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Large Scale Investigation of Harmonic Summation in Wind- and PV-Power Plants

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***Abstract*— Wind- and PV-power plants must respect harmonic emission limits in order to pass the certification process. Estimating the harmonic emission of a power plant, based on the measurement of a single unit still is a challenging task. German research project "NetzHarmonie" has been initiated in 2015 with the final aim to propose improved rules for the characterization of the harmonic emissions of wind- and solar power generation units (PGU). This paper presents specific measurement results regarding summation rules in Wind- and PV-power plants.**

***Index Terms*—harmonics, harmonic modelling, harmonic summation, background distortion, network impedance, inverter**

I. Introduction

As presented in [1] most standards worldwide require using the summation law according to IEC 61000-3-6. Different summation exponents may be used but most of these standards assume the PGU having a current source behavior and do not take into account the harmonic phase angle. As demonstrated and discussed in [2] [3] [4] [5], both assumptions are at least far from reality. As shown in [3], [6] and [7] the grid impedance and the number of identical PGUs within a power plant can largely influence the harmonic emission. The harmonic angle stability and the resulting constructive or destructive behavior of several PGUs have been proven to vary widely depending on their nature (induced by background distortion, PWM, clamping effects). This paper presents specific measurement results from Wind- and PV-power plants regarding summation rules. Two main aspects make the presented results first of a kind:

- The cooperation within a large consortium including wind turbine and solar inverter manufacturers, grid operators, certification bodies, research institutes and universities leads to a consistent data base. Voltages and currents (up to 137 channels) were measured during several weeks at several points within a selected power plant. A sampling rate of 50 kHz and precise time synchronization based on global positioning system (GPS) were used.
- The grid impedance and the number of connected PGU could actively be modified. The resulting frequency dependent Impedance (park with grid) was measured on the medium voltage side. An overview of the impedance measurement method and equipment is given in [8].

II. Results from 8 MW wind-power plant

A. Measurement Setup

The Wind-power plant consists of four identical 2 MW wind- turbines connected in a string configuration to the MV-grid. The 110 kV transformer substation is situated approximately 8 km away from the point of common coupling (PCC). Harmonics were measured at each PGU and at the PCC. Harmonic measurements were performed with solely one PGU connected and with four PGU connected. The impedance was measured at the connection point of the fourth PGU and later at the PCC.

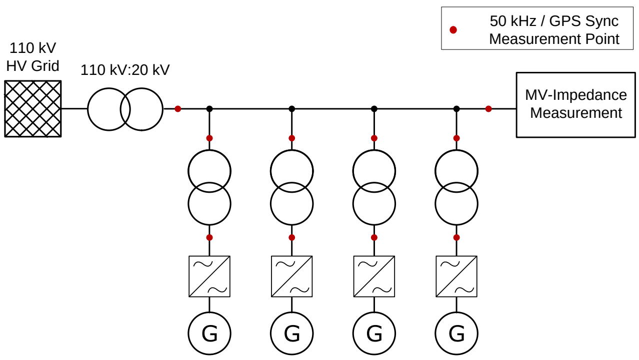

Fig. 1 Structure of the investigated wind power plant and locations of the synchronized measurement points.

B. Harmonic Measurement Results

1) One PGU versus 4 PGUs:

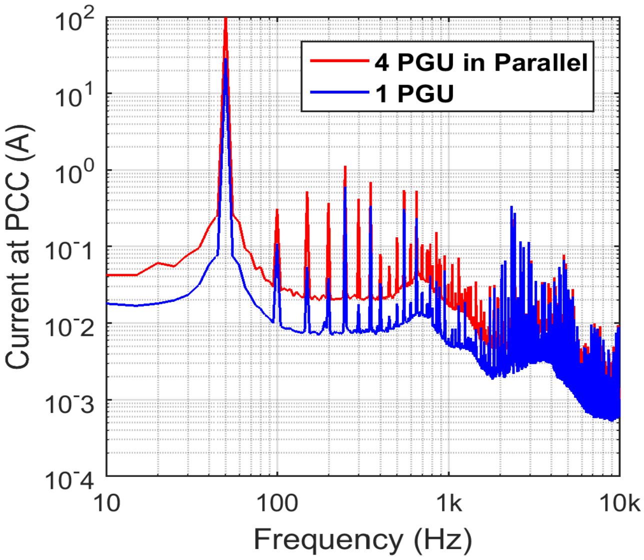

Fig. 2 Measurement of current spectrum (5 Hz resolution) at PCC.

Fig. 2 shows the current spectrum measured at the PCC in two different configurations of the plant: with solely one PGU connected and with 4 PGUs connected. The aggregation interval of the harmonic spectra is one minute and the wind-speed i.e. the PGU output power can be considered as constant (50% of nominal power). Due to the switching pattern (non-constant switching frequency), harmonic emissions are widely spread, up to higher frequencies. It can be noticed that the upscaling from one to 4 PGUs is not constant for each spectral ray. Nevertheless, the overall spectral distribution seems to stay stable.

2) Evaluation of Summation Law:

Sub-grouping according to [9] is applied to the harmonic measurements from Fig. 2. The spectrum from a single PGU and the summation law with coefficient according to [10] are used to extrapolate the result for 4 PGUs. Finally, the real measurements (red) are compared to the extrapolation results (green) for harmonics, inter-harmonics and high order harmonics respectively in Fig. 3, Fig. 4 and Fig. 5. Compared to the measurement, the extrapolation using summation law leads to an underestimation of harmonics emissions up to the 34th harmonic order and to an overestimation above the 35th harmonic order. Mismatch with scale factor up to 6 can be observed.

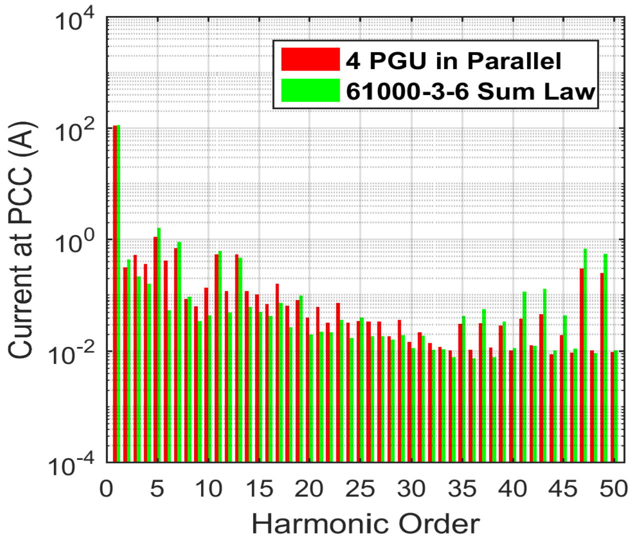

Fig. 3 Comparison of sub-grouped harmonic emission at PCC.

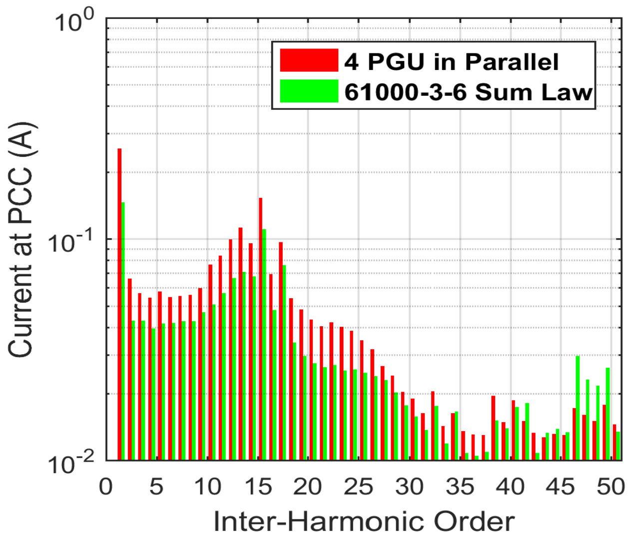

Fig. 4 Comparison of sub-grouped Inter-harmonic emission at PCC.

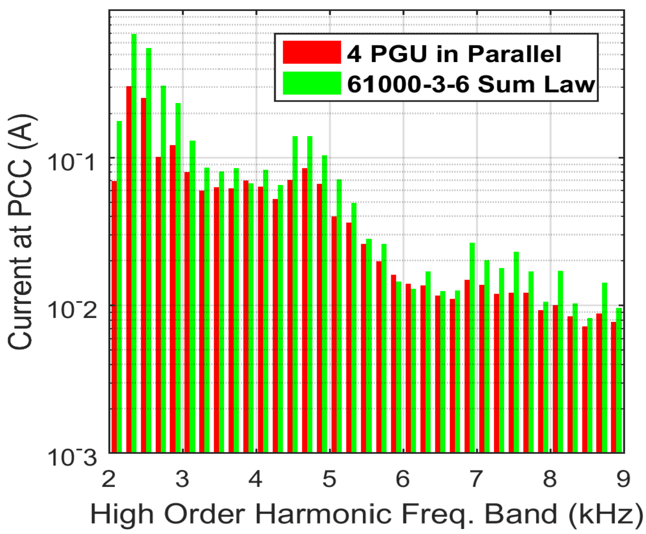

Fig. 5 Comparison of high order harmonic emission at PCC.

III. RESULTS FROM 5 MW PV-POWER PLANT

A. Measurement Setup

The PV-Power Plant consists of five inverter stations with a power of approximately 1 MW each. The stations are connected in a star topology, each station beeing connected to the PCC with its own MV-cable. Four stations are strictly identical, each consisting of 3 PV- inverters with rated power of 350 kW. The fifth station shows a larger diversity, consisting of 350 kW, 100 kW and 30 kW units. Only measurements with identical PGU will be considered in the following analysis, the fifth station is switched off and will not be considered. The grid side series impedance can be modified using the adjustable series inductor of a LVRT test system, which was connected between the MV-grid and the PCC. The impedance is measured at the PCC. Harmonics are measured at the PCC, at each station transformer and at each PGU.

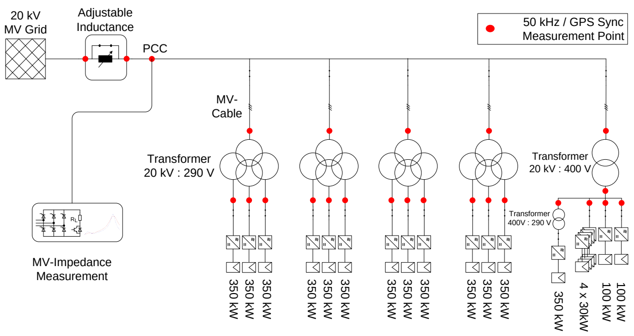

Fig. 6 Structure of the investigated PV power plant and locations of the synchronized measurement points.

B. Test Plan

The adjustable inductor was changed stepwise from 8mH to 35 mH introducing an additional series impedance between 2,49 and 10,92 Ohm. For each value of this impedance, a switch-off sequence was performed. The PV-Power-Plant is switched off stepwise, first entire stations then single PGU, leading to the short-circuit ratios (SCR) presented in TABLE I. The SCR is the ration between the available short circuit power at a dedicated connection point and the nominal power of the connected PGU. Each state was maintained for at least one minute and an impedance measurement was performed in each plant configuration.

TABLE I TESTED CONFIGURATIONS AND RESULTING SHORT CIRCUIT RATIO AT PGU CONNECTION POINT

			1 Station	2 Stations	3 Stations	4 Stations
Adjustable Series Impedance (Ohm)	Number of PGU Connected					
	1	2	3	6	9	12
None (Bypass)	17.45	11.43	8.50	7.89	7.36	6.90
2.490	16.81	10.89	8.05	7.15	6.43	5.84
3.954	16.46	10.60	7.81	6.78	5.99	5.36
6.350	15.91	10.14	7.45	6.25	5.38	4.72
10.921	14.96	9.38	6.84	5.43	4.51	3.85
	Resulting short circuit ratio SCR					

C. Harmonic Measurement Results

1) One PGU vs 12 PGU (4 Stations):

Fig. 7 shows the current spectrum measured at the PCC in two different configurations of the plant: with solely one PGU connected and with 12 PGU connected. The aggregation interval is one minute and the solar irradiance i.e. the PGU output power can be considered as constant (50% of nominal Power). The two corresponding impedances - measured at the PCC on phase L1 – are represented on the same frequency scale. As expected, the amplitude of characteristic harmonics rises with the number of connected PGUs. The PWM sidebands harmonics are recognizable around 3 kHz and 6 kHz. But in contradiction with the assumption of a current source behavior, the overall spectral distribution is not constant. Two resonances can be identified in the impedance measurement. The first moves from 1150 Hz down to 845 Hz when the number of PGUs rises. The second moves from 5 kHz down to 2.5 kHz. As a result the displacement is also clearly visible in the current spectrum, especially regarding interharmonics. In the presented case, applying the summation law based on the assumption of a current source behavior will lead to a mismatch, overestimating parts of the spectrum and underestimating others.

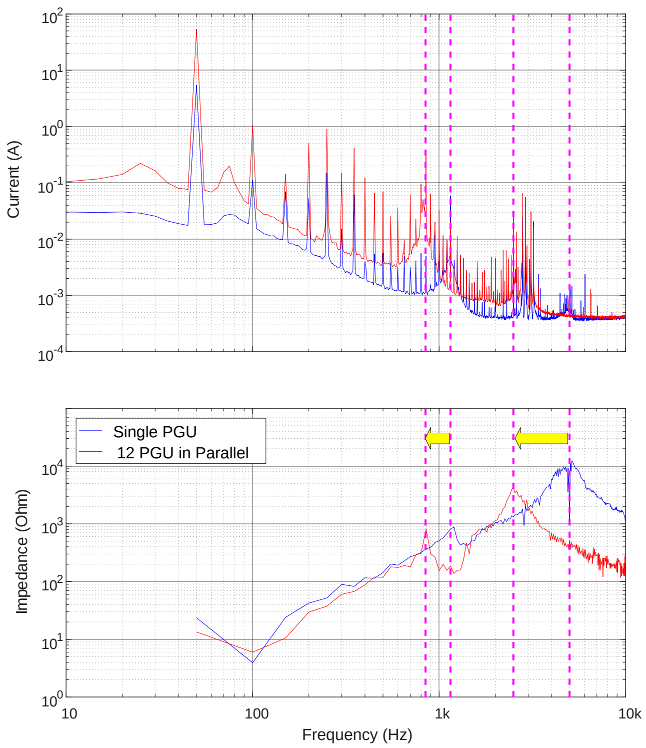

Fig. 7 Measurement at PCC with a 10,921 Ohm series Impedance Top: Current spectrum at PCC, Botom: Impedance at PCC.

The measurement is reproduced without additional impedance and the results are shown in Fig. 8. In that situation, the short circuit ratio at PCC is much higher and the measured impedance is mainly defined by the grid impedance. Therefore it is by far less influenced by the number of connected PGUs. A frequency drift of the emission peaks linked to the impedance does still appear (1180 Hz down to 940 Hz) and can mainly be linked to the change in short circuit ratio at PGU connection point. Indeed, the impedance at the PGU connection point is mainly determined by the station´s transformer leakage inductivity. For that reason the SCR and the current spectrum changes significantly when scaling up from one PGU to 3 PGU´s inside on station.

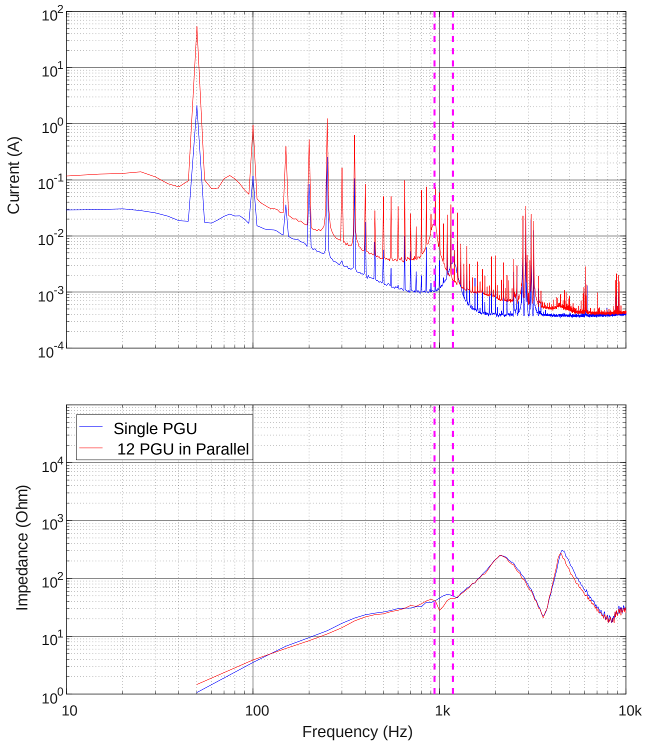

Fig. 8 Measurement at PCC without series impedance
Top: Current spectrum at PCC, Botom: Impedance at PCC.

2) Evaluation of Summation law:

Harmonic summation analysis was performed by analogy with the wind power plant investigations, as described in II.B.2. The summation law was used to extrapolate the current spectrum from one PGU up to 12 PGUs. The real measurements (red) are compared to the extrapolation results (green) in Fig. 9. The use of summation law leads to a significant overestimation of the emissions for the harmonic orders 20 to 30 and an underestimation for the harmonic orders 8 to 17. The same behaviour can be observed even more clearly in the inter-harmonic spectrum in Fig. 10. For the high order harmonics in Fig 11, it must be noticed that the range 3.7 kHz – 9 kHz is largely overestimated by the summation law. Indeed, the currents emission of a single PGU and of 12 PGU have similarly low amplitude in that frequency range as shown in Fig. 7. Strictly applying the summation law result in an amplification of measurement noise here.

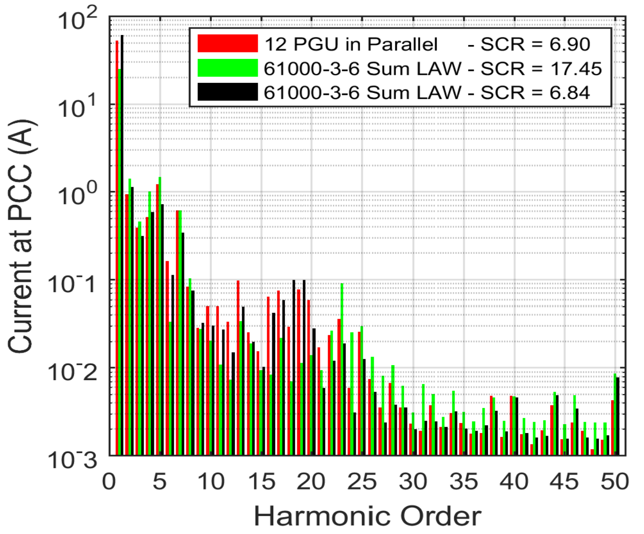

Fig. 9 Comparison of sub-grouped harmonic emission using equivalent impedance before extrapolation to 12 PGU.

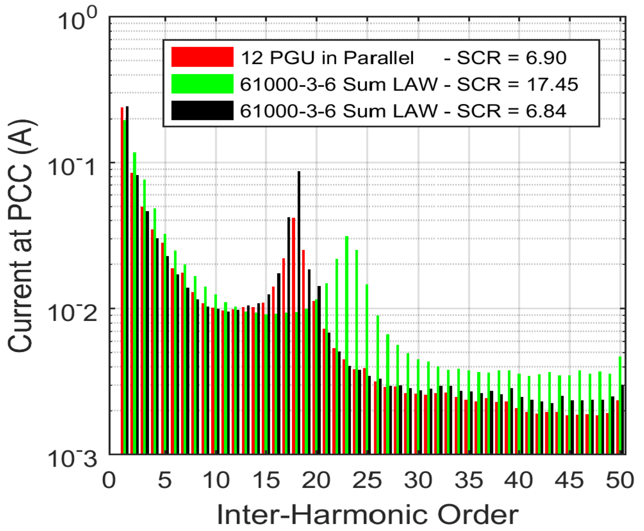

Fig. 10 Comparison of sub-grouped inter-harmonic emission using equivalent impedance before extrapolation to 12 PGU.

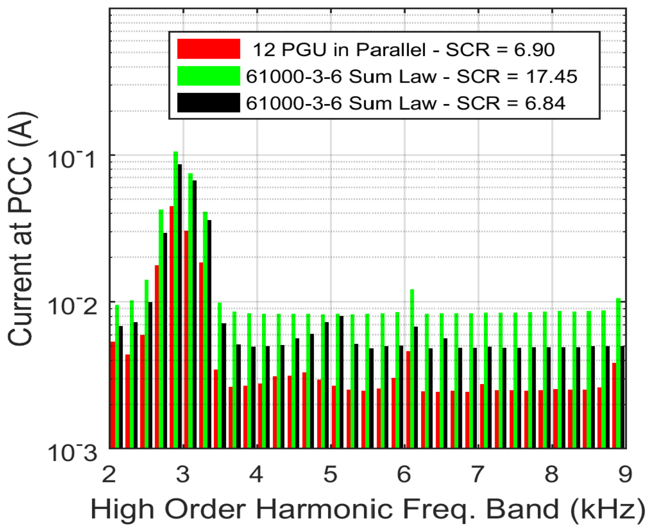

Fig. 11 Comparison of high order harmonic emission at PCC.

3) Considering the Equivalent Impedance:

As demonstrated in [11] and validated by measurements in [3], increasing the number of identical inverters at the grid connection point can be seen as equivalent to increasing the grid impedance for a single inverter. As a result, when a number N of identical inverters are connected in an identical manner to a common grid connection point, the dynamic behaviour of the system can be analysed by modelling or measuring solely one inverter connected to a grid with an impedance N times higher than the real impedance of the grid. This is illustrated in Fig. 12 and will be referred to as the „equivalent impedance“ in this paper. In the present case, each PGU consist of one inverter, but this may differ depending on the PGU concept.

We will use this concept to improve the prediction of the spectrum. The target is to estimate the harmonic emission of 12 PGUs connected in parallel to the MV-grid (see TABLE I, top right). This configuration yields a short circuit ratio SCR = 6.90 at the PGU´s connection point. Consequently, a harmonic measurement with a similar SCR ratio i.e. a similar equivalent impedance shall be taken prior to the use of summation law. Measurements with solely one PGU and SCR = 6.9 could not be achieved during the measurement campaign, but measurements with 3 PGU and SCR = 6.84 will be used instead.

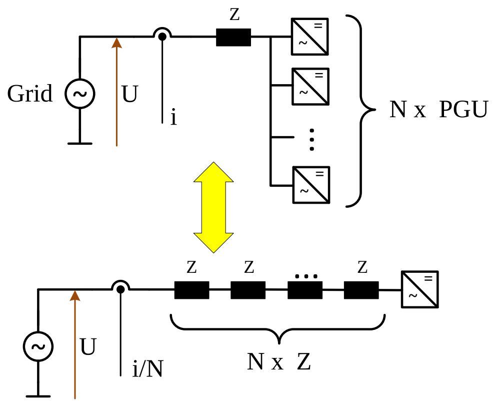

Fig. 12 Equivalent impedance illustrated with series impedances.

The summation law is applied again, but based on the emission of 3 PGU and the current spectrum is extrapolated to 12 PGUs using a scale factor N = 12/3 = 4. The results are shown in Fig. 9, Fig. 10 and Fig. 11 (black) and appear to be a much better representation of the measurement (red) regarding the spectral distribution of the harmonic emission. This is clearly visible for inter-harmonics in Fig. 10, the predicted spectrum (black) yields a much better match to the measurement (red) than the simple application of summation law without considering the equivalent impedance (green).

Regarding the high order harmonics, both summation methods still produce an overestimation of the emission around 3kHz. Especially above 4 kHz, the result given by the summation law still lead to an amplification of measurement noise. The deviation between both summation methods is just due to the different scaling factors applied (from 3 to 12 PGU in black, from 1 to 12 PGU in green).

4) Considering a Co-Phasal Factor:

When several devices (consumers as well as PGU) are connected in parallel to a PCC, the phase angle of their harmonic current contribution must be taken into account in order to calculate the resulting harmonic current. Contributions may add if the phase angles are identical or cancel each other when phase angles are in opposition. The summation formula proposed in [10] allows to consider generic situations like constructive superposition when using an exponent β = 1, uncorrelated superposition (β = 2) or lightly correlated (β = 1.4). But no summation exponent can be used with this formula to represent a harmonic cancellation. Another approach introduced in [12] is the use of a co-phasal factor (CPF). As illustrated in Fig. 13, the CPF is defined as a quotient of the geometrical sum to the arithmetical sum of the relevant harmonic. It must be calculated for each DFT window based on the GPS-synchronized measurements of 2 or more PGUs. The <u>CPF is not the prevailing angle ratio!</u> For a dedicated DFT-window and harmonic frequency, the CPF gives an indication if two or more PGU´s are injecting with the same phase angle (CPF = 1) or result in a cancellation (CPF = 0). The CPF does not give indication about the harmonic angle stability over time. Fig. 14 shows the calculated CPF for 3 PGUs inside one island (red) and for 4 stations in parallel (blue) averaged over 10 minutes.

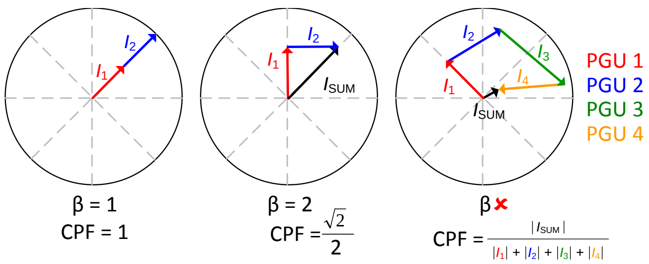

Fig. 13 Illustration of the co-phasal factor and the β exponent.

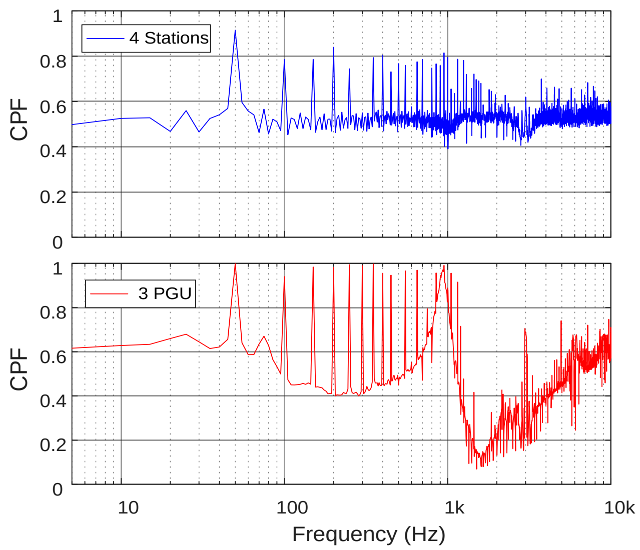

Fig. 14 CPF for 3 PGU in parallel and for 4 Stations.

On PGU level, high CPF values can be reached even for high frequency, typically around the resonance frequency (940 Hz) and the PWM sidebands (3 kHz, 6 kHz). But also cancellation effects can be observed around 1650 Hz. Considering the stations, lower CPF are achieved also for the fundamental frequency. The different cable length and reactive power injections can introduce phase shifts at the fundamental frequency, resulting in phase shifts on the fundamental-related harmonics, thus reducing their CPF.

IV. Comparing Wind and PV results

The use of summation rules has shown in both cases inaccuracy compared to the measurements at PCC. As a general observation, high frequency contents seem to be overestimated by summation rules. Probable causes are the non-consideration of harmonic cancellation effects and of the measurement noise limit in the current standards. The large variety of technologies (topologies, switching patterns, generators etc.) among Wind- and PV-PGU forces to consider these results with prudence.

V. Conclusions

The presented results are confirming the fact that assuming a pure current source behavior for harmonic summation is not accurate. Especially under weak grid conditions, the number of connected PGU influences the impedance at the PCC. This can result in resonances and high harmonic emissions triggered by the PGU and/or by grid background distortions. In that case, evaluating a PGU solely based on current emissions seems not sufficient. Considering the grid and the PGU's impedance could be additionally considered. Both the identification of the grid and the PGU´s impedance are challenging tasks and special efforts must be considered.

When connecting several PGUs in parallel, the shifting of emission peaks towards lower frequencies cannot be reproduced by the given summation rules. This leads to an under-estimation in the lower frequency range and vice versa. In order to predict the emission of a power -plant, the targeted equivalent impedance at the PGU connection point should be considered before applying any summation rule. Measuring a single PGU with the targeted equivalent impedance i.e. the expected short circuit ratio will allow a much better prediction of the harmonics spectral distribution.

The analysis of phase angle has shown that harmonic emissions of several PGUs can be correlated up to high frequencies, but also that harmonic cancellation can occur. The currently used summation formula considers uncorrelated signals but does not allow taking harmonic cancellation into account. The use of a co-phasal factor CPF could be considered instead. Switching patterns (PWM, deadtime control) and their synchronization have a major influence on the achieved CPF. Therefore, CPF should preferably be technology dependent. The CPF is also dependent of the number of PGUs in parallel, as shown in [5].

Finally, the measurements have shown that, especially when scaling to a large amount of PGU, measurement noise limit (including numerical post-processing) should be considered before applying any summation law.

Other aspects such as the simultaneity of the PGU´s power production can have a relevant influence on the summation and are under investigation.

Acknowledgment

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