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On the Aggregated Modelling of Large-Scale Wind Farms for Harmonic Studies

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Abstract. In this paper, the aggregated modelling of large-scale wind farms for harmonic studies is considered. The limitations of the harmonic emission assessment based on the IEC 61000-3-6 summation rule are analysed in a probabilistic framework. An iterative probabilistic procedure based on the Quasi Monte Carlo technique is proposed and applied to a simplified electromagnetic transient model of an exemplary wind power plant. Then, detailed results obtained are used to quantify the above mentioned limitations of the summation rule.

Keywords. Aggregated Inverter-Based Resources, Harmonics, IEC summation rule, IEEE St. P2800, Power Quality.

1. Introduction

The global shift towards renewable energy has introduced a new category of generators in power systems known as Inverter-Based Resources (IBRs), which include technologies like wind turbines (WT), solar photovoltaic (PV) arrays, as well as battery energy storage systems. Unlike conventional synchronous generators, IBRs connect to the grid through a power electronic interface. This raises concerns about their potential impact on power quality, particularly in the form of harmonic distortion. Standards such as IEEE Std. 1547 and IEEE Std. 2800 have set limits on harmonic emissions (up to the 50th harmonic) for IBRs in distribution and transmission networks, respectively [1], [2].

Several IBR harmonic models have been proposed in the relevant literature [3]-[6] and, recently, a new paper has been published by the IEEE Task Force on Harmonic Modelling Simulation and Assessment [7]. This paper presents insights into modeling of IBR units, aiming to offer tutorial guidance, research outcomes, practical considerations, and best practices for modeling IBRs in industry-focused harmonic studies at commonly encountered frequencies. On the other hand, harmonic assessment of IBR plants is still a topic under discussion. IBR plants' assessment is crucial for many applications, such as: i) plant design verification; ii) standard limits compliances (e.g. IEEE Std. 2800); iii) avoiding resonance problems for utilities.

Many IBR plants such as wind farms (WFs) or PV farms, can contain hundreds of individual IBR units. It is possible to represent all IBR units of a plant using their models and then to build a complete model for the entire IBR plant, either in time or in the frequency domain. This model shall include the circuits of the IBR units, the models of the unit transformers, connecting cables, shunt capacitors, and multiple circuit branches. Moreover, the interconnected utility system shall be included, in the form of a network model representing the utility system adjacent to the IBR plant site or a set of equivalent frequency-dependent impedances presenting different configurations of the utility system. The interconnected utility is also expected to provide the background harmonic voltages at the interconnection point. Eventually, the already complex construction of the complete model can be prohibitive for the huge quantity of detailed data needed, which should be derived from different sources (utility company, electric power plant owner, power converter's manufacturer).

As an alternative, the aggregated model of an installation, where several emitting sources are connected, can be conducted by means of suitable models able to predict the emission from the installation at a specific bus as a whole. Among the harmonic aggregation methods [7], the IEC 61000-3-6 summation rule (IEC-SR) [9] is still suggested due to its practicality. One recent example is the ongoing discussion for the development of the application guide IEEE P2800.2: recommended practice for test and verification procedures for IBRs interconnecting with bulk power systems. However, it is well known that the IEC-SR has limitations, particularly with modern harmonic sources [10]-[16]. The model's parameters (the well-known exponents α) in the standard were based on old data, primarily from studies on the grid commutated converters, and may no longer accurately reflect modern devices like the switching converters of the IBRs. Research shows that applying this summation law can lead to inaccurate results, as evidenced by studies on WF and PV plants, where harmonic currents were mis-estimated across various frequencies. Revision of the IEC-SR and of α exponents to better account for phase angle differences and randomness in emissions is strongly recommended.

In this paper, the aggregated modelling of large-scale WFs for harmonic studies is considered. The limitations of the harmonic emission assessment based on the IEC-SR with modern harmonic sources, such as IBRs, are analysed in a probabilistic framework. An iterative probabilistic procedure based on the Quasi Monte Carlo (QMC) technique is proposed and applied to a simplified electromagnetic transient (EMT) model of an exemplary wind power plant. The detailed results are then used to quantify the above mentioned limitations of the IEC-SR. This is done by solving the non-linear equation represented by the IEC-SR where, for each harmonic order, the only unknown variable is the exponent α. The estimated exponent is compared to the corresponding value in [9].

The paper is organized as it follows. The problem statement is described in Section 2. The proposed probabilistic methodology is detailed in Section 3. In Section 4 the results of numerical experiments on a WF composed of 4 WTs are shown. The conclusions are in Section 5.

2. Problem Statement

Fig. 1 shows a general scheme of a WF composed of several single WTs. The aim of the study is to determine the harmonic currents and voltages at the Point of Common Coupling, PCC (or Point of Measurement POM) which result from the phasor combination of the contributions of the single WTs' IBRs interacting with the grid. As known, the general scheme can include configurations in which radial feeders are collected at the PCC by a transformer. The considered topology includes several electrical components such as WT converters, WT generators, WT MV/LV transformers, WT filters, lines, collector, HV/MV transformers and so on.

The harmonic currents and voltages at PCC depend on the WF topology, the background distortion of the grid and the operating conditions of IBR WTs that are linked to several variables such as wind conditions, WT reactive power set-point and HV grid operating conditions. Among them, several variables are uncertain, for example, the wind speed and the background distortion of supply voltage.

A possible approach to obtain the aforementioned aim can be based on the use of a fully detailed EMT model of the entire system.

EMT simulations are based on detailed time-domain models of all electrical components of the grid and the wind farm, including accurate models of WTs with thorough switching modelling that can provide a precise representation of the IBRs behaviour. EMT simulations can provide accurate results of the harmonic behaviour of the WF; on the other hand, considering the high number of WTs present and the complexity of these models it may result in a significant computational time. Moreover, assuming that a probabilistic framework is essential for a comprehensive and reliable estimation of harmonic distortion levels, the computational time can result unacceptable.

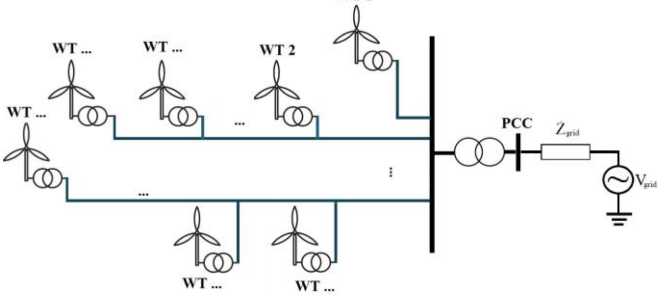

Fig. 1. General scheme of a wind farm with several WTs.

Eventually, simplified time domain models may reduce the computational burden of EMT simulations given that the impact on the harmonic distortion analysis would be negligible.

A. IEC 61000-3-6 Summation Rule

An alternative and practical aggregate harmonic modelling approach is that based on IEC 61000-3-6 summation rule (IEC-SR) [9]. Starting from the single IBR unit model, either in the time or frequency domain, it is then possible to build a whole model for the entire IBR plant. When the harmonic phase angles of the single IBR contributions are unknown, the probabilistic harmonic phasor summation suggested by [9] can be expressed as follows:

$$X_h = \sqrt[\alpha_h]{\sum_i X_{hi}^{\alpha_h}} \tag{1}$$

where: X_h is the aggregated voltage/current magnitude at harmonic order h, with $h = 2, 3, \ldots H_{max}$ (H_{max} is the maximum harmonic order), X_{hi} is the magnitude of the corresponding contribution of each wind turbine at the PCC, with i=1, 2,…, N_{WT}, and α_h is an exponent as defined in Table I.

TABLE I: IEC-SR PROPOSED EXPONENTS

Harmonic order	$h < 5$	$5 \le h < 10$	$h > 10$
α_h	1	1.4	2.0

In [5] a good overview of the nowadays suitability of the IEC-SR to capture the behaviour of modern harmonic sources is reported. In [10] new alpha exponents are recommended. In [11] harmonic limits verification for an offshore WF connection to the transmission system in the U.K. is conducted with 3 methods, including the IEC-SR which showed always pessimistic results (i.e. emission levels higher than the other two methods). Similar conclusions are given in [12] for a system-level study of a large WF composed of Type 4 WT. In [13] it was shown that the harmonic phase angles cannot be ignored as done by the IEC-SL for grid code compliance. [14] concludes that if large PV plants are built using multiple identical individual PV inverters, the IEC-SR exponents are not suitable and arithmetic summation (α_h=1 ∀h) should be used to sum up harmonic currents of individual units, independently from the harmonic order. An exactly opposite conclusion was found in [15] where the common approach used in Australia of adding arithmetically emissions from multiple identical harmonic sources is strongly criticized. In conclusion, [16] shows the comparison and the correlation between some alternative summation calculations with the IEC-SR. It is worth concluding that given that the IEC-SR is widely adopted, a great effort is needed to look for more appropriate exponent values, in particular for the IBRs.

3. Methodology

Reference is made to the exemplary scheme of WF shown in Fig. 2. The AC grid is modelled as an equivalent voltage source, ideal or distorted, in series with a Thevenin impedance. For simplicity, the topology of the WF is based on a single radial feeder where only four WTs are connected by means of their MV/LV transformer at different distances from the PCC.

The scheme of the single WT considered is reported in Fig. 3. It is based on a permanent magnet synchronous generator (PMSG) with full size back-to-back converters consisting of a pulse-width modulated (PWM) voltage source converter

(VSCs), the grid-side converter (GSC), with an interfacing output filter and a machine-side converter (MSC) with a dc chopper for the dc bus. Converters controls regulate dc voltage, active and reactive power of the WT. The active power depends on the wind conditions and is determined by the maximum power point tracking function implemented in the MSC while the dc-voltage and the reactive power - whose setpoints are received by the centralized WF control system - are implemented in the GSC. More details are given in [17]. The entire system has been firstly implemented in a fully detailed EMT model (FM). However, due to the aforementioned need to perform a probabilistic study, two levels of complexity reductions are required:

i) a simplified WT time domain model (SM) to minimize the computational burden of EMT simulations keeping acceptable accuracy of the results;
ii) a probabilistic procedure that applies Quasi Monte Carlo (QMC) approach [18] to reduce the number of trials required by the traditional Monte Carlo (MC) method.

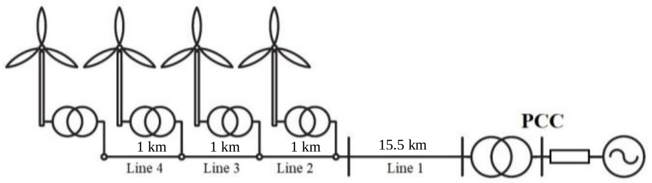

Fig. 2. Scheme of the wind farm under study.

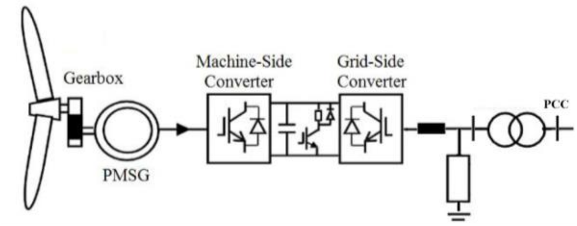

Fig. 3. Scheme of the wind turbine under study.

A. Model Simplification

The simplified WT EMT scheme is shown in Fig. 4. It is based on the approximation that all the dc-side components of the WT behind the dc smoothing capacitor can be substituted by a controlled current source with a reduced impact on the harmonic distortion at PCC. This approximation assumes that the dynamic behaviour of the ac and dc parts on the machine side can be considered decoupled from the grid side dynamics [17].

The input signal of the controlled current generator is obtained from the instantaneous power at dc link – measured offline on the FM of the single WT in different discretised operating conditions – divided by the measured dc voltage on the smoothing capacitor. Thus, it is possible to create a set of vectors of measured power versus time representing the behaviour of the turbine mechanical system and MSC.

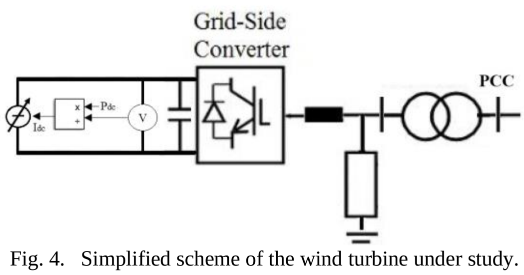

Fig. 4. Simplified scheme of the wind turbine under study.

B. Quasi Monte-Carlo Simulations

Numerous probabilistic analysis techniques are reported in the literature, each presenting distinct advantages and disadvantages, particularly in their treatment of uncertainties associated with input random variables. Examples of these techniques include MC simulation methods, point estimate techniques, and scenario-based approaches. In this paper, the QMC simulation method is adopted. QMC is characterized by a reduced number of trials compared to conventional MC; thus, it is particularly suitable for applications where EMT simulations are needed.

Unlike traditional MC methods that use (pseudo) random numbers, QMC uses low-discrepancy deterministic sequences to simulate underlying values ([18]-[19]). Discrepancy measures the uniformity of point distribution within the unit hypercube. These sequences facilitate the generation of representative samples from the probability density functions (PDFs) relevant to practical problems. Various methods exist for producing low discrepancy sequences [18]. Among these, the Sobol sequence [19] is noted for its popularity within QMC applications, particularly for its uniform performance in higher dimensions.

By starting with the generated uniform Sobol sequence, inverse transform sampling can be employed to derive a set of samples that reflect the PDF associated with the statistical characteristics of each input random variable. Inverse transform sampling is a fundamental technique for generating random sample numbers from any cumulative distribution function (CDF). For each term S_k of the Sobol sequence, which is uniformly distributed over the interval [0, 1], a random variable Y_k with CDF F_{Y_k} can be generated:

$$Y_k = F_{Y_k}^{-1}(S_k) \quad (2)$$

where $F_{Y_k}^{-1}$ is the generalized inverse of F_{Y_k}.

QMC trials were conducted using wind speed and background harmonic voltages (magnitude and phase), as the random independent input data.

C. Iterative Probabilistic Procedure

Fig. 5 shows the iterative probabilistic procedure for the estimation of the IEC-SR exponents $\hat{a}_h$ at all the harmonic orders of interest. To resolve equation (1) and find $\hat{a}_h$, the harmonic amplitudes X_{hi} of the single WT contribution at the PCC and the aggregated harmonic amplitudes X_h at the PCC are needed. In particular, X_h is calculated simulating the simplified EMT model of the scheme in Fig.2 with all the WTs connected, while X_{hi} is obtained simulating the simplified EMT model with only one WT connected at a time. This strategy leads to a number of EMT configurations to be simulated equal to $N_{WT} + 1$. Thus, once known the topology of the WF, for each configuration, the probabilistic QMC procedure is applied starting from the trials of the random input variables obtained from their PDF characterizations.

For each iteration j of the QMC ($j=1,2, \ldots M$), the input data are the WF configuration, the wind speed and the background harmonic supply voltages (magnitude and phase). Once the input data are known, the M EMT simulations are executed to obtain the current waveforms at the PCC.

The spectral analysis of these waveforms allows obtaining the determinations of the harmonic currents for each harmonic order h (X_{hi} and X_h). At the end of the QMC procedure, the output will be composed of $(N_{WT}+1)M$ vectors of H_{max} harmonic components, $N_{WT}\,M$ for $\boldsymbol{X}_{hi}$ and M for $\boldsymbol{X}_h$, each of dimension H_{max}.

Finally, resolving the non-linear equation (1) in only one variable α_h, by using, for example, the Newton-Raphson method, the determinations of the estimated $\hat{a}_h$ are obtained.

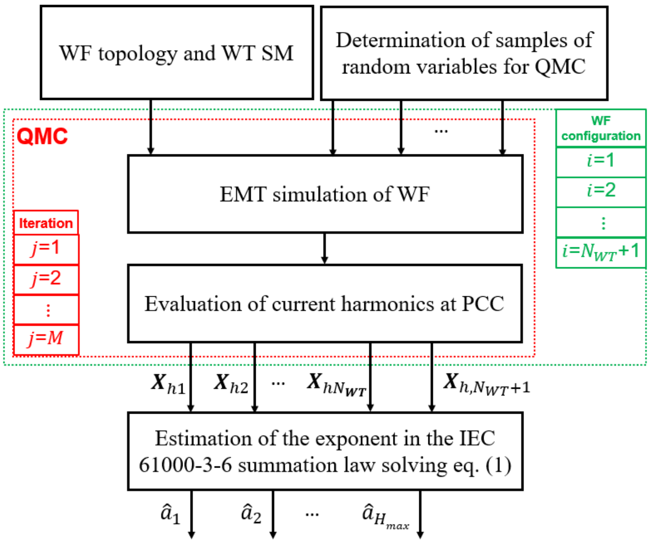

Fig. 5. Iterative procedure for estimation of the IEC-SR exponents.

4. Case-Study

This case study aims to verify the accuracy of the proposed WT SM and to estimate the values of $\hat{a}_h$ of the IEC-SR applying the proposed iterative QMC procedure.

A. Circuit Description

The WF system shown in Fig. 2 includes a collector HV/MV transformer that connects the WF to the 50 Hz transmission system (PCC) [17]. WTs are all twins and distributed along the feeder with four cables. The scheme of the WT is shown in Fig. 3 and is based on PMSG with a full size back-to-back converter, filters and an LV/MV transformer. The main data of the WT circuit are reported in Table II, other data of the converters' control systems are available in [17] and in [20]. The WF was implemented in a full detailed EMT model in Matlab/Simulink.

TABLE III: MAIN PARAMETERS OF THE CONSIDERED WIND FARM

WF Parameters	**Value**
V_{PCC}	25 / 110 kV
$S_{tr,n}$	20 MVA
$R_{tr}, L_{tr}, R_{tr,m}, L_{tr,m}$	0.007 pu, 0.10 pu, 500 pu, 500 pu
WT Parameters	
V_1^{WT}/V_2^{WT}	0.575 / 25 kV
$S_{tr,n}^{WT}$	2.5 MVA
P_n^{WT}	2 MW
Q_{set}^{WT}	0 MVAr
WT speed (cut_{in}, cut_{off}, w_n)	6 m/s, 30 m/s, 11 m/s
$R_{tr}^{WT}, L_{tr}^{WT}, R_{tr,m}^{WT}, L_{tr,m}^{WT}$	0.0017 pu, 0.05 pu, 500 pu, 500 pu
C_{DC}	90 mF
V_{DC}	1100 V
$R_{filter}^{WT}, L_{filter}^{WT}, C_{filter}^{WT}$	0.015 pu, 0.15 pu, 90 uF
PWM modulation index m_f	63

B. Accuracy Verification of the Simplified Model

The results of the simplified model described in sub-section 3.A, have been compared with those of the FM in sixteen different scenarios: each of the four turbines has been run alone for four wind speed conditions (i.e. 8 m/s, 9.8 m/s, 11.3 m/s and 15 m/s) corresponding to four powers generated equal to 25%, 50%, 75% and 100% of the nominal power, respectively. Moreover, the accuracy of the SM model was verified in the presence of background distortion of the supply voltage. In particular, the supply grid was supposed to be distorted with odd harmonics with magnitudes equal to 0.75% of the nominal value from 3rd to 49th (half of the limits of the Standard IEEE 519 [22]) and to 0.25% of the nominal value from 51th to 69th (not considered in [22]); phase angles were supposed to be equal to zero.

Fig. 6 shows the boxplot of the magnitude error of the harmonic current emission simulated by the SM, evaluated with reference to the FM and in the percentage of the WT's rated current, versus the frequency for all 16 simulations. It is worth to remember that the whisker extremes of the boxplot correspond to the 1st and 99th percentiles, the box to the two interquartiles and the red segment to the median. The harmonics considered include both low and high frequencies to validate the SM model even at high frequencies typical of PWM. It is possible to observe that the introduced simplification gives very accurate results as the error doesn't exceed 0.03 % in all the frequency ranges of interest. Finally, it is worth underlining that the mean value of the computational time of SM simulations is two orders of magnitudes lower than that of FM.

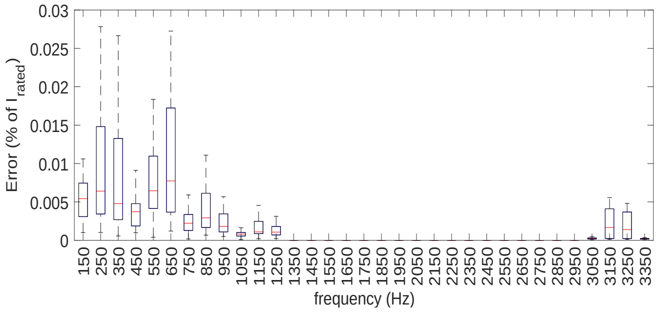

Fig. 6. Boxplot of the magnitude error of the harmonic current emission obtained by SM versus the frequency.

C. Estimation of the IEC-SR Exponents

The WTs SM is used in the probabilistic iterative procedure shown in Fig. 4 to estimate the actual exponent coefficients and to compare their values with those reported in Table I for $h=1,\dots H_{max}$.

The selected input random variables of the QMC are: i) the wind speed and ii) the magnitude and phase angles of the odd background harmonics in the supply voltage.

Wind speed is assumed to be a discrete random with the probabilities equal to 0.58, 0.23, 0.11 and 0.08 of the four wind speed values 8 m/s, 9.8 m/s, 11.3 m/s and 15 m/s. These probability values are deducted by using measured values of wind speeds in the South of Europe from 2016 to 2018 [21]. With reference to the background distortion, supply voltage includes odd harmonics from the 3rd to 69th with magnitudes and phase angles normally distributed with the same mean values reported in the previous paragraph. The standard deviation of the magnitudes was set to 1/3 of the mean value (with negative values set to 0), and that of the phase angles equal to $\pi/3$. Globally, the number of variables is 69 and the QMC trials are evaluated to be $M = 160$ [23].

For each of the 160 sets of samples of the input random variables, for each configuration, an EMT simulation of 1 s was carried out and the currents of each WT together with the currents at PCC have been stored. All the WTs are assumed to receive the same wind speed neglecting interference effects (e.g. shadow effect) without loss of generality of the proposed approach.

For each of the five currents stored, the DFT analysis has been performed and the non-linear equation (1) is resolved for each current harmonic obtaining 160 determinations of the estimated exponent $\hat{\alpha}_h$.

Fig. 7 reports the boxplots obtained by applying the proposed iterative procedure. The estimated values of the exponent $\hat{\alpha}_h$ for each harmonic are reported together with the values suggested by IEC-SR and reported in Table I.

Fig. 8 shows the comparison between the harmonic currents at PCC obtained with the proposed model and the harmonic currents obtained by applying equation (1) with the IEC-SR exponents of Table I.

From the analysis of results shown in Fig. 7 and in Fig. 8, it can be observed that for the considered WF topology:

- the values of the estimated exponents $\hat{\alpha}_h$ for harmonic orders lower than 13 and higher than 19 are close to the values proposed by IEC and characterized by small standard deviations;
- larger differences are observed in the case of some harmonic orders between the 13th and 19th;
- most of the estimated $\hat{\alpha}_h$ are characterized by reduced standard deviations; increased dispersions are observed in case of some harmonics between 11th and 19th and for the 49th;
- most of the exponents are larger than the ones suggested in Table I except for the 5th and 7th harmonic orders.
- For 5th, 7th and 11th harmonic magnitudes of the aggregated current by IEC-SR are underestimated; on the contrary from the 13th to 19th IEC-SR overestimates the aggregated currents while for the rest of the harmonic orders, the results are close to each other.
- The results show that in the frequency range where higher differences are evident, a resonance phenomenon should be investigated.

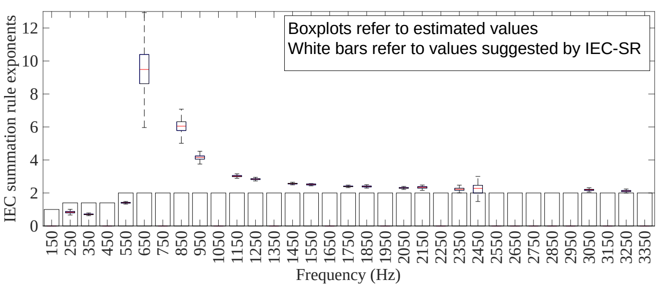

Fig. 7. Comparison between the exponent values suggested by IEC-SR and those estimated by the proposed method.

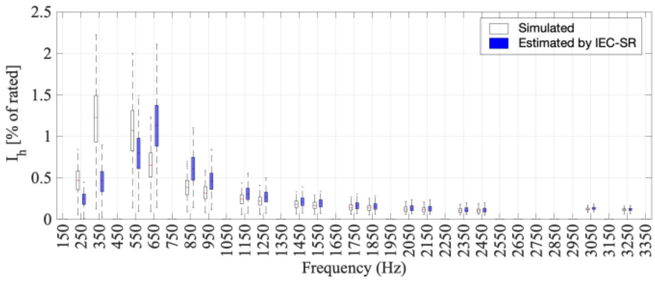

Fig. 8. Comparison between the measured emission harmonic currents at PCC obtained by the SM (Simulated in the legend) and those obtained applying IEC-SR (Estimated by IEC-SR in the legend).

5. Conclusions

In this paper, the aggregated modelling of large-scale wind farms for harmonic studies has been considered. The limitations of the harmonic emission assessment based on the IEC-SR with modern harmonic sources, such as IBRs, have been analysed in a probabilistic framework. An iterative probabilistic procedure based on the QMC technique has been proposed and applied to an exemplary wind power plant.

The detailed results in the time domain have been then used to quantify the above mentioned limitations of the IEC-SR. This has been done by solving the non-linear equation represented by the IEC summation law where, for each harmonic order, the only unknown variable is the exponent α. The estimated exponent α is compared to the corresponding value suggested by IEC-SR. It is proved that, for the considered WF topology, the presence of resonance phenomena can lead to inaccurate results of the IEC-SR.

Ongoing activities will be focused on the development of new aggregation models for different WF topologies, different WTs reactive power control strategies and different grid configurations. Furthermore, the research will be focused on the applicability of the proposed approach for different grid configurations and wind farm layouts considering the extension of the accurate aggregated modelling also in the range of the high-frequency spectral components. Finally, the applicability of indices like those proposed in [24],[25] and simplified time domain models and/or frequency domain models as discussed in application guide IEEE P2800.2. will be investigated.

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