Methodology for the determination of the influence of the background harmonic voltage distortion on the measured harmonic currents of Wind Turbines and PV Inverters

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***Abstract*—In this paper a review of the state of the art methods for the efficient identification of the influence of the background harmonic distortion of the electrical grid to the harmonic currents measured at the terminals of wind turbines and PV inverters is performed. Selected methods are applied based on actual field measurements and the relevant results are presented and discussed.**

Keywords-component; grid compliance; harmonic currents; harmonic limits; IEC & IEEE standards, harmonic distortion;

I. INTRODUCTION

The presence of harmonics may have multiple harmful effects on the safe, reliable and efficient operation of the power systems such as damages of the electrical devices, increase of the electrical losses and hindering of the correct operation of protections systems. Harmonic distortion has become a major issue for grid operators and equipment manufacturers during the last years, because the number of inverter-based equipment, which connect to the network, has substantially increased. Especially regarding wind turbine (WT) and photovoltaic (PV) stations, power converters are almost exclusively used, because they feature several control capabilities, which can be exploited for the maximization of the output energy, optimize the response characteristics and improve the quality of the produced power. As a consequence, wind and PV stations emit harmonic currents to the grid, which may reach high levels in power systems with large renewable energy penetration if no proper measures for their control are taken to keep them within certain limits.

For the accurate and reliable estimation of these harmonic current emissions, two basic steps are necessary: (a) the establishment of a dedicated measurement procedure and (b) the development of proper tools for the efficient evaluation of the relevant harmonic levels. Starting from the first step, the current practice in the measurement of harmonics, is to follow the IEC Standard 61400-21 [1] for WTs and the IEC 61000-4-30 [2], for all types of power supply systems. Both these standards rely on IEC 61000-4-7 [3], which is the most recognized international standard on harmonics measurements and instrumentation for all types of power supply systems and grid connected equipment.

The above measurement procedures are adopted by all measuring laboratories and certification bodies involved in the PQ and grid compliance certification of WTs and PV inverters and are considered as basis for the evaluation of compliance with the relevant limits. However, it is experienced that the measured harmonic currents are often strongly influenced by the background voltage harmonic distortion, by resonances of the grid impedances and by other disturbances in the grid at the point of connection. This means that the harmonic values included in the PQ measurement reports, are not always representative of the actual harmonic emissions of the tested units but contain components which are attributed to the grid influence, where the WT or PV inverter either acts as a passive consumer of harmonics coming from the grid or actively improves the harmonic voltages. In addition, the question of accurate estimation of harmonic currents on power plant level based on the summation of the harmonics of individual WT or PV inverter units is still under investigation within the renewable energy community.

Although certain studies can be found in the literature for the identification of the background noise and its influence on the measured harmonics (i.e. [4]-[5]), the further investigation of dedicated methodologies for the identification of this influence is still not at mature stage. With the aim to cover this topic, an informative methodology for the determination of the grid influence is already included in the German guideline FGW-TR3, Rev.24 [6] and also adopted in the new IEC 61400-21-1 standard [7], which is expected to be released until the beginning of 2018. According to these standards, a group of procedures are described to help determining if the measured harmonic levels are affected by the background distortion of the grid. A very interesting approach for the analysis of the harmonic contribution of customers at the point of common coupling

(PCC) is presented in [8], while a thorough investigation is currently ongoing in Germany, within the framework of a dedicate research project "*Netzharmonie*" [9], funded by the German State, which in turn reveals the importance of the subject, especially in countries with high level of renewable energy penetration.

With regard to the power system of India, the regulations, so far, have been mainly focused on the frequency and power factor of the electricity supply. The current requirement for harmonics in the Regulation of the Central Electricity Authority (CEA), [10]-[11], is that the voltage and current harmonic limits as well as the measurement point and the measurement method shall be in accordance with the IEEE 519 standard [12]. This requirement is expected to remain in the upcoming second amendment of the CEA Regulation [13]. Nevertheless, a guide for the proper interpretation of the measured results for the reliable evaluation of grid compliance is still missing.

In the present work, a review of state of the art methods for the efficient determination of grid influence on the measured harmonics is performed based on the long-term experience of UL DEWI gained from actual field measurements and from participation in several working groups and research projects in Germany and worldwide. The most prominent methods are then applied to actual harmonic measurements and important conclusions are drawn, which can be exploited for the constitution of a concrete methodology for harmonics assessment.

As for the structure of the paper, in Section II, the current practice for the harmonic measurements and assessment is presented in detail. Section III includes a review of the most prominent methods for the determination of grid harmonic bias. In Section IV, selected methods are applied to real measurements data and the most significant results are presented in graphical form. Finally, the main conclusions of the present work are summarized in Section V.

II. Harmonics Measurement and Assessment Methodology for WT and PV Stations

A. Basic principles of 61000-4-7 standard

As mentioned in the previous section, the basic principles for the harmonic measurements and instrumentation are defined in the IEC 61000-4-7 standard [3]. According to this standard, the evaluation of harmonics is based on the application of FFT, using consecutive rectangular windows, whose width is equal to 10 fundamental frequency periods (for 50 Hz systems), corresponding to a 5 Hz frequency resolution.

Fourier analysis assumes stationarity of the measured signals. When the signal magnitude is fluctuating, as is the case in WT and PV units, spectral leakage occurs, i.e. the energy of harmonic components spreads to neighboring frequencies. To improve assessment accuracy, IEC 61000-4-7 stipulates the application of *grouping*, which consists in the quadratic summation of harmonic magnitude components in a range of a few adjacent frequencies, to form groups represented by one equivalent central frequency (integer or interharmonic). Hence, the magnitude G_n of the nth-order integer harmonics is obtained (up to the 50th order) by the quadratic summation of the FFT components at frequencies $n \cdot f_1$ and their sidebands at $n \cdot f_1 \pm 5$ Hz:

$$G_n^2 = \sum_{i=-1}^{1} C_{n \cdot 50 + i \cdot 5}^2 \tag{1}$$

where C denotes coefficients obtained from the FFT.

Similar to integer harmonics, interharmonics are evaluated at the mid-frequencies between integer harmonics (i.e. at 75, 125, 175,…, 1975 Hz, for 50 Hz systems), by grouping the FFT coefficients within an interval of ±15 Hz around the mid-frequency point (e.g. from 60 Hz to 90 Hz for the 75 Hz interharmonic component), while high-frequency components, in the range above 2 kHz up to 9 kHz, are calculated in 200 Hz increments (i.e., at midpoints of 2100, 2300 and 2500 Hz etc.), again by grouping the corresponding 5 Hz frequency components.

B. Harmonic assessment according to IEC 61400-21

The *grouping* procedure of IEC 61000-4-7 [3] is sufficient for taking into account the fluctuating nature of the harmonic emissions of WTs and PV inverters on a very short term basis (a few fundamental periods). However, the main feature of renewable energy sources is that their output is changing from 0% to 100% of the nominal power (P_n). This feature is covered by the IEC 61400-21 standard [1], which refers purely to WTs.

According to this standard, the "grouped", 10-cycle harmonics, calculated according to IEC 61000-4-7, shall be post-processed for the calculation of 10-min average values and the maximum values are presented in a table for each active power bin and for each harmonic order, for the entire power range of the examined WTs, as soon as a minimum of 3 data samples per power bin are collected during the field measurement campaign. Recognizing the wide fluctuation of harmonic magnitudes, even within the same power bin, the expected new IEC 61400-21-1 [7] is proposing the calculation of the 95th percentile of the average 10min harmonic currents (instead of the maximum ones) and the collection of at least 7 measurements per power bin and harmonic order. The resulting harmonics are finally quoted in the PQ certificates or measurement reports of commercial WTs respectively, which are then being used by network operators for assessing compliance with power system harmonic emissions planning levels, as given in [12] and [14]. It should be mentioned that, according to the new IEC 61400-21-1 [7], in case the harmonic currents are clearly influenced by the background grid harmonic distortion, the measured harmonic values can be reduced by a relevant amount, which has to be adequately explained through the use of a proper method.

C. Harmonic results according to IEEE 519

Although the harmonic measurements according to the current IEC 61400-21 standard [1] are widely used for the certification testing of WTs, the relevant results may not be directly comparable with the relevant limits, as defined in IEEE 519 standard [12] and the IEC 61000-3-6 Technical Report [14]. In these standards, the harmonic limits are expressed in principle as 95th or 99th percentiles of a weekly period (instead of a maximum value as in IEC 61400-21), the individual 10-min values should be aggregated using rms method (instead of arithmetic average) and, in addition, very

TABLE I. COMPARISON BETWEEN IEC AND IEEE STANDARDS WITH REGARD TO THE HARMONIC EVALUATION PROCEDURE

Parameter / procedure	**IEC 61400-21, Ed.2**	**IEC 61400-21-1, Ed.1, CDV**	**IEEE Std519**
Instrumentation	Compatible with IEC 61000-4-7 and 61000-4-30		
Averaging time	10 min	10 min	3s / 10 min
Number of measurements	≥ 3 for each 10 % power bin	≥ 7 for each 10 % power bin	≥ 24h for 3s and ≥ 7days for 10min
Aggregation method	Arithmetic	Arithmetic	Geometric
Statistical assessment	Max of all measurements per power bin	95th percentiles of all measurements per power bin	95th and 99th percentiles for each 24h
Parameter	Current	Current	Current / Voltage

short time harmonics are requested (3-second values). The main differences between the current IEC 61400-21 [1], the IEEE 519 [12] and the expected new IEC 61400-21-1 [6] standards are summarized in TABLE I.

It should be stressed at this point, that the harmonic measurement method proposed by the IEEE 519 standard is mainly oriented to loads operating at contact power. From that perspective, measurement on daily and weekly basis may not cover all power levels in case of WTs and may not be sufficient. Therefore, it is recommended that the power-bin-wise measurement procedure is adopted, as per IEC 61400-21. The averaging time and the aggregation method of IEEE 519 can be applied afterwards for the evaluation of the harmonic results.

D. Additional analysis methods according to IEC 61400-21-1 and FGW-TR3 guideline

The common characteristic of the IEC 61400-21 and IEEE 519 standards is that they require only the calculation of the magnitudes of harmonic line currents. However, the performance of additional analyses like the *phase angles* and the *symmetrical components* are appearing to be necessary for providing valuable information for the nature and the origin of the measured harmonics as well as for the evaluation of the harmonic currents on the power plant level.

- *Calculation of harmonic phase angles*

Two kinds of harmonic phase angles are identified:

(a) the phase angle between the harmonic current and the fundamental frequency of the voltage, which allows the analysis of the summation of harmonic currents at a power plant level from the harmonic currents of each single WT of PV inverter:

$$\varphi_{h1} = \varphi_{U_{h1}} - \varphi_{I_h} \tag{2}$$

(b) the phase angle between the harmonic current and the respective harmonic voltage, which indicates the direction of the current flow in combination with the impedances of the grid and the power generating unit (PGU):

$$\varphi_h = \varphi_{U_h} - \varphi_{I_h} \tag{3}$$

As the grouping methodology, defined in IEC 61000-4-7, does not incorporate the phase angles, the harmonic components without grouping calculated over 10-grid cycles have to be used in the analysis.

To provide a common approach in the evaluation of the statistical behavior of the harmonic phase angles, the Prevailing Angle Ratio (PAR) is implemented, as introduced in [6] and [6]:

$$PAR = \frac{|Vector\ sum\ of\ harmonic\ components|}{Arithmetic\ sum\ of\ harmonic\ components} \tag{4}$$

This PAR indicates the stability of the harmonic phase angle. A PAR close to zero shows a random distribution of the phase angle, which implies significant cancellation effect in the summation of harmonics at the power plant level. On the other hand, a PAR close to 1 shows a very stable phase angle during the aggregated time period, which means that expected effect on the total harmonic current of a power plant is bigger but they can also be exploited for the identification of the grid bias with higher reliability.

- *Symmetrical components*

Applying the FFT to the sampled time-domain data, the phasors of the harmonic current and voltage components are readily obtained for each phase. The symmetrical component transformation can then be applied to derive the sequence components of the currents/voltages for each harmonic order, as seen in the following formula (for the currents):

$$\begin{bmatrix} \tilde{I}_1 \\ \tilde{I}_2 \\ \tilde{I}_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \tilde{I}_a \\ \tilde{I}_b \\ \tilde{I}_c \end{bmatrix} \tag{5}$$

where $a = e^{j120^o}$, I_1, I_2, I_0 represent the positive, negative and zero sequence components, while I_a, I_b and I_c correspond to the line currents of each phase.

Understanding the sequence characteristics of the harmonics is important to perform harmonic analysis on the grid where a WT or PV inverter is connected. First of all, propagation of zero sequence harmonics may be inhibited, depending on the connection group of the transformers (such as the commonly utilized YΔ configuration), including the WT/PV step-up transformer, if the measurements have been obtained at the LV terminals of the unit. Further, the zero-sequence impedance of network elements is significantly different than the positive or negative sequence one (the latter two being equal to each other, in networks consisting of “passive” elements). As a general rule, characteristic harmonics of orders $3k$-1, $3k$ and $3k$+1 (k integer) encountered in power systems, are typically negative, zero and positive sequence, respectively [15].

III. METHODS FOR THE DETERMINATION OF GRID HARMONIC BIAS

A. Identification of daily pattern

The voltage total harmonic distortion (*THD_U*) at a grid node is a result of the contribution of all the neighboring loads, which inject or absorb harmonics. Obviously, the level of the *THD* depends on the type and the rating of these loads. For example, in industrial areas, the local grid is dominated by harmonics related to the operation of electrical machinery and power converters while in domestic areas, the harmonics that appear are attributed mainly to the harmonic emissions of house appliances and devices, like computers and other electronic equipment. The common characteristic of these types of loads is that they are varying during the day. As a consequence, the relevant harmonics show also a diurnal pattern, which depends on the load curve. High levels of harmonic distortion appears during hours of high loading of the system and vice versa. This could appear during working hours in industrial areas or during the evenings and the weekends in domestic areas. On the other hand, harmonic behavior of WTs is exclusively dependent on the wind and not on the time of day (this is not valid for PVs). This means that if the magnitude of a measured harmonic displays a clear diurnal variation, this is a strong indication of bias. If the harmonics display no diurnal pattern, this does not necessarily mean that these harmonics are not subject to bias. The voltage quality at the WT connection point can be deteriorated by loads and neighboring WTs or PV stations.

In order to identify if daily trends appear to specific harmonics, a long term measurement campaign should be scheduled. According to IEC 61400-21-1 and FGW TR3 [6]-[6], measurements of voltage and current harmonics and WT/PV inverter active power for at least one full week are required, supposing that sufficient number of data are collected for each power bin of 10% P_n (≥ 7 records x 3 phases = 21 10-min time-series).

The collected data should be then graphically and statistically analyzed, separately for currents and voltages and for each harmonic order. If a significant correlation appears among the same harmonic orders of different days, while no correlation of the WT active power with the current and voltage harmonics is identified, this is an indication of grid bias.

B. Effect of the PGU operating point on harmonics

A central issue in assessing WT harmonic current emissions is their dependence on the operating point of the WT, i.e. how the magnitudes of individual harmonic components vary at different wind speed/output power conditions. This investigation is practical to be considered in conjunction with the diurnal pattern one. If a strong power dependency of individual harmonic currents can be recognized it is often interpreted as an indication that the measured PGU feeds in the harmonic current. However, this method should be considered only together with the other methods proposed in this Section, because misleading interpretation are still possible due to the complex interaction between the harmonic source and the grid influence [6].

C. PGU filter testing

PGU filters are often play a controversial role in the harmonic spectrum. In general, they reduce the generated harmonic currents of the PGU, but may also absorb harmonic currents from the grid, which could lead to misleading measurement results. It is also possible that harmonic filters may form resonance points with the upstream transformer and other inductive and capacitive grid components [6].

The testing procedure proposed in FGW-TR3 guideline includes the systematic switching of the filters with the PGU ON and OFF successively and possibly at different grid conditions. The duration of the propose procedure is at least 5h.

D. Swithing of the neighboring PGUs or loads

The operation of other PGUs or consumers in the neighborhood of the tested WT or PV inverter may affect the measured harmonic emissions. To minimize the influence of background distortion on measurement results, it might be helpful to shut down the sources of interference during the measurement. It should be noted that this will also change the grid impedance seen from the PGU under test, which may also influence the harmonic emission.

These tests can be performed in one single day. However, the main practical difficulty in applying such a procedure during actual certification campaigns is to agree on a convenient test plan with the neighboring PGU owners/manufactures, which is not always feasible.

E. Measurements at no load

The evaluation of the voltage harmonics provides a possibility to see the effect with and without the PGU in operation. With this method it is not possible to check the harmonic current. However, voltage harmonics with and without operation of the tested WT indicate the response of the tested turbine to the existing distortion in the grid. If some of the measured voltage harmonics are higher when the turbine is disconnected it can be concluded that the harmonic currents of the tested turbine at these harmonic frequencies are reducing the grid voltage distortion. The measurement should be repeated different times of the day and turbine power in order to find out if the harmonic current depends on the harmonic voltage level when the turbine is shut down [6].

F. Measurement at an AC source

Ideally, connecting the WT/PV inverter to a grid simulator with a very low *THD_U* (indicatively < 1%), it would reveal the real harmonic spectrum of the tested unit. However, this is technical feasible only if the AC source has sufficient capacity to feed the PGU or to accept the PGU's power.

G. Measurement at different grid impedances

Harmonics measurements on the same WT or PV inverter but at different sites or using additional series impedance between the unit under test and the grid, may lead to different results as a result of the different grid bias and resonance effects. They may contribute to identifying the bias and may support verification of the harmonics models. Furthermore, if harmonics measurements at one site are more strongly influenced by grid bias than at a different site, the measurement results with the lower bias influence may be used [6].

The series impedance tests can be carried out with the voltage dip test equipment (LVRT-Container), as shown in Fig.1. The principle of operation of the LVRT-Container is based on the classical voltage divider, consisting of a series impedance Z_1 and a short circuit impedance Z_2. In the relevant tests, only Z_1 can be used at selected values, which is equivalent to testing at a grid with different short circuit power.

The relevant test plan may consists of the following steps:

- *Step 1*: Measurement of at least 10 min without the series impedance (PGU in normal operation)
- *Step 2:* Measurements of minimum 20 min with the series impedance connected (PGU in normal operation)
- *Step 3:* Measurement of at least 5 min with the series impedance connected (WT disconnected)
- *Step 4:* Measurement of at least 5 min after the disconnection of the series impedance (WT disconnected)

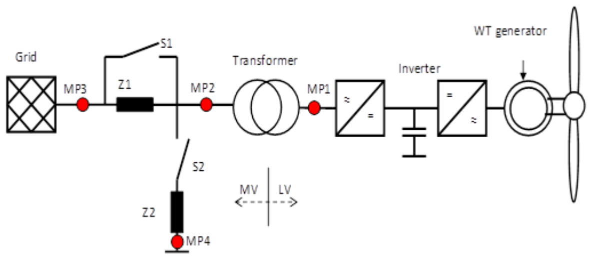

Fig. 1. Usage of low voltage ride through test setup for the altering the series impedance Z_1 upstream of the PGU. The configuration is valid also for PV and other power generating units as well as for power plants < 10 MW

- *Step 5:* Measurement of minimum 10 min after the disconnection of the series impedance (WT in normal operation)

The above steps shall be repeated for two different configurations of the series impedance Z_1 and for at least two operating points of the PGU, depending on the rating of the PGU. Indicatively at partial load a value of 30% Pn can be selected while at full load, power should be above 90% of P_n. It is advised that the PGU is operating at set-point active power in order to preserve constant power conditions during the tests.

H. Estimation of actual grid harmonic impedance through no load LVRT tests

Estimation of the actual grid impedance may provide a valuable tool for the reliable estimation of the expected harmonic voltages from the measured harmonic currents. A reference guide on the assessment of the network harmonic impedance based on measurement methods was initially introduced in [16] and adopted in the IEC TR 61000-3-6 [14].

By exploiting the no load test measurements at the grid side during an LVRT testing campaign, using the setup of Fig. 1 (point MP3), it is possible estimate the measured grid impedance for each harmonic order through the application of the following formula:

$$Z_h = \frac{\Delta U_h}{\Delta I_h} = \frac{U_{fault,h} - U_{prefault,h}}{I_{fault,h}} \qquad (6)$$

The calculated value of Z_h includes both the grid harmonic impedance and the superimposed LVRT test system impedance Z_1+Z2, which is known and highly inductive. By subtracting this impedance from Z_h, it is possible to derive an estimation of the actual harmonic impedance at the point of connection of the PGU.

The grid harmonic impedance estimation can be used afterwards for the extraction of the expected harmonic voltages from the measured harmonic currents of the PGU, included in the PQ measurement reports:

$$U_h = Z_{h,grid} \cdot I_{h,PGU} \qquad (7)$$

I. Identification of harmonic direction

Even with a good approximation of the grid harmonic impedance, as described in the previous paragraph, eq. (7) is still not fully accurate for assessing compliance with the voltage harmonic limits, because the measured PGU harmonic currents may contain a large part due to the existing grid influence.

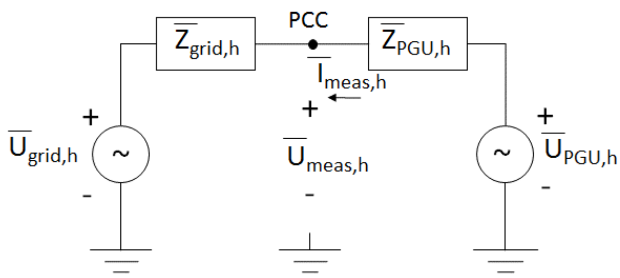

Fig. 2. Harmonic Thevenin equivalent of the grid showing the harmonic contribution from the PGU and the grid side [8]

The calculation of the harmonic power flow using the phase angles between harmonic voltage and currents (eq. (3)), provides a first indication of grid bias, in case a change in its direction appears for a certain harmonic frequency. However, the accurate separation of the measured current into a part attributed to the PGU and a part attributed to the grid remains a challenging task and it is subject to certain scientific approaches in the literature. UL DEWI is currently investigating a novel approach for the separation of harmonic contribution between the grid and the customer at the Point of Common Coupling (PCC), as introduced in [8].

The method is based on the exploitation of the complex values (magnitudes and phase angles) of the measured voltages and currents at the PCC of a PGU and the Thevenin representation of the grid harmonic equivalent, assuming the reliable knowledge of the grid harmonic impedance (see Fig. 2).

By comparing the position of the complex ratios between measured voltages and currents (U_{meas}/I_{meas}) on the complex plane with the grid and PGUs harmonic impedances, useful information is obtained regarding the interaction between the PGU and the grid, as will be shown in in the next Section.

IV. EXAMPLE CASE STUDIES ON SELECTED METHODS

A. Examination of the daily pattern

As explained in the previous Section, existence of strong background daily pattern provides a strong indication that the main source of the relevant harmonic frequency is the grid, assuming that the effect of the PGU active power level is eliminated (e.g. by considering measurements at different power levels). UL DEWI is developing a systematic methodology for the identification of possible daily pattern, based on the evaluation of the correlation coefficient among the harmonic profiles of the examined days. According to this methodology, the examined days are separated into groups of common consumer activities (weekdays, Saturdays, Sundays, holidays). For each group the correlation among the harmonic profile of each day is calculated, based on hourly averages, for each harmonic frequency. Harmonic frequencies that appear to have high correlation (indicatively >0.5), can be considered as mainly coming from the grid. In Fig. 3, a graphical representation of the methodology is presented. Fig. 3(a) presents the Taylor diagram, where the correlation coefficients of a certain number of weekdays, with one reference day are presented on the plane. The blue contours correspond to correlation coefficient values, while the x and y-axis display the values of the average standard deviation of the data sample. As shown in Fig. 3(a) the 5th order harmonics lie above the *0.5* correlation coefficient contour, which in turn provides an indication of grid bias for this specific frequency. Fig. 3 (b) illustrates the hourly average of a certain data set of

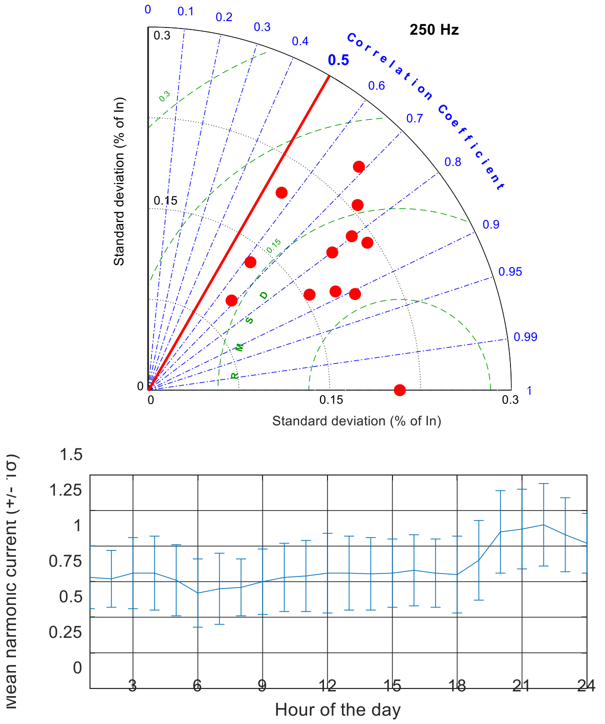

Fig. 3. (a) Taylor diagram representation for the assessment of the daily pattern of the 5th order harmonic current and (b) and time series average hourly values with the relevant standard deviation.

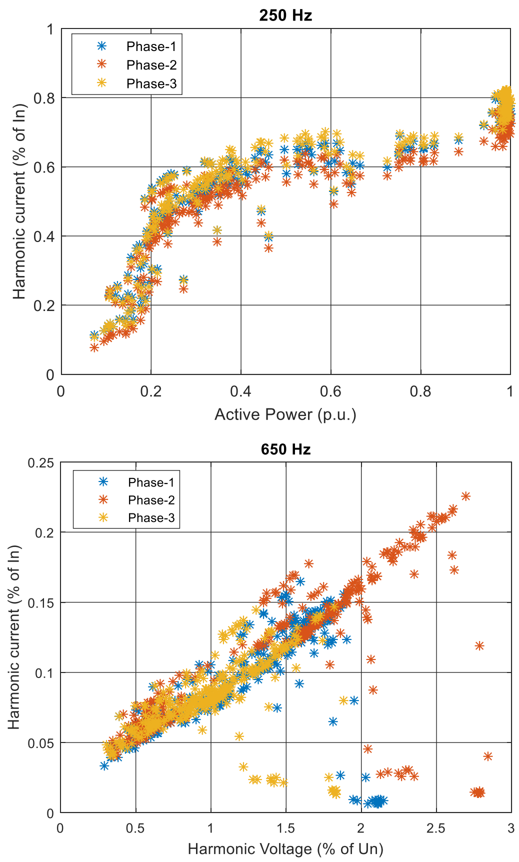

Fig. 4. Dependency of the measured harmonic currents of a WT on the output power and harmonic voltage

weekdays (typically more than one week is desirable), along with the corresponding standard deviation.

B. Effect of the PGU operating point on harmonics

The dependency on power should be preferably examined in conjunction with the investigations of the daily pattern. If a discrete trend is recognized, as shown in Fig. 4 (a), it is an indication that the measured WT of PV inverter influences the harmonic current that flows into the grid. On the other hand, a linear (proportional) relationship between harmonic current and voltage, as shown in Fig.4 (b) is an evidence of notable grid influence on the appearing harmonic currents. However, the complex interaction between the source of harmonic interference and the grid distortion, is possible to lead to incorrect interpretations [6]-[6]. For this reason, it is suggested that the possible conclusions from this investigation are considered in relation to the rest methods presented in this paper.

C. Swithing of the neighboring PGUs or loads

UL DEWI has participated in certain noise measurement campaigns, where the neighboring PGUs where systematically being switched ON and OFF and the changes in the measured current emissions where analyzed for each harmonic frequency of interest, an example of which is presented in this paragraph. The test plan includes also a period where the tested PGU is also not in operation, where the background voltage harmonic distortion of the grid is examined. In Fig. 5, the comparative results of the harmonic current distributions between two different states are presented, for two characteristic frequencies (5th and 11th order). It is clearly visible that when the neighboring WT is in operation, the measured harmonic currents of the WT under test are higher. This might be due to, for example, the change of the grid impedance seen from the tested WT when the nearby WT is switched or due to the emission of additio-

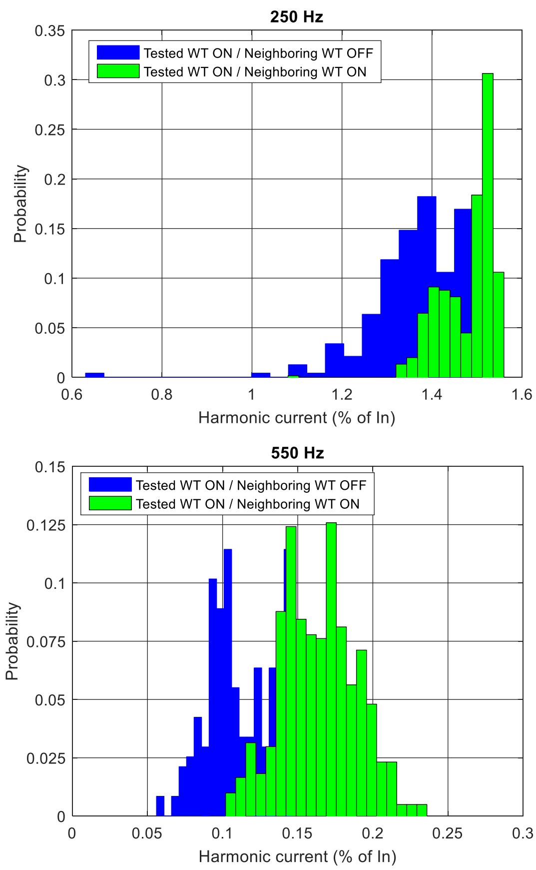

Fig. 5. 5th and 11th order harmonic current distribution measured during the performance of switchings of a neighboring WT.

nal harmonics from the neighboring WT, which interact with the one from the WT of interest. However, the overall conclusion is that the harmonic currents presented in the PQ test reports are clearly site dependent and this should be taken into account during the assessment of grid compliance.

D. Measurements at no load

During the test presented in the previous paragraph, measurements of the background voltage harmonic distortion have been also performed and the results are shown in Fig. 6, for the 250 Hz component. It is noticed that the voltage harmonics under no load conditions, are generally higher than when the two WTs are in operation. This can lead to the conclusion that the relevant 5^{th} order harmonic currents of the WT under test reduces the grid bias at this frequency [6].

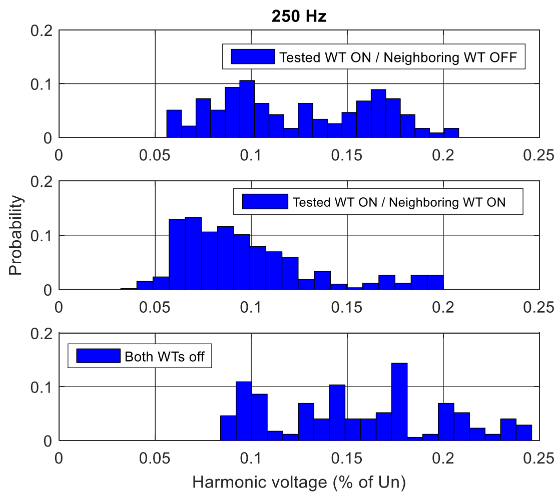

Fig. 6. Measurement of background 5^{th} order harmonic voltage during a noise measurement campaign at a wind farm

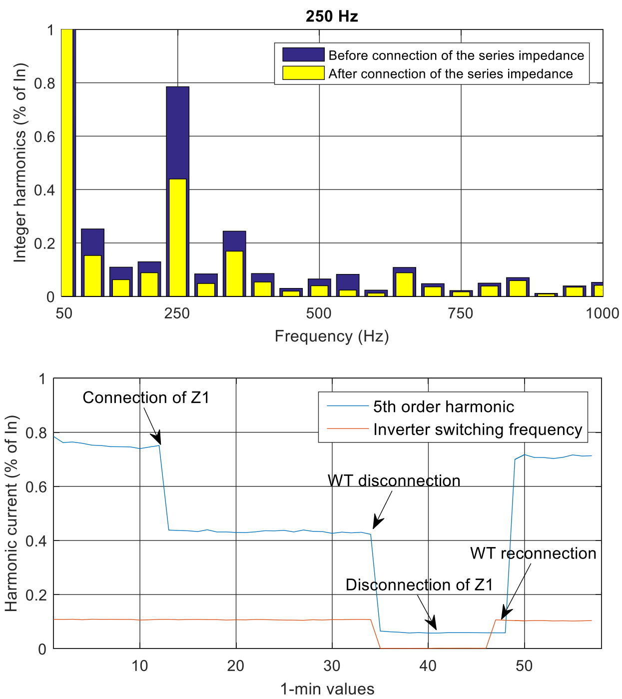

Fig. 7. Effect of the additional series impedance (Z_1) on the measured WT currents: (a) Comparison of the harmonic spectrum with and without Z_1 and (b) Effect of the switching temporal sequence on the 5^{th} order harmonic and on the switching frequency of the inverter of the WT under test.

E. Measurement at different grid impedances

The presented test has been implemented with the use of UL DEWI LVRT test equipment of Fig. 1. The test plan described in Section III, paragraph G was implemented. The analysis results show that the connection of the additional impedance had a clear influence on the magnitude of some harmonic frequencies, which is an indication that they are dependent on the grid conditions, while some other frequencies are fairly less affected, which in turn provides a strong indication that the relevant harmonics are mainly coming from the WT, as shown in Fig. 7.

F. Harmonic emission direction

As described in the previous Section, a novel approach for the determination of the harmonic contribution at the PCC from the PGU and the customer is proposed in [8]. The methodology is implemented by UL DEWI and applied to actual field measurements. The complex ratio of the measured harmonic voltages and currents is represented with the red dots in Fig.8. The relevant harmonic impedance is estimated through 0% no load tests based on (6), which corresponds to a value of Zgrid,5=38 Ohm, as shown in Fig.9. If these ratios lie in the upper area of the graph of Fig.8 (blue isocycles value > 1), this means that the PGU raises the harmonic level at the PCC, where the lower area (<1) means that the relevant harmonic voltage is raised by the grid.

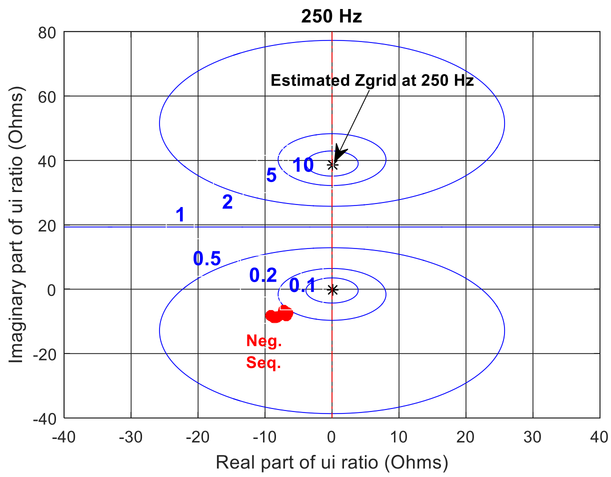

Fig. 8. Harmonic Thevenin equivalent of the grid showing the harmonic contribution from the PGU and the grid side [8]

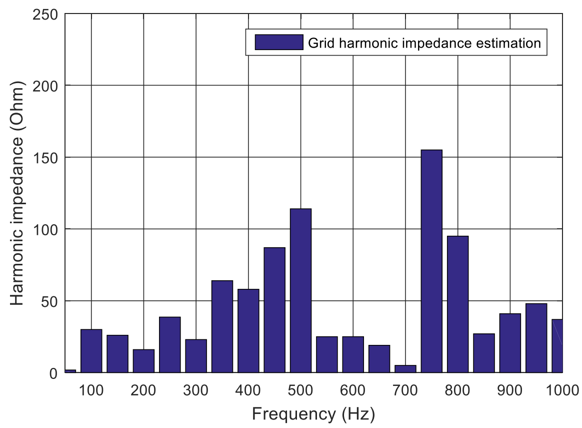

Fig. 9. Estimation of grid harmonic impedance based on voltage dips no-load tests at 0%.

I. CONCLUSIONS

In this paper, a review of state of the art methods for the efficient identification of the grid contribution to the harmonic currents measured at the terminals of wind turbines and PV inverters is performed. Certain methods are applied to actual field measurements and the relevant results are presented and discussed.

The analysis shows that it is possible to improve the accuracy of the measured harmonic currents by applying a systematic harmonic assessment procedure. This could be performed, for example, in case the harmonic currents included in the WT or PV inverters certification report reveal potential violation of the limits imposed by the grid operators or in cases when resonance conditions are likely to appear based on the local grid characteristics. Especially for India, for the efficient assessment of compliance with the limits included in the IEEE 519 standard it is also necessary that the relevant measurement and evaluation procedures are adapted accordingly.

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REFERENCES

[1] IEC 61400-21 Wind turbine generator systems, Part 21, “Measurement and assessment of power quality characteristics of grid connected wind turbines”, Ed. 2.0, 2008-08.

[2] IEC 61000-4-30 Electromagnetic compatibility (EMC) – Part 4-30, “Testing and measurement techniques – Power quality measurement methods”, Ed. 3.0, 2015-02.

[3] IEC 61000-4-7 Electromagnetic compatibility (EMC) – Part 4-7, “Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto”, Ed. 2.1, 2009-10.

[4] S. Tentzerakis, F. Santjer, M. Bärschneider, “Methodology for the evaluation of the wind turbine harmonic emissions”, 12th German Wind Energy Conference (DEWEK), Bremen, Germany, 19/20 May 2015.

[5] R. Vazquez, M.A. Muñoz, M. Alonso, H. Amaris, C. Alvarez, “Background harmonic distortion measurement at power networks with wind farms”, International Conference on Renewable Energies and Power Quality (ICREPQ’16), Madrid (Spain), 4-6 May, 2016.

[6] FGW e.V., Technical Guideline 3, ‘Determination of the electrical characteristics of power generating units and systems in medium-, high- and extra-high voltage grids’, Revision 24, 01.03.2016.

[7] IEC 61400-21-1 Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines, Ed.1, Committee Draft for Vote (CDV), 2017-03.

[8] Kaveh Malekian, “A novel approach to analyze the harmonic behavior of customers at the point of common coupling’, 9th International Conference on Compatibility and Power Electronics (CPE), Portugal, June 2015.

[9] F. Santjer, K. Nolopp, S. Tentzerakis, S. Adloff, I. Athamna, M. Muehlberg, M. F. Meyer, M. Jordan, R. Klosse, K. Kuech, F. Ackermann, J. Meyer, M. Domagk, M. Pourarab, “Characterization of Harmonic Emission of Individual Wind Turbines and PV Inverters based on Measurements, Part II – Wind Turbines”, 15th Wind Integration Workshop, Vienna, Austria, 15/17 November 2017.

[10] Central Electricity Authority (CEA), “Technical Standards for Connectivity to the Grid – Regulations 2007”, New Delhi, the 21st February 2007.

[11] CEA, “Technical Standards for Connectivity to the Grid – Amendment Regulations, 2013”, New Delhi, the 15th October 2013.

[12] IEEE Standard 519-2014, “IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems”.

[13] CEA Draft Regulations, “Draft second amendment in CEA (Technical Standards for connectivity to the Grid) Regulations, 2007”, Public Notice, October 2016.

[14] Technical Report IEC/TR 61000-3-6, “Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems”, Edition 2.0, 02-2008.

[15] J. Arrillaga, N.R. Watson, «Power System Harmonics», Second Edition, 2003, John Wiley & Sons Ltd, ISBN: 0-470-85129-5.

[16] A. Robert, T. Deflandre, Joint CIGRE & CIRED Working Group CC02“Guide for assessing the network harmonic impedance”, 14th International Conference and Exhibition (CIRED 97), 2-5 June 1997, IEE Conf. Publ. No. 438, Vol. 1.