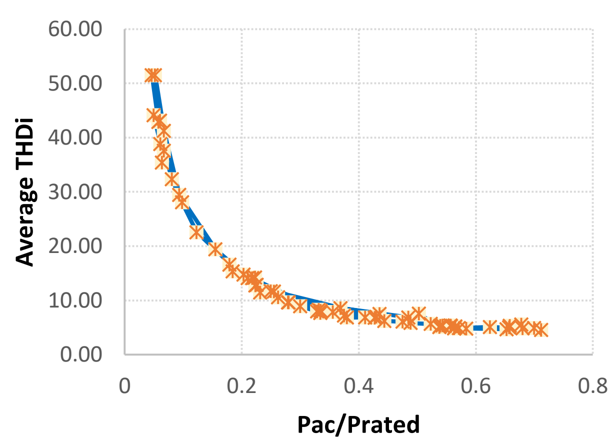

Fig17. THDi as the function of relative power in May.

When plotting the graph between harmonic distortion in the current (THDi) and relative power it is seen that they are inversely proportional (Figure 17 and 19 for the month of May and December respectively).

Table 1 contains the minimum, average and maximum power values for power factor above 0.9 obtained from the testing in May and December.Maximum power at which power factor is above 0.9 is 71% of rated power and minimum is 8% od rated power for summer whereas for winter maximum power is 41% of rated power and minimum is 8% of rated power.Power for harmonic distortion in current values more and less than the recommended can be referred toTable 2.THDi should be less than the recommended value by IEEE, above that value harmonic distortion can impact the power quality severely.At 20% of rated power THDi is within the limits but below 20% it increases beyond the limit in May whereas in December THDi goes beyond the advised value at and below the power at 30% of rated power.

Table 1. **Power** generated in the months of May and December when the **power factor is greater than 0.9 (or 90%).**

Months	Minimum power (Watt)	Average power (Watt)	Maximum power (Watt)
May	8087	4037.068	71170
December	8336	22334	41318

Table 2Power values from the inverter for **THDi within and more than the recommended value** in the months of May and December respectively.

Months	THDi	Power (Watt)	Average Power (Watt)
May	Within the recommended value	20310 or more than 20310	43854
	More than recommended value	18478 or less than 18478	8810.18
December	Within the recommended value	32568 or more than 32568	37892
	More than recommended value	30664 or less than 30664	14782

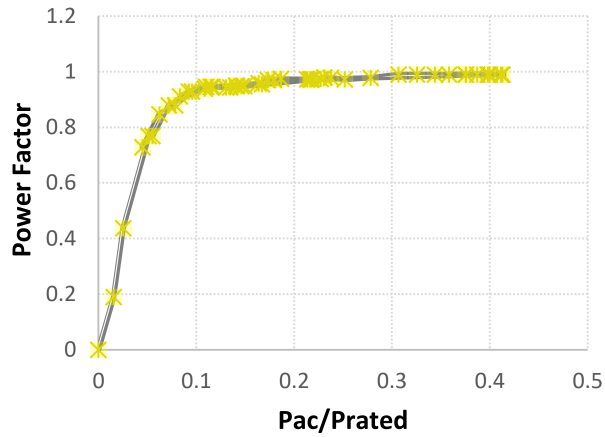

Fig18. Power factor as the function of relative power in December.

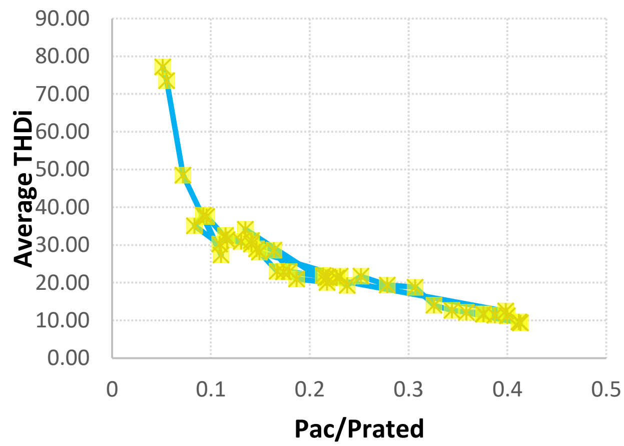

Fig19. THDi as the function of relative power in December.

Ahead given is Table 3 that have the minimum relative power value for power factor above 0.9. It is the same for both May and December. So, at 8% of relative power the power factor is above 0.9.

Table 3. Minimum relative power for power factor greater than 0.9.

Month	Relative Power
May	0.08
December	0.08

In May the time for which total harmonic distortion in current is under limit is approximately 7 hours whereas in December it is reduced to approximately 2 hours only, refer table 4 for exact timing. This concludes that total harmonic distortion in current is found for longer times in winter than in summer.

Table 4. Time for which THDi valuesare within the recommended value.

Month	Time
May	9:10 am- 16:40 pm
December	12:50 pm- 14:20 pm

0.99 power factor (or 99%) is achieved at minimum power 33% of rated power in summer and in winter minimum power is 32% of rated power. In may this high value of power factor is maintained for approximately 5 and a half hour and in December only for 1 and a half hour. Refer table 5 for exact values.

Table 5. Power generated and time period for which the power factor obtained is greater than 0.99.

Months	Power (Watt)		Time
	Minimum	Average	
May	33188	51787	10:00 am-15:30 pm
December	32568	37892	12:50 pm- 14:20pm

5. CONCLUSION

In the work examined here, tests were done on a 100kW system and data was collected in two different seasons to cover the range of changes in the power quality parameters. Through the tests the inverse proportionality relation of power factor with total harmonic distortion in current is obtained.The curves extracted from the data present the relationship between power generated by inverter and its power quality parameters, power factor and current total harmonic distortion in this case. Comparison is also presented for the summer and winter month and it is deduced that power quality is impacted more in winter months like December than in summer months like May. After reading the data it is concluded that from 12:50 pm to 14:20 pm, power factor is above 0.99 and THDi is within the limits of recommended value in both the months of May and December.So, these are the most productive hoursfor a Solar Rooftop PV System to work all around the yearwith least impact on the power quality parametersfor normal weather conditions in Ghaziabad, Uttar Pradesh, India.

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