POWER QUALITY ANALYSIS OF A GRID TIED 3.3 kWp ROOFTOP SOLAR PHOTOVOLTAIC SYSTEM WITH BATTERY STORAGE

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Abstract

This paper outlines the initial results for power quality analysis (PQA) of a single phase 3.3kWp photovoltaic (PV) system with battery storage connected to a low-voltage system at the Council for Scientific and Industrial Research (CSIR), Pretoria campus. The purpose of this study is to understand the harmonic distortion behaviours for three different sky conditions: clear, moderate and cloudy condition. The measured current harmonic distortions are categorized to different order intervals as per NRS 097-2-1:2017. The categorized maximum current harmonic distortions of each hour interval within a day are compared against the requirements stipulated in NRS 097-2-1:2017. The measured current harmonic distortions are inclusive of existing harmonics in the building, hence it is difficult to quantify the harmonics generated from the solar PV. The future plans include measurement of these harmonics in the building without PV to determine the baseline and then calculate the harmonic distortions originating from the PV system for different sky conditions.

Keywords: Power Quality; Grid-tied; Harmonic Distortion; Solar Photovoltaic.

1. Introduction

Grid-tied PV systems are the fastest growing Renewable Energy Source (RES) for power generation today. The quality of the electricity produced from PV directly depends on the amount of solar irradiance. Changes in weather conditions, rainfall and cloud movements affect the output power from PV. The primary reason for variable output power from PV is due to cloud movements. These power fluctuations on a grid-tied low voltage network also causes harmonic distortions in current waveforms [1]. PV inverters are the main source of injecting current harmonics into the network. The injected harmonics can increase power losses in the system [2].

There's a motivation worldwide to conduct power quality analysis as more embedded generators particularly solar PV systems are connected to low voltage utility grid. High penetration of intermittent PV cause voltage fluctuations in grid, voltage rise and reverse power flow, power fluctuations in grid, variation in frequency and grounding issues. PV penetration in low voltage distribution network also causes harmonic distortion in current and voltage waveforms [3]. Power quality analysis include harmonic distortions, reverse power flow, voltage fluctuations and power fluctuations. These parameters must comply with the governing standards in order to ensure the safe operation of connected loads and cleanliness of the supply.

1.1 Topology of the system under test

A 3.3kWp photovoltaic system is installed on the roof of Building 34, and the output is connected to the low-voltage network in the building. The PV system consists of 10x 327Wp mono-crystalline modules and a 1x 5 kW AC grid connected inverter with integrated 2 kWh battery storage. A Si Reference cell pyranometer is installed adjacent to the solar PV system to measure the in-plane available at the site, and the data is stored at 30 second intervals. A 3 channel Yokogawa WT500 power quality analyser with a tolerance of ±0.01% is used to measure the power flow and monitor the power quality parameters. Channel 1 measures the AC output power from the inverter, Channel 2 measures the DC power from the PV arrays and Channel 3 measures DC power from the battery storage. AC and DC signals are measured and recorded by the WT500 Power Quality Analyser every 10 seconds. The harmonic distortions of voltage and current from the 1st to the 50th order on real time is recorded with the other data such as active power, reactive power, apparent power, power factor and frequency. The generated DC power from the modules during the day time charges the battery while feeding the excess power into the grid. The battery is configured to discharge the stored power to the grid when the PV generation is low and when the PV system is no longer generating at the end of the day.

The topology of the PV plant with the power quality analyser is presented in Figure 1.

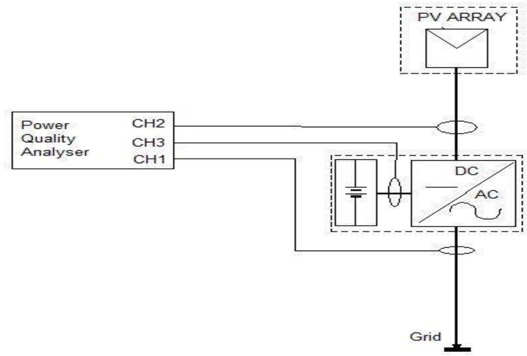

Fig.1 Topology of PV plant with power quality analyser

Figure 2 presents the daily total solar PV generation, discharge from the battery, and irradiance data for a period of 3 months. The amount of energy discharged by the battery is determined by the sky conditions. When the sky is clear, the battery discharges only at the end of the day, i.e. when the PV stops generating. When the sky is completely overcast or cloudy for a few periods in a day, the PV generation drops below the threshold point and the battery discharges. When there is sufficient irradiance, the PV generates above the threshold, and the battery is charged and excess energy is fed to the grid. On the 1st of February, we only connected half the total number of modules on the system hence the energy generated is low relative to insolation. On 15 February, all 10 modules were connected.

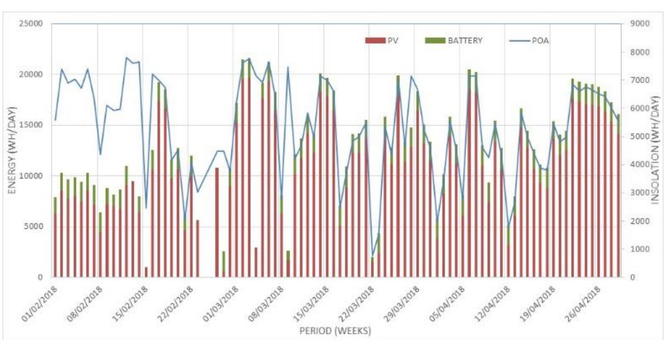

Fig.2. Daily Solar PV Energy, Battery Energy and Solar Irradiance

1.2 Applicable standards for Harmonic standards

In line with the current Renewable Power Plant (RPP) Grid Code, embedded generators smaller than 1000kVA connected to low-voltage network forms part of category A generators, with the subcategories as follows:

- A1:0-13,8kVA; Rated power is in the range from 0 to 13,8kVA, inclusive of 13,8kVA.
- A2:13,8kVA-100kVA; Rated power is in the range greater than 13,8kVA but less than 100 kVA.
- A3:100kVA-1MVA; Rated power is in the range 100kVA but less than 1 MVA.

PV systems utilize static power converter technology to convert DC to AC, and the compatibility of the PV output and the grid network is to be maintained. The NRS 097-2-1:2017 Clause 4.1.10 stipulates the maximum allowable harmonics and waveform distortions for the power supply feeding from embedded generation into utility grid [4]. The below clauses pertain to the level of harmonics that can be injected to grid.

- Only devices that inject low levels of current and voltage harmonics will be accepted. The higher harmonic levels increase the potential for adverse effects on connected equipment.
- The embedded generator output shall have low current distortion levels to ensure that no adverse effects are caused to other equipment connected to the utility system.

The maximum harmonic current distortion as percentage of rated current is provided in Table 1:

Harmonic Order	H<11	11≤h<17	17≤h<23	23≤h<35	35≤h
Percentage of rated current (Odd harmonics)	4	2	1.5	0.6	0.3
Percentage of rated current (Even harmonics)	1	0.5	0.38	0.15	0.08

Table1. Maximum harmonic distortion as percentage of rated current

3. Results and discussion

The analysis of real-time measured data for three months is presented in this section. Based on the measured daily irradiance profile, three conditions were determined (clear, moderate and cloudy sky) to analyse the behaviour of power quality parameters from the solar PV system. The clear sky indicates no cloud movements with average irradiance >800W/m^2, moderate sky indicates passing clouds with average irradiance 400 ≤ 800W/m^2 and cloudy sky indicates fully overcast sky with average irradiance of <400W/m^2 in a day. The measured with respect to time interval for a single day for clear, moderate and cloudy sky conditions is presented in Figure 3.

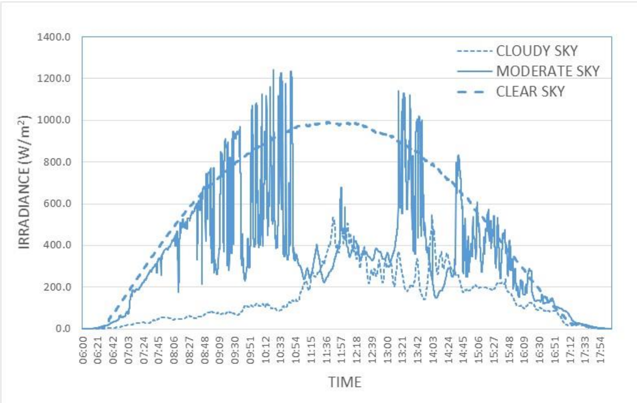

Fig.3. Clear, moderate and cloudy sky

On clear sky conditions, the solar irradiance profile follows the bell curve without any fluctuation and peaks at solar noon. The moderate sky condition has lot more fluctuation from high to low within short periods. Under cloudy sky conditions, the measured irradiance is low and the short term variation is somewhere in between clear and moderate sky conditions.

The measured DC power, AC active and reactive power and power factor (PF) for clear, moderate and cloudy conditions are presented in Figure 4, 5 and 6.

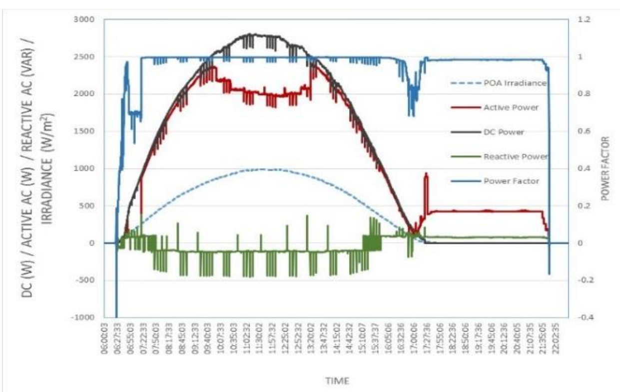

Fig.4. AC Active and Reactive Power, DC power and PF for clear day

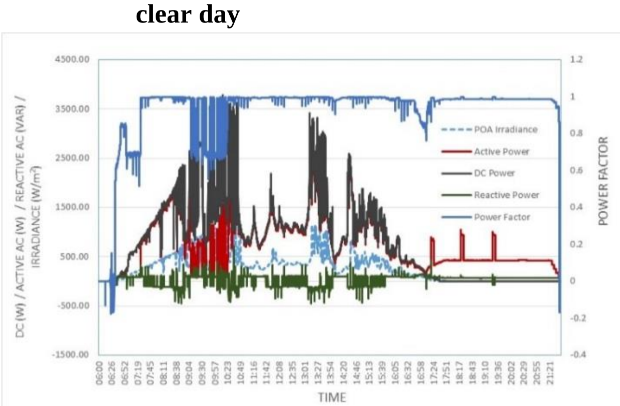

Fig.5. AC Active and Reactive Power, DC power and PF for moderate day

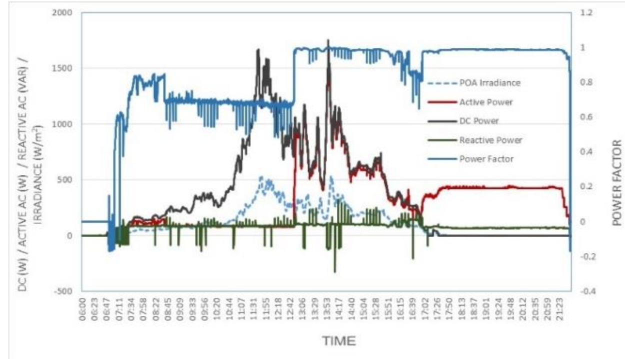

Fig.6. AC Active and Reactive Power, DC power and PF for cloudy day

The DC, AC active, and AC reactive power are strongly dependent on solar irradiance. Fluctuation in the solar irradiance leads to changes in the DC power produced by the PV modules causing active and reactive power to fluctuate and power factor to vary. The active and reactive power also vary during the charging of the battery. During the battery discharge, variation in active, reactive and power factor is low. When the fluctuation in the irradiance is low, the stability in the power factor is high (0.8 to 0.99). On moderate and cloudy sky conditions, a power factor drop up to 0.5 was observed when there was fluctuation in irradiance. As the irradiance increases in the early morning hours, the battery starts charging for a short period causing reduction in the active power supplied to grid, and the rest of the battery capacity is charged during the day while feeding excess active power to the grid.

The instantaneous harmonic distortions measured for current is segregated to different categories specified in NRS 097 standard. The real time instantaneous harmonics distortion data is measured every 10 seconds interval. The maximum value for every hour is determined for each category of harmonic orders for all three sky conditions and it is compared with the requirements. The maximum odd and even current harmonics for every hour in a day on a clear, moderate and cloudy sky condition is presented in Figures 7 to 12.

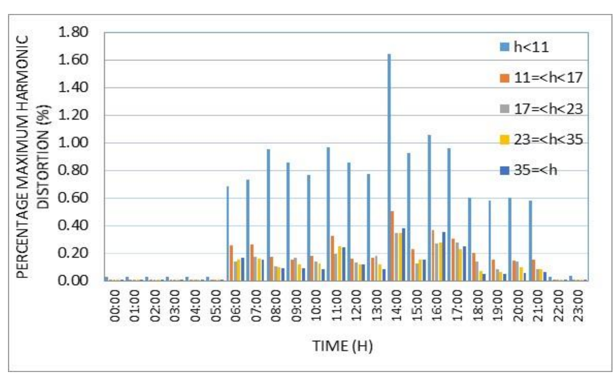

Fig.7. Hourly odd harmonic current distortions for clear day

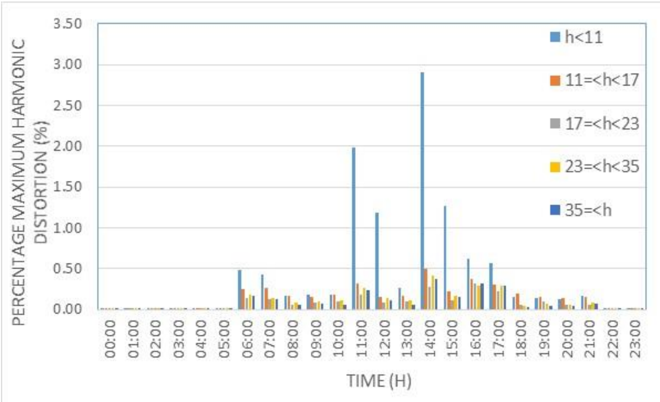

Fig.8. Hourly even harmonic current distortions order for clear day

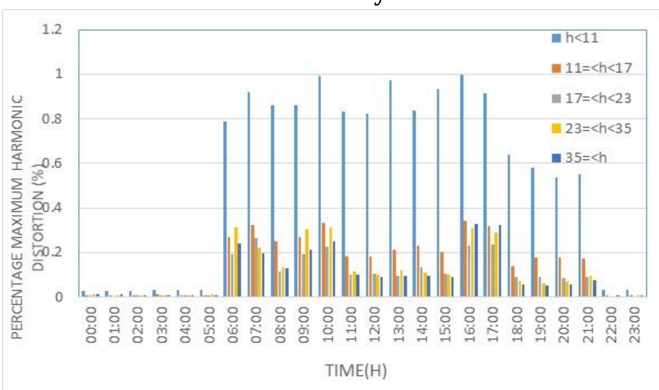

Fig.9. Hourly odd harmonic current distortions for moderate day

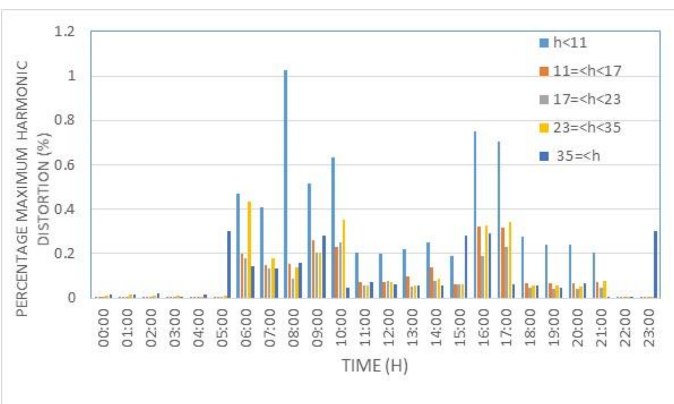

Fig.10. Hourly even harmonic current distortions order for moderate day

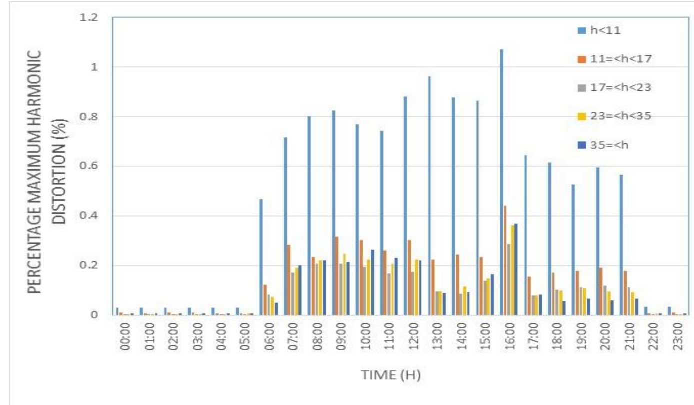

Fig.11. Hourly odd harmonic current distortions for cloudy day

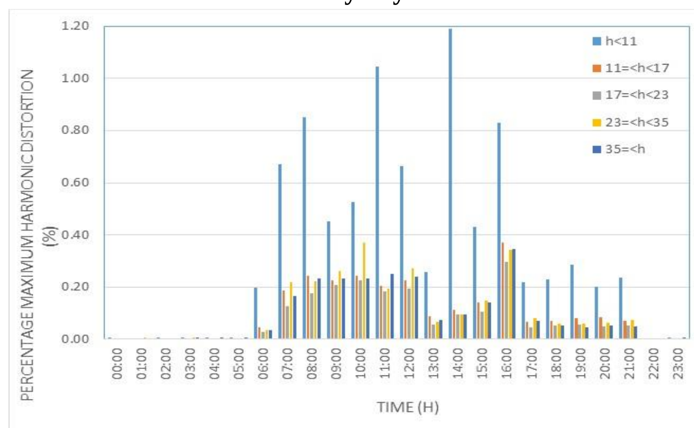

Fig.12. Hourly even harmonic current distortions order compared to NRS standard requirements for cloudy day

Under clear, moderate and cloudy sky conditions, the odd harmonic distortions for order $h<11$, $11\le h<17$, $17\le h<23$, $23\le h<35$, $35\le h<50$ were less than 4%, 2%, 1.5%, 0.6%, 0.3%, respectively, and all the measured values were well within the requirements stipulated in NRS standard.

Under clear sky conditions, the hourly maximum even harmonic distortions for order $h<11$ were beyond the limit of 1% in 4 occasions. The order $11\le h<17$ and $17\le h<23$, the measured even harmonics were within the limit of 0.5% and 0.38%, respectively. For order $23\le h<35$ and $35\le h<50$, there were instances of 5 and 8 occasions where the measured values were exceeding the limit of 0.15% and 0.08% respectively.

Under moderate sky conditions, the hourly maximum even harmonic distortions for order $h<11$ were above the limit of 1% on 1 occasion. The order $11\le h<17$ and $17\le h<23$ were within the limit of 0.5% and 0.38%. For order $23\le h<35$ and $35\le h<50$, the measured even harmonics were above the limit of 0.15% and 0.08% in 5 and 6 instances.

On a cloudy sky condition, the hourly maximum even harmonic distortions for order $h<11$ were beyond the limit of 1% in 2 occasions. For order 11≤h<17 and 17≤h<23, the measured even harmonics were within the limit of 0.5% and 0.38%, respectively. For order 23≤h<35 and 35≤h<50, there were instances of 8 and 9 occasions where the measured values were exceeding the limit of 0.15% and 0.08%, respectively.

The measured harmonics are without knowing the baseline of existing harmonics in the building. Further studies will be carried out to understand the baseline harmonics without PV and the respective PV contribution will be analysed.

5. Conclusion

The initial results of power quality analysis carried out on 3 different sky conditions are presented in this paper. The real time measured data for a period 01st February to 30th April 2018 is analysed. Depending on the irradiance conditions that determine clear, moderate and cloudy conditions, 09th, 12th and 22nd of April were chosen for analysis. The initial results of the power quality analysis indicate the active, reactive and power factor are affected by the varying irradiance and battery charging. During battery discharge, no fluctuation or stable output is observed in active, reactive and power factor. The maximum odd harmonics distortion identified every hour under those 3 sky conditions were well within the allowable limits defined in NRS standard. The maximum even harmonic distortions were observed to be beyond the limit for h<11, 23≤h<35 and 35≤h<50 order in couple of instances. These measurements are taken without the baseline measurement of existing harmonics in the building.

For further analysis, the PV system network will be isolated from the building and the baseline power quality parameters will be measured in order to find the existing harmonic distortions present in the power supply or generated by the local loads.

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