Inspection of Interharmonic emissions from a Grid-tied PV Inverter in North Sweden

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Abstract— **The main objective of the paper is to investigate the existence of interharmonic emissions from an MPPT driven grid-connected PV inverter, identify their severity and persistence. The presence of interharmonics in the measured current from a PV installation is linked to direct and diffused solar irradiation as well as a high ramping rate of the irradiation causing variations in both active and reactive power. The paper sets forth a set of observations and inferences, which is an appendage to the ongoing research on the power quality aspects of solar power. Three different case studies are evaluated in detail using signal processing tools like STFT and FFT.**

Index Terms—**Electrical Power distribution, Power Quality, Interharmonics, Photovoltaic systems.**

I. Introduction

The Global Photovoltaic generation capacity by the end of 2016 had grown 33% compared to previous year [1]. Owing to the increasing amount of power electronic based photovoltaic units (single phase and three phase) introduced into the grid all over the world, it is crucial to explore the power quality phenomena occurring on the grid and define proper standards.

The major power quality issues addressed until now are [2]:

- Characteristic harmonics (odd harmonics up to 2 kHz for single-phase installations; odd non-triple harmonics for three-phase installations).
- Low-order non-characteristic harmonics (even harmonics and interharmonics up to 2 kHz, also odd triple harmonics for three-phase installations)
- Supraharmonics (frequency-components in the frequency range 2 to 150 kHz)
- Single rapid voltage changes, flicker and other voltage-magnitude variations at timescales below 10 minutes.
- Supply voltage variations at time scales of 10 minutes and longer.

Presently, there is limited literature investigating interharmonic emissions originating from PV Inverters. Compared to harmonics, interharmonic related problems are relatively rare and the need to measure or mitigate interharmonics is uncommon [3] especially for PV installations.

Interharmonics in grid current is a relevant topic of research because interharmonics can cause voltage fluctuations and light flickering. Also, with the introduction of energy efficient lightings like LED lamps, which could be sensitive to the presence of higher order interharmonics [4], it is significant to investigate the distortions in grid current.

The explanations behind the existence of interharmonic emissions from a PV inverter are not yet understood fully; one reason being that it is difficult to obtain the designed controller parameters of commercial PV inverters under test [5]. MPPT control is likely the origin/cause of the interharmonic emissions transferred to the grid current. This becomes particularly pronounced in very low-power operating modes, due to the increased flatness of the P–V curve of connected panels [6]. The interharmonics close to fundamental or an integer harmonic can cause flicker. Therefore, detecting those interharmonics for flicker troubleshooting is desirable [7]. Flicker contribution from changes in reactive power has also been observed in some PV installations. The analysis should be performed using measurements from additional PV installations to determine the extent of this phenomenon [2].

A recent publication relating interharmonics and PV inverters concludes with the necessity of performing further studies about the intrinsic interharmonic emissions e.g. related to cloud-coverage variations (fast clouds passages) on large PV plants [8]. One of the cases addressed in this paper is partially looking into this fact too, even though it is not a large PV plant. More case studies are required to derive definitive conclusions.

In Section II basics of interharmonics are discussed. Section III describes the methodology adopted for measurements and analysis with location details. In Section IV the results and observations are presented. In this paper, Spectrograms are plotted with respect to the variation of active and reactive power, for the selected periods of measurement to exemplify interharmonic emissions in grid current and grid voltage.

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II. INTERHARMONICS

A. Definitions

The term 'Interharmonics' is defined as any frequency which is not an integer multiple of the fundamental frequency. The interconnection of two asynchronous systems can result in interharmonic emissions, for example as in electric drive systems, static frequency converters, voltage source inverters etc. [9]. Other sources of interharmonics can be attributed to transformer saturation and switching process, arc furnace operations etc. [9].

Identifying the correct source of interharmonic generation in a system is not straightforward. There are no vivid general conclusions about the reasons behind interharmonic generations especially in PV inverters, as they are studied and mitigation techniques are proposed on a case by case basis. This demands the stringent need for further research on interharmonics, as advanced power electronic technology is widely deployed for greater system flexibility in grid operations nowadays.

III. MEASUREMENT AND ANALYSIS

The measurements used in this study are carried out on a regular basis at a 20 kW, 3Ø fixed axis tracking PV installation on an office building at Skellefteå, North Sweden. An Elspec Power Quality analyzer is installed at the particular location. The case studies described in this paper corresponds to the dates 23/05/2017, 29/05/2017 & 5/01/2017. The peculiarity in the timings of sunrise and sunset discussed in the following sections is due to the geographical location of the place (Skellefteå, North Sweden with a latitude of 64.7502° N, 20.9509° E) and time of the year for measurement.

There are two rows of PV panels each with 21 strings with a 45° tilt to South and each connected to a 10 kW inverter. The measurements are done at the parallel combination of these two inverters and the grid which is the Point of common coupling (PCC). A maximum power point tracking algorithm using 'Incremental conductance method' is implemented in the PV inverter, constantly working to maximize the output from PV array. The algorithm updates the PV voltage to follow quick changes in solar irradiance (30 W/m^2) [10].

Since the measurement location is an office building with the PV installed on a rooftop, there is a possibility of other equipment's connected close to the panel during working hours. Emission from this equipment could impact the voltage and, in the form of secondary emission, the measured current. These three days were particularly chosen for analysis so as to obtain (a) a smooth profile of the variation in solar power (solar irradiance), (b) random power variations and (c) low power generation for short time (winter season) respectively.

The analysis is done using the concept of STFT (Short Term Fourier Transform) with zero window overlapping giving a frequency resolution of 0.1 Hz and a time resolution of 1 second on phase 'a'. The sampling frequency is equal to 10 kHz. STFT is used as a tool to portray the time-varying interharmonic patterns on a logarithmic scale for better viewability. More emphasis was given to frequency resolution to view the expected low-frequency interharmonic components according to existing literature. The magnitudes of the observed patterns are further calculated using FFT analysis with 0.1 Hz frequency resolution using a Hanning window taking into account the window coherent gain [11].

IV. RESULTS AND DISCUSSIONS

A. Results of measurements on 23/05/2017

Measurements were collected from 00:00 am to 23:50 pm on 23rd of May 2017(about one month before the summer solstice in the Northern hemisphere), each of 10-second duration every 10 minutes. There were 144 measurements. The spectrogram is the concatenation of all the measurements taken per day and is the appropriate way to show a timely variation of frequency and power. The smooth profile of active power with respect to the time of measurement of the day, as shown below in Figure 1, resembles a clear sky irradiance. Note that direct sunlight only reaches the panel several hours after sunrise (at instant A in Figure 1).

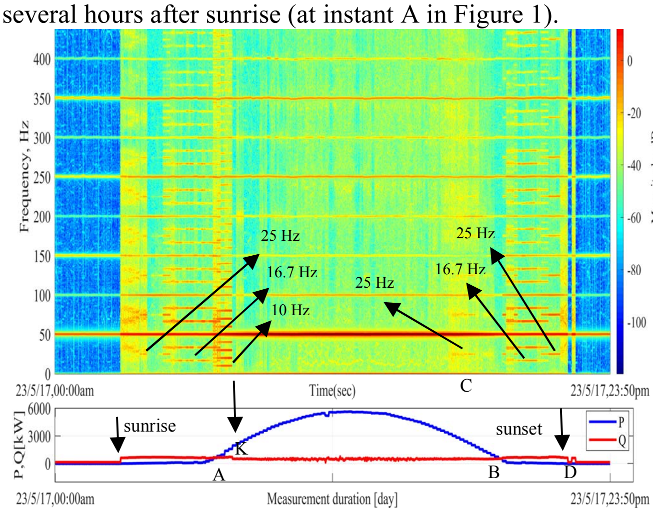

Figure 1 STFT spectrum of grid current on 23/05/2017

The Spectrogram of grid current in all the evaluated cases shows a clear discrimination between day and night. The blue color in the spectrogram corresponds to night time, i.e. before sunrise (02:48 am) and after sunset (22:21 pm) on a particular day.

The distinguished interharmonic frequency components are 10 Hz, 16.7 Hz, 25 Hz and their multiples, all occurring at different instances. The corresponding magnitudes are shown in Figures 2, 3 & 4. Mostly, these low-frequency emissions occur after sunrise and before sunset, where the reactive power is greater than active power production. It was also verified that these emissions persisted for a time scale of minimum 20 seconds and a maximum 2 minutes.

Points A(6:50 am) & B(19:10 pm) are explicitly marked in Figure 1 as these are the extremes where the active power production starts to increase more than reactive power and thereafter the interharmonic emissions rarely exist, rather than the 10 Hz components existing for some more time (Point A to K) and some emissions are seen at point C. Point A can be considered as the MPPT awakening instant and Point B can be considered as the MPPT shutting down instant. Point D (after sunset) shows that a variation in reactive power makes a clear change in the spectrogram.

The authenticity of these interharmonic emissions was verified using FFT spectrum for each measurement as well as by testing the STFT code introducing synthetic signals.

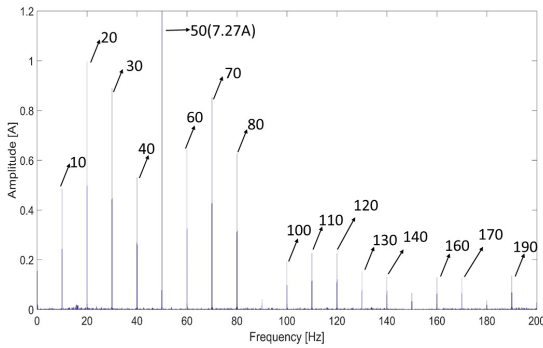

Figure 2 spectrum of a measurement showing 10 Hz emissions & its multiples observed on 23/05/2017 at a time 07:30 am.

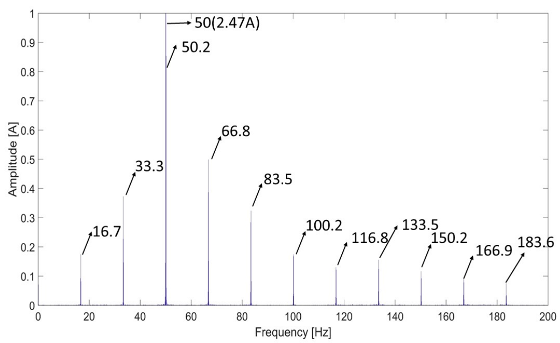

Figure 3 spectrum of a measurement showing 16.67 Hz emissions & its multiples observed on 23/05/2017 at a time 20:50 pm.

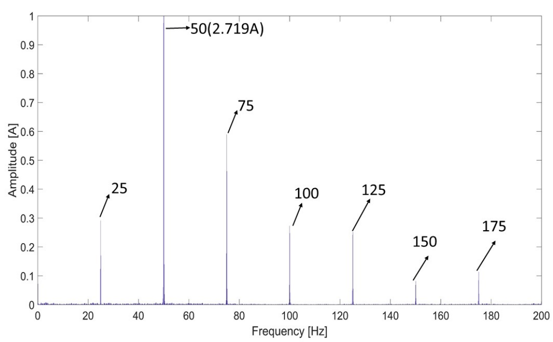

Figure 4 spectrum of a measurement showing 25 Hz emissions & its multiples observed on 23/05/2017 at a time 21:30 pm.

From the FFT spectrums as shown in Figure 2,3 and 4 , it is seen that the magnitude of the low-frequency interharmonic emissions in grid current is in the range 0.3 to 3.46% of the per phase rated current for the considered frequency range and all these measurements belong to low power regions (less than 23.66 % of the rated power). The slight emissions seen at Point C occurs at 29.8% of power generation.

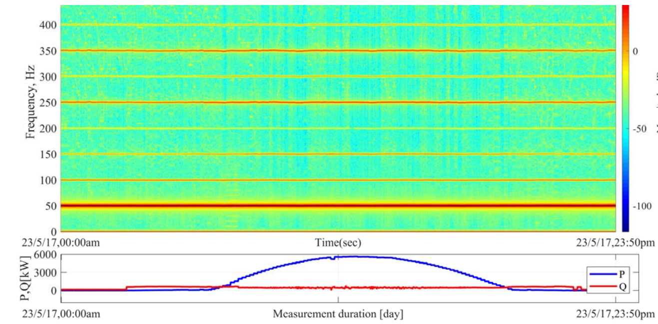

Figure 5 STFT spectrum of AC Voltage

The AC voltage spectrum seen in Figure 5 has no visible difference between night and day as in the grid current spectrum. The inverter output voltage is maintained equal to the grid voltage by the inverter feedback control strategy. The AC voltage didn't show up any interharmonic emission patterns in any of the cases (hence are excluded in the paper for the other dates).

At night, the direction of power flow is reversed, with a capacitive power factor and during the day power factor is maintained close to unity. This condition is the same for all the dates.

B. Results of measurements on 29/05/2017

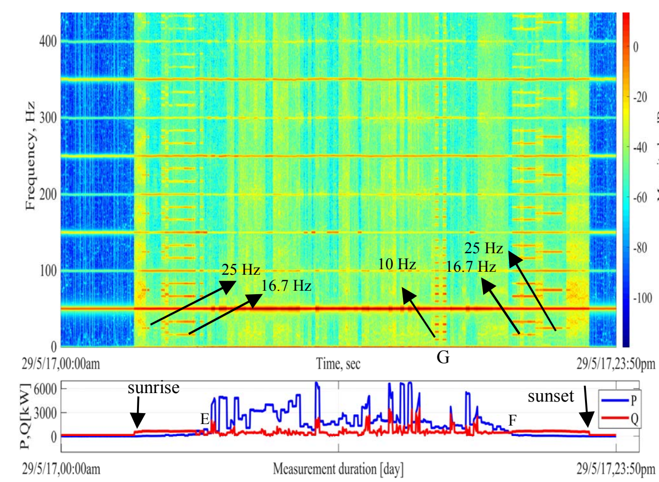

Figure 6 STFT spectrum of grid current on 29/05/2017

The measurements collected on this day corresponds to random power variations. The high variations may be due to cloud shading. There are instances when the particular phase attains a maximum power of 6.6 kW and even slightly exceeds the maximum power in a few instances. This can be due to reflections from the cloud.

As similar to Figure 1, it can be concluded that the low-frequency emissions are seen mostly after sunrise (2:30 am) to the point where MPPT algorithm wakens up (Point E) and from the point MPPT algorithm shuts down (Point F) to sunset (22:41 pm). At both these instants, the reactive power is more than active power production. But this condition cannot be generalized as 10 Hz emission & it multiples can be seen (Point G) neither of these situations, with an active power production exceeding the reactive power. Point E corresponds to morning 6:00 am and Point F corresponds to evening 19:20 pm. In this duration, the pattern of variation of active and reactive power is quite similar.

The 16.7 Hz and 25 Hz emissions as seen in Figure 6, corresponds to a power generation of less than 3%.

The FFT spectrum of interharmonic emissions shown in Figure 7 below, corresponds to a power generation of 16.212% of the rated power (Point G). The magnitude of 10 Hz components and its multiples are in the range .29% to 2.85% of the per phase rated current for the considered frequency range.

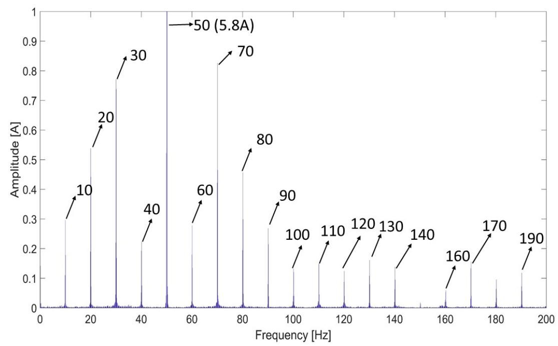

Figure 7 spectrum showing 10 Hz emissions at Point G

In the above two cases, the time duration between Points A and B as in Figure 1 and Points E and F as in Figure 2, can be considered as working hours/office time of the office building. So, it was necessary to verify the origin of interharmonic emissions observed at either side of working hours/office time. It was to be checked whether they resulted from external events prior to the initiation of working hours like ventilation starting up, elevator working etc. or the result of interaction between PV inverter and other office equipment's or only related to Sun and PV inverter operation. In view of above, another day was considered during the winter season, when there is sunlight only short time and no active power production, the results of which are discussed in Section III. *C*.

Also, it is evident from Figures 1 and 6 that the interharmonics are located in most of the occasions where the MPPT-driven PV inverter produces low power. Even after sunrise, there exists a delay time for the inverter to start up for an appreciable active power production and also inverter shuts down producing inappreciable power sometime before sunset. The solar irradiation being indirect on the PV panel due to the parabolic nature of the track of sun is most likely the reason for the delay in an active inverter operation.

Another explanation in meteorological terms is as below. Global Horizontal Irradiance (GHI) is a combination of the Direct Normal Irradiance (DNI) reaching the panel and the Diffuse Horizontal Irradiance (DHI).

$$GHI = DNI*Cos\ \Theta_z + DHI$$

When sun's azimuth angle(Θ_z) is approximately ≥ 70 degrees (note: sun's elevation angle is complementary of azimuth angle), a relatively high air mass results in a large fraction of GHI originating from the diffuse component; and the high solar zenith angle in combination with an elevated air mass results in rather low photovoltaic power production [13]. The low photovoltaic production hence with the inefficiency of inverter MPPT control has created the interharmonic emissions.

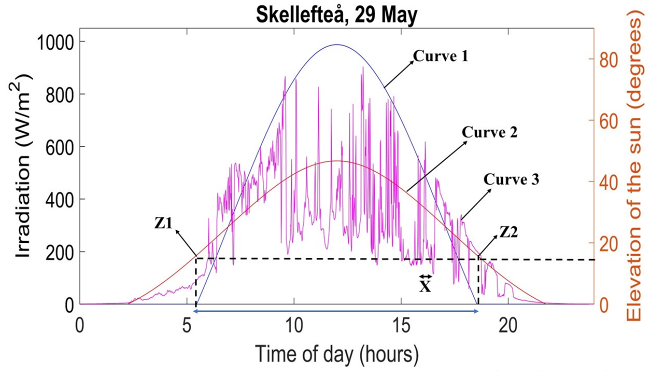

Figure 8 Curve1, Curve 2, Curve 3 representing DNI, elevation angle and Actual irradiance measured respectively on 29/05/2017

Curve 1 in Figure 8 corresponds to the DNI reaching the tilted panel on 29/05/2017 if the sky is clear and Curve 2 represents the sun's elevation angle based on latitude, both programmed in MATLAB. Curve 3 represents the actual irradiance reaching the panel measured from the weather station in Skellefteå on 29/05/2017. The time span of the DNI as marked in Curve 1 coincides with the duration between Points E and F in Figure 6. Below the marked Points Z1 and Z2, where there is no DNI reaching the panel with an elevation angle ≤ 20 degrees (azimuth angle ≥ 70 degrees) is the low power region with interharmonic emissions. The then actual irradiance ≤ 200 W/m^2. Region X marked in Curve 3 shows a high Ramping rate event [14] with solar irradiance variation from 617.7 to 157.8 W/m^2 in less than 20 minute due to fast cloud passages and this is likely the reason for interharmonic emissions at Point G, Figure 2.

C. *Results of measurements on 5/01/2017*

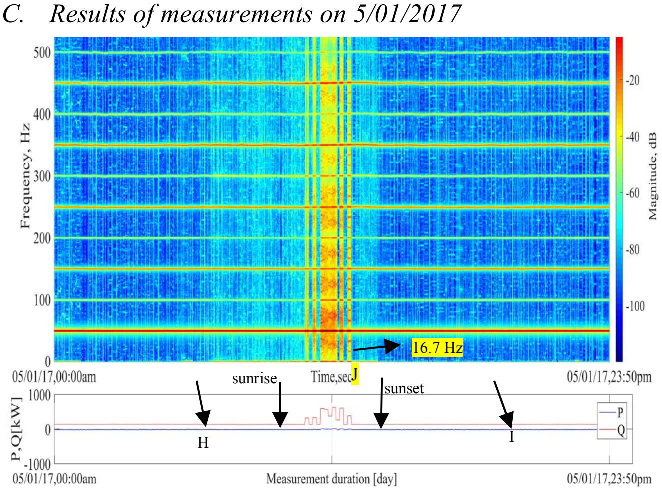

Figure 9 STFT spectrum of grid current on 05/01/2017

The measurements represented in Figure 9, corresponds to winter climate (January), where the mean temperature of the day was around -25^0 Celsius with sunrise at 9:32 am and sunset at 13:52 pm. Throughout the period of measurement, the reactive power is more than active power production. In

fact, there is no active power generation and 98 % of the time power is slightly negative.
The magnitude of 16.7 Hz emissions and its multiples are less than 0.7% of per phase rated current as seen in Figure 10.

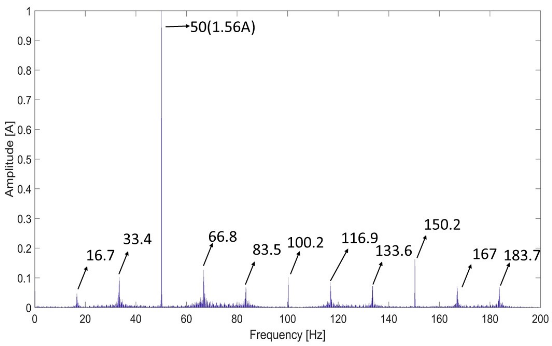

Figure 10 FFT spectrum showing emissions at Point J

Points H and I in Figure 9, corresponds to the time of 6:00 am and 19:00 pm which can be considered as the office time. From Figure 9, it is clear that the low-frequency emissions exist independent of the location of working hours. Therefore, one could conclude that these interharmonic emissions are independent of any probable external disturbances during the onset and offset of working hours.
The instance with interharmonics present, shown in Figure 9, appears within the time zone of sunrise and sunset. This leads to the conclusion that they are related to sun and PV inverter operations alone. Point G in Figure 6 also validates this conclusion.

V. COMPARISON OF MEASUREMENTS

To quantify the effect of interharmonics, subgrouping was done as in the standard IEC61000-4-7 with a 200ms window and a 5 Hz resolution [15], but with a Hanning window taking into account the window coherent gain and a grouping factor, together defined as the grouping gain [12].
The Total Interharmonic Distortion (TIHD) in absolute value was calculated in each of the cases for the grid current and grid voltage respectively (represented as TIHC, TIHV) as explained in the reference [6]. The results are tabulated as shown in Table 1.

TABLE I. TABLE SHOWING A COMPARISON OF TIHC,TIHV

Dates of measurement	max (TIHC) in grid current (A)	max (TIHV) in grid voltage (V)	Peculiarity of the day
23/05/2017	2.034	0.68	Smooth power variation
29/05/2017	1.641	0.68	Random power variation
05/01/2017	0.622	0.67	No active power generation

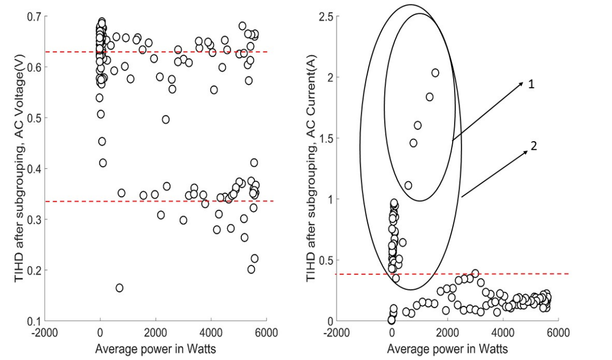

Figure 11 (a) Variation of TIHD in grid voltage with Power (b) Variation of TIHD in grid current with Power on 23/05/2017

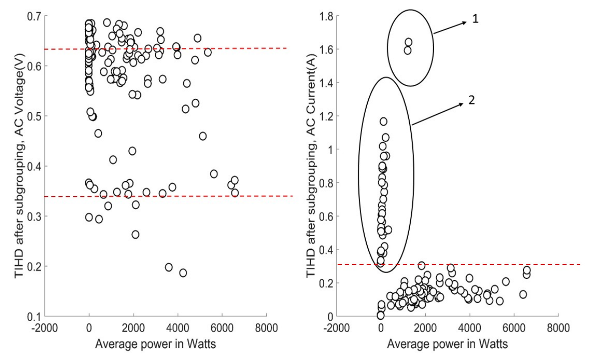

Figure 12(a) Variation of TIHD in grid voltage with Power (b) Variation of TIHD in grid current with Power on 29/05/2017

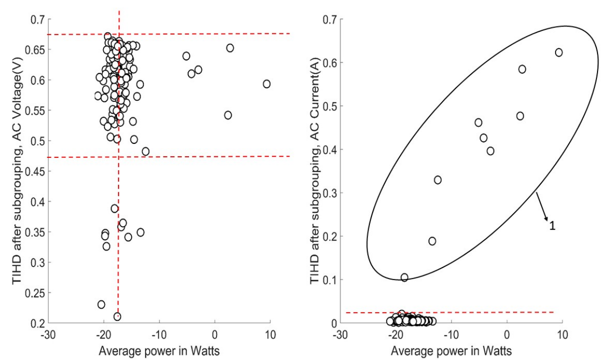

Figure 13 (a) Variation of TIHD in grid voltage with Power (b) Variation of TIHD in grid current with Power on 05/01/2017

The first encirclement of Figure 11(b) corresponds to the period from Point A to K in Figure 1 and they are responsible for the highest TIHD value in grid current. The second encirclement corresponds to TIHD contributed mostly by the low power regions until MPPT awakening or after MPPT shutting down instances as discussed before. During working hours the TIHD in grid current was mostly below 0.3A.
The first encirclement of Figure 12(b) corresponds to the Point G marked in Figure 6 and is where the highest TIHD values are found. The second encirclement corresponds to TIHD contributed mostly by the low power regions observed until MPPT awakening or after MPPT shutting down

instances as discussed. During working hours, the TIHD in grid current was found below 0.3A.

In Figure 11(a) & 12(a) it is observed that TIHD in grid voltage is mostly situated around 0.63V and 0.34V irrespective of the time of occurrence for all ranges of power.

As seen in Figure 13, the active power generation is very low and for limited instants. The encirclement in Figure 13 corresponds to the time 11.20 am to 12:30 pm, the instance interharmonics present in grid current as shown in Figure 9. All other points have a TIHD very low (near to zero). The TIHD in grid voltage is mostly seen in the range 0.5-0.7V and occasionally around 0.35V.

From these observations, one could conclude that the highest TIHD in grid current occurs for low power regions below a threshold of around 2000W. Worth mentioning is that lower TIHD values in grid current are also found at a power level below 2000W as seen in Figure 11, 12 and 13. A low power production alone cannot be thus contribute to cause high levels of interharmonics.

The highest value of TIHD in grid voltage occurs for all ranges of power.

VI. CONCLUSIONS

From the 3 different case studies of the chosen PV installation demonstrated in this paper, it can be concluded that interharmonic emissions most likely appear after sunrise and before sunset in the instances where (a) reactive power is more than active power production (b) there is a transition in the direction of power flow from negative to slightly positive as it is a transition from night to daytime and (c) is also the region where the sun's elevation angle is ≤ 20 degrees and GHI comprising mainly of DHI which was found to be ≤ 200 W/m^2. The inefficiency of MPPT during the specified period due to the increased flatness of P-V curve, which could not activate the inverter for an appreciable power production, is one of reasons for these seen interharmonic emissions.

But this condition cannot be generalized, as there are instances explained above where interharmonic emissions appear contrary to it, where (a) direct irradiance reach the PV panel and (b) MPPT driven PV inverter is able to produce active power more than reactive power.

A day with high variability in cloud passages resulting in a Ramping rate event can also result in the generation of interharmonic emissions. It is also worth noting that all Ramping rate events did not necessarily result in interharmonic emission. Relating interharmonic emissions with Ramping rate events and MPPT operation is hence somewhat stochastic.

From these observations, one could derive at the conclusion that these low-frequency emissions depends on the events like location of sun; the angle at which solar ray is incident on the PV surface which can be subjected to the type of tracking, tilt angle and direction of PV panel; cloud passages; all these significantly along with how efficient is the operation of MPPT in PV inverter.

All these interharmonic emissions are observed for a power level threshold of less than 30% of the rated for the particular installation. More case studies are required to verify the threshold as it will serve as an index for the testing of PV inverter for the manufacturers before connecting to the grid.

These low-frequency emissions are seen for a time scale of 2 minutes in the majority of the cases, which can be a source of flicker depending on the magnitude and interaction with other possible external events. A relation between reactive power, flicker, and interharmonics is yet to be established from further studies.

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