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Equivalent Modelling of Wind Farms for Probabilistic Harmonic Propagation Studies

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Abstract--This paper investigates the effect of modelling of different aspects of wind farms (WF) as a first step towards development of the equivalent harmonic model initially of WF, and later of other types of converter connected generation, for studies of harmonic propagation and mitigation in power electronics (PE) rich transmission networks. The aim of the study was to establish a set of scaling factors that can be used when modelling the entire WF as a single probabilistic harmonic generator in harmonic propagation studies, considering different WF configurations, weather conditions, harmonic cancellation effects, individual wind generator availability, cable disconnection, and the influence of the non-ideal external grid. The importance of modelling resonance and individual characteristic harmonics on the equivalent modelling of WF has also been established. The results facilitate the assessment of global contribution of PE connected RES to harmonic levels in transmission networks and more generally harmonic propagation studies in large PE rich transmission networks.

Index Terms--harmonics, Monte Carlo simulations, power electronics, resonance, uncertainty, wind farms

LIST OF ABBREVIATIONS

DFIG	Doubly Fed Induction Generator
EG	External Grid
PCC	Point of Common Coupling
PE	Power Electronics
PQ	Power Quality
RES	Renewable Energy Source
SC	Short Circuit
SF	Scaling Factor
THD	Total Harmonic Distortion
WF	Wind Farms
WT	Wind Turbines

I. INTRODUCTION

Power quality (PQ) disturbances and variations result in a significant financial losses to both network operators and end users. Power system harmonics, as one of the most important PQ phenomena, are closely associated, among the others, with operation of power electronics connected equipment. The ever-growing penetration level of power electronics (PE)

renewable generation, including wind farms, is in line with the world's commitment to tackle climate change. In the document published in 2019 by the UK government [1], a third of British electricity is set to be produced by offshore wind power by 2030. Other governments and countries have pledged similar commitment and a large amount of funds have been invested to achieve this goal. In order to accommodate a significant growth in connections of wind farms (WFs), and other PE connected renewable generation, transmission and distribution networks are facing significant challenges in terms of power quality and security. As far as WFs are concerned, there have been mainly concerns about voltage fluctuation and voltage flicker in the past, due to the stochastic and intermittent nature of their operation. With the increased proliferation of non-linear power electronics (PE) interfaced renewable energy sources (RES) and other transmission technologies (WFs, PV generation, FACTS devices and HVDC converters, etc.) however, the potential harmonic issues are gaining significant attention [2,3]. Harmonics could lead to equipment overheating, insulation stress and load disruption, thus leading to significant financial losses. Considering that installed capacity of RES connected to the system through PE interface is significant and constantly increasing, the study of the influence of PE connected generation on harmonic levels in the system is highly needed.

Several studies [4-6] have been carried out in this area in recent years using a variety of methods such as two-port network theory, load flow analysis and power loss method. However, the scope was usually limited to cable or impedance reduction based on the assumption that the wind generators always operate at rated capacity and with fixed harmonic injections. In addition, the interconnected cables were assumed to be of the same type and the same length, which is not the case in real WFs.

This paper is one of the first, if not the first to model probabilistically a WF for harmonic propagation studies considering a combination of different WF operating points and characteristics (e.g., WF configurations, weather conditions, harmonic cancellation, resonance, individual WT availability, cable disconnection, and non-ideal external grid). Considering stochastic and intermittent nature of operation of WFs and uncertainties associated with system operation and loading, probabilistic harmonic modelling and analysis are adopted as more suitable than conventional deterministic approach, for harmonic studies in power electronics rich power networks.

The WF models are developed in DigSILENT/PowerFactory 2018 SP1. The test network is simulated through probabilistic analysis by performing Monte-Carlo simulations. The 95th percentile of total harmonic distortion (THD) and individual harmonics calculated at the point of connection of WF are

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used as an index in the study to analyse different aspects of plant modelling.

II. METHODOLOGY

A. WF Configurations

In the modelling of the illustrative WF, the wind farm model at the point of common coupling (PCC) to the external power grid consists of a collector bus connected to a total of 48 wind generators and two types of connection transformers to account for different voltage levels. The voltage level of the plant is 0.69/33/138 kV. The most commonly used connection configurations of wind generators in practical WFs namely, parallel, star and T configurations, shown in Fig. 1, Fig. 2 and Fig. 3, respectively are considered in this study. In the parallel or radial configuration, WTs are connected in strings of cables (8 strings with 6 WTs each in this study). The number of WTs on one string depends on the capacity of the generators and cables. The strings are then connected to the collector bus. In the star or starburst configuration, several generators are connected to a central node by individual cables and then the central nodes are connected to the collector bus (6 central nodes with 8 directly connected WTs each in this study). In the T or central configuration, the power is collected at a single bus from generators in two “T connected” branches (2 branches with 24 WTs each in this study) and then transmitted to the collector bus [7-9].

Fig. 1. WF with parallel configuration

Fig. 2. WF with star configuration

Fig. 3. WF with T configuration

B. Modelling of Generators

Doubly Fed Induction Generator (DFIG) model available in DigSILENT/PowerFactory is used to model individual wind generator as the DFIG is currently dominant type of wind generators commercially used in large WFs worldwide. This is because of its lower cost than full rated converter connected generators and better power quality of generated power than that provided by fixed speed generators [10, 11]. Nevertheless, other types of wind generators could be used equally well without any loss of generality of the proposed approach. The individual wind generators are modelled as 2 MVA units operating with a power factor of 0.8 and a blade diameter of 88m. Each WT, however, is modelled in harmonic studies using Norton equivalent with probabilistic injection of individual harmonic current magnitudes and angles. (Note: Any other type of wind generator for which harmonic injection profile is available could be equally well used in these studies.) Weibull distribution (Fig. 4 (a)), commonly used to describe the wind speed variation during the year [12], is used for modelling WF power output in this study. Based on Fig. 4 (a),

Fig. 4. (a) Weibull distribution (adopted from [12])

Fig. 4. (b) Illustrative equivalent circuit combining equivalent models of the WF and external grid

appropriate probability distributions of respective WT power outputs are generated in MATLAB and sampled randomly (500 random values) for each individual wind generator. These 500 random values of power output of individual WT's are then transferred to DigSILENT, so that in each of 500 iterations each individual generator is modelled as an independent probabilistic power injection.

C. Modelling of Cables and Transformers

Generally, in most power system analysis tools, the transmission lines and cables are modelled as π equivalent circuit [4, 13]. In most cases, WTs are connected through AC Cross-

Linked Poly Ethylene (XLPE) 3-core submarine cables with a Copper or Aluminium conductor [8]. Cable parameters used in this study are adopted from the technical datasheet of Lillgrund wind power plant [14]. With more generators connected in one string, the cross section of cable should be larger in order to withstand the accumulated current. The cross section of cables representing the numbers of wind generators in one string is depicted in Fig. 5. The distance between WTs is normally 5-8 times that of rotor diameters [8]. Thus, the length of cables between WTs and cables connected to collector bus is assumed to be 0.5 km and 2 km, respectively, which warrants the use of conventional π equivalent circuit to represent the cables. Furthermore, due to relatively short sections of cables, the phase transposition is not an issue. Transformers connecting the WTs to the medium voltage bus and those connecting the WF to the grid are typically delta connected on the secondary side which prevents the flow of zero sequence components into the grid. Since the analysis here is focused on the THD at the PCC, the positive sequence representation is sufficiently accurate.

Fig. 5. Different cross-sections of cables in WF model

The skin effect refers to a phenomenon in which the current distribution within the conductor is uneven when there is alternating current or alternating electromagnetic field flowing through conductor, thereby increasing the resistance and power loss. As recommended in [13], the skin effect in cables and transformers is modelled based on equation (1) and (2), respectively.

$$Z_C(h) = \sqrt{h}(R_C + jX_C) \quad (1)$$

$$Z_T(h) = \sqrt{h}R_T + jhX_T \quad (2)$$

Where R_C and X_C represent the resistance and reactance of the cable at the fundamental frequency, $Z_C(h)$ represents the series impedance of the cable at h-th harmonic. R_T and X_T represent the resistance and the reactance of the transformer at the fundamental frequency, $Z_T(h)$ represents the series impedance of the transformer at h-th harmonic.

D. Modelling of Harmonic Injections

The harmonic current/voltage magnitudes and phase angles injections by individual harmonic sources vary in reality depending on the source operating conditions. Hence, the range of harmonic injections for each order harmonic used in the study is based on the results of long-term measurements and of the harmonic spectrum of PE interfaced generation reported in [15, 16]. The ranges of harmonic injection magnitudes of individual harmonics in this study are determined from the probability distribution of the available long-term harmonic measurements for harmonics from 2nd to 25th, covering different operating conditions of the wind farm. Once the histogram of harmonic measurements is produced, the normal distribution is fitted such that its mean value corresponds to the mean value of measured harmonics and that the measured range of harmonics is covered by $\pm 20\%$ variation around the mean with

3σ confidence. In this way a provision is made that a very small percentage (0.3%) of the harmonic magnitudes can be outside the measured range of harmonics. The individual harmonic injections are then randomly sampled from this distribution. Phase angles of each harmonic are randomly sampled from 0° to 180° , following uniform distribution.

Measurements of harmonics up to 50th and even higher, in recent times, are recommended and highly desirable when feasible. In particular, measurement of both magnitude and phase angle of harmonics. According to standard EN 50160 [17], typical upper limit for harmonic measurements in Europe at transmission voltages is 50th harmonic, however if the risk of resonance at higher harmonics is deemed to be low, the upper limit can also be the 25th harmonic. In this study, as an illustrative example of the methodology developed, harmonics up to 25th order only are used as higher order harmonics were not available in provide field measurement results at real wind farm. The key issue with accurate equivalent modelling of different harmonic sources is the availability of appropriate spectra of harmonic magnitudes and angles, which could be made available if a particular wind farm is to be modelled. The probabilistic modelling of harmonic sources applied in this study is equally applicable to modelling of any type of harmonic source and of any order of harmonic injections.

The harmonic injections from each wind generator are obtained by multiplying the fundamental current of the wind generator by the appropriate coefficient of harmonic spectrum obtained from long term measurements. The fundamental current variations are determined considering different wind turbine output (randomly sampled from Weibull distribution representing wind turbine output during the year). The harmonic coefficients of each harmonic order are also sampled randomly, within corresponding predefined ranges for each harmonic determined from long term measurements, following uniform distribution to account for variability/stochastic harmonic generation of power converters at different operating points.

The Monte Carlo simulations considering different probability distribution of injected harmonics is conducted to represent the probabilistic operation of the WF. The same harmonic injection is modelled in each of the three phases.

According to [18, 19], the entire WF can be modelled as a Norton equivalent circuit consisting of a harmonic current source (I_h) and an impedance (Z_I) connected in parallel while the external grid which is usually modelled as the Thevenin equivalent circuit comprised of a harmonic voltage source (E_h) and an impedance (Z_2) in series. The combined equivalent model of the test system is illustrated in Fig. 4 (b). The frequency scan is performed in DigSILENT/PowerFactory, to calculate frequency-dependent equivalent impedance, as seen from the PCC bus, of the wind farm (Z_I) [20]. The impedance characteristic is computed for a given frequency range containing series and parallel resonances in the network. For qualitative analysis, the equivalent impedance of the external grid (Z_2) can be represented as the ratio of the square of the external-grid harmonic voltage and external-grid short circuit fault level [20].

Each WT is represented as an independent harmonic current source. Based on the equivalent circuit of Fig. 4 (b), each voltage harmonic at PCC (U_{PCC}^h) can be calculated using (3).

$$U_{PCC}^h = \frac{Z_1 Z_2}{Z_1 + Z_2} I_h + \frac{Z_1}{Z_1 + Z_2} E_h \quad (3)$$

E. Modelling of the Wake Effect

The wake effect occurs in the wake (“shadow”) area when the wind speed falls and the WT in the wake harnesses less energy from the wind. It leads to an uneven distribution of wind speed in a WF and subsequently, affects the operating status and output of the WT [21]. Since the wake effect depends on the WT location, it is possible to model it as a scaling factor (sf) with respect to WT separation [8]. In this study three wind directions are considered to illustrate the wake effect: horizontal (wind blowing from left to right), vertical (wind blowing from bottom to top) and diagonal (wind blowing from lower left to upper right corner at an angle of 45° with respect to the horizontal line). The selected scaling factors (as illustration) are given in Fig. 6 for a WF with parallel connection of WTs with diagonal, 45° direction of wind. The wake effect scaling factors for star and T connection are roughly the same.

Fig. 6. Wind blows from lower left to upper right at 45°

F. The Flow Chart of the Adopted Algorithm

The simulation algorithm used in this study is represented by a flow chart in Fig. 7. Appropriate probabilistic WT power outputs based on sampled (500 samples) Weibull distribution is generated in MATLAB and transferred to DigSILENT/PowerFactory. The Weibull distribution is sampled 500 times randomly and independently for each individual WT resulting in 500 different values of harmonic injection per harmonic order and per WT.

III. CASE STUDIES

A. Wind Farm Case Studies

For the assessment of WF harmonic contribution following disconnections/unavailability of individual WT, different operating points of WTs (based on Weibull distribution), wake effect and different WF configurations are considered. The WF case studies are classified by configuration. As an illustration, the WTs for the parallel configuration, are grouped and named as shown in Fig. 8. PC 0 refers to the case when all WTs are connected; StC 1 refers to one string of WTs disconnected; with additional strings of WTs disconnected, the cases are named as StC 2- StC 8, respectively. Similarly, RwC 0

Fig. 7. Flow chart of simulation algorithm

refers to all WTs connected. Cases with a row of WTs disconnected are named as RwC 1- RwC 6. As in previous two cases, with each group of diagonal WTs disconnected, the cases are named as DgC 1- DgC 6, respectively. WEC 1-3 refers to cases considering the wake effect for three selected wind directions: horizontal, vertical and diagonal, respectively. They are simulated by considering different scaling factors as discussed above. In order to analyse the impact of different WF configurations, additional case study of 16 randomly disconnected WTs, including the wake effect, are considered for each of the three configurations. Note that the StC 8, RwC 6 and DgC 7 are the same representing no WTs connected. The simulation cases for star and T configurations are roughly the same as parallel. All power injections by each WT follow the Weibull distribution.

Fig. 8. Names of WF groups (parallel configuration)

B. Effect of External Grid on Harmonic Propagation

To demonstrate the effect of the external grid short-circuit (SC) fault level on harmonic propagation, the external grid is considered to be ideal without harmonic voltage distortion. According to [22], it is usually assumed that the external grid SC fault level is between 1000 MVA for a weak grid and 3000 MVA for a strong grid. In this case, the harmonic load flow and frequency scan are performed when the SC power varies within this interval. The results of 95th percentile THD at PCC

for all three WT configurations are illustrated in Fig. 9. It can be seen that there are two resonance points for parallel configuration which occur at a SC fault level of 400 MVA and 1300 MVA, respectively. Apart from the resonance point, the THD tends to decrease as the SC fault level increases.

Fig. 9. THD curve with different SC fault levels and configurations

According to (3), when the external grid is ideal, there is no harmonic voltage injection ($E_h = 0$). Hence, the harmonic voltage at PCC (U_{PCC}^h) can be calculated by (4). Since there is no WT disconnection, the equivalent impedance of the internal WF (Z_1) is a constant. With the increase in the SC fault level, the equivalent impedance of external grid (Z_2) falls. Therefore, the THD at PCC drops as the external grid SC fault level increases.

$$U_{PCC}^h = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2}} I_h \quad (4)$$

For all three configurations, scenarios where the external grid SC fault level is higher than 2000 MVA are much more robust and with low harmonic distortion levels (THD=0.28%). When the SC fault level is between 1300 MVA and 2000 MVA, the parallel configuration results in the highest harmonic distortion, while the star and T configurations have much smaller THD values at the PCC. For the scenarios with lower SC fault level (especially less than 1300 MVA), however, it is possible to have higher harmonic distortions due to resonance.

The results of frequency scan, for all three WF configurations and for corresponding SC fault levels when peaks in THD values occur, are shown in Fig. 10.

Fig. 10. Frequency scan when resonance occurs for different configurations

It can be seen that the THD peaks for particular SC level and WF configuration are the consequence of harmonic resonance occurring at different harmonic for different WF configurations and SC fault levels. For example, high THD values for SC fault levels of 120 MVA and 1000 MVA in case of the T configuration are the consequence of harmonic resonance at 19th and 23rd harmonic, respectively, while for the star configuration, harmonic resonance occurs at 17th and 19th harmonic for SC fault levels of 300 MVA and 1000 MVA, respectively, and results in correspondingly high THD values shown in Fig.

9. Table I summarises the SC fault levels, harmonic orders and THD values corresponding to resonant conditions observed for different WF configurations and illustrated in Figs. 9 and 10. It can be seen that the occurrence of the resonance can significantly increases the THD at PCC, e.g., the resonance at 19th harmonic increases the THD value by more than 400 % ($\frac{1.48-0.28}{0.28} * 100\% = 428.6\%$), in case of parallel WF configuration and 1300 MVA SC fault level. It is very important therefore to consider a range of harmonics and the SC fault level at PCC of the WF when studying harmonic injection by the WF.

TABLE I
SUMMERISED RESONANCE DATA

	Short Circuit Fault Level	Resonant Harmonic Order	THD
Parallel	400 MVA	17	2.11%
	1300 MVA	19	1.48%
Star	300 MVA	17	2.27%
	1000 MVA	19	1.66%
T	120 MVA	19	3.34%
	1000 MVA	23	1.37%

Fig. 11 illustrates the influence of the non-ideal external grid on the THD with the variation of SC fault level for parallel configuration. (The curve trends for star and T configurations are similar to the one shown for parallel configuration.) In general, the presence of harmonic voltage distortion in the external grid increases the THD values at PCC in the range between 0.35% to almost 2%. Resonance still occurs at the same short-circuit fault level since the harmonic voltage distortion at the external grid does not change the equivalent impedance seen from the PCC bus. Hence, the non-ideal external grid does not move the resonant point but only contributes to the increase of THD at PCC.

Fig. 11. THD curve of non-ideal and ideal external grid with SC fault level for parallel configuration

The trend of THD curves in Fig. 11 can be explained using equation (5), which is deduced from (4). The higher the SC fault level, the lower the external-grid equivalent impedance (Z_2). As a consequence, the influence of harmonic current injection (I_h) on each order of harmonic voltage (U_{PCC}^h) decreases gradually, whereas that of harmonic voltage injection (E_h) increases gradually. Eventually, when the SC fault level is higher than 2000 MVA, the THD at PCC tends to be stable.

$$U_{PCC}^h = k (Z_2 I_h + E_h), \quad k = \frac{Z_1}{Z_1 + Z_2} \quad (5)$$

Based on the above discussion, the 2000 MVA SC fault level is chosen to represent the external grid in non-resonant

conditions for all three configurations, while the 1300 MVA SC fault level is chosen to represent the resonant condition for parallel configuration in the following studies.

C. WF model as single harmonic source

To confirm the possibility to model the entire WF as a single harmonic source with appropriate scaling factors, only one wind generator is simulated considering 500 probabilistic harmonic injections, using Monte-Carlo simulations. The results are then multiplied by 48 and compared with the results obtained with all 48 WTs modelled as harmonic sources and connected in three configurations, excluding the wake effect. Fig. 12 shows the fitted Normal distribution used to compare the mean values (μ) and standard deviations (σ) for three different configurations, when the external grid is considered ideal with 2000 MVA and 1300 MVA SC fault level.

Fig. 12. Fitted Normal distribution with 2000 MVA SC fault level (a) and 1300 MVA SC fault level (b) for different equivalent models of WF

It can be seen from Fig. 12 that when the external grid SC fault level is 2000 MVA, the standard deviations of the equivalent models are roughly the same, i.e., the dispersion of the values are similar. Compared with the results obtained using single WT multiplied by 48, the mean value is 9.7% ($\Delta = \frac{0.1581-0.1427}{0.1581} * 100\% = 9.742\%$) lower for parallel configuration, 16.7% lower for star configuration and 23.8% lower for T configuration, i.e., there is substantial variation in the results. Therefore, if the WF is modelled as a single probabilistic harmonic generator, it is necessary to add a scaling factor for different WF configurations, i.e., 0.90 ($0.1427/0.1581 = 0.90$) for parallel, 0.67 for star and 0.83 for T configuration.

In case of 1300 MVA SC fault level, a scaling factor of 1.02 should be used for a star configuration and of 1.1 for T configuration. For the parallel configuration the differences in standard deviation and mean value are excessive due to the occurrence of resonance. In other words, if the THD results from single WT are simply multiplied by 48 to represent the effect of the entire WF in case of resonance, a relatively large separation in distributions appears, compared with the cases without resonance. Therefore, as a first approximation for exploratory studies not requiring very high accuracy, if the parallel configuration is modelled as a single harmonic source, a scaling factor of 3 ($0.75/0.24=3$) can be considered. The utilization of this scaling factor is accurate under this circumstance, but not generally applicable for WFs in parallel configuration with different number of wind turbines when their external grid short circuit fault level is 1300 MVA. However, the high value of scaling factor may still be expected for various resonance conditions.

D. Effect of Cancellation on Harmonic Propagation

The harmonic cancellation occurs when two harmonic injections with opposite phase angles cancel each other, thus decreasing the total value of resulting harmonic distortion. The harmonic injection of the WF model used in this study assumes probabilistic harmonic injection with random phase angle (0° - 180°). The effect of harmonic cancellation for all three configurations is studied by comparing harmonic injection of both phase angle 0° and randomly varying between 0° - 180° . The results of THD at PCC are given in Table II. The table also presents the corresponding reduction percentage of THD after harmonic cancellation.

It can be seen that the effect of harmonic cancellation is notable. It reduces the 95th percentile of THD at PCC by approximately 33%. The reduction percentage is roughly the same for different external grid SC fault levels and different configurations. Therefore, if the WF is modelled as a single harmonic source with fixed phase angle of harmonic injections, the effect of cancellation should be modelled using the same scaling factor of $K_C=0.66$ ($0.48/0.72=0.66$), irrespectively of the type of configuration and the external grid SC fault level.

TABLE II
PARAMETERS OF NORMAL DISTRIBUTION

			Parallel	Star	T
SC fault level 1300 MVA	THD (%)	Phase angle 0°	2.14	0.72	0.76
		Phase angle (0° - 180°)	1.42	0.48	0.51
	Reduction percentage (%)		33.6	33.3	32.8
SC fault level 2000 MVA	THD (%)	Phase angle 0°	0.40	0.30	0.36
		Phase angle (0° - 180°)	0.27	0.20	0.24
	Reduction percentage (%)		32.5	33.3	33.3

To sum up, the WF can be modelled in a first approximation as a single probabilistic harmonic generator with appropriate scaling factor K_I , summarised in Table III, to account for different plant configurations and with harmonic attenuation factor of $K_C=0.66$ to account for harmonic cancellation, if all injected harmonics have the same phase angle. Even though the obtained scaling factor K_I is developed based on a WF with 48 wind turbines, when calculating the scaling factors though, the number of turbines get cancelled through division, so, the effect of the number of wind turbines is eliminated. Therefore, the scaling factor K_I can be applied generally for THD estimation of WFs with different number of wind turbines such reducing the number of variables to be considered.

TABLE III
SCALING FACTOR K_I REPRESENTING DIFFERENT CONFIGURATIONS AND HARMONIC CANCELLATION

	WF Parallel	WF Star	WF T
2000MVA	0.90	0.67	0.83
1300MVA	3	1.02	1.1

E. Effect of Wind Generator Disconnections/Unavailability

In the following studies the WTs are disconnected in string/row/ diagonal by setting their output to zero, to repre-

sents the WT unavailability. Among all the cases for different configurations, the worst case is PC 0 (all WTs connect) with 1300 MVA SC fault level, which results in 95th percentile THD of 1.4%. In this case, the 19th harmonic exceeds the IEC 61000-3-6 standard [23] limit (1%) due to resonance. Compared with the other harmonics, the 19th harmonic shows the largest contribution to the overall THD. Moreover, the mean values and standard deviations of the 5th, 7th, 17th, and 23rd harmonic pdf curves are approximately the same but larger than those of the 11th, 13th and 25th harmonic. In other words, in case of WT disconnections, the influence of the 5th, 7th, 17th, and 23rd harmonics on THD is greater than that of the 11th, 13th and 25th harmonics, but much less than the 19th harmonic.

In comparison, the scenarios with parallel configuration with 2000 MVA SC fault level result in much lower THD at PCC. When the results are normalised based on PC 0, i.e., with all WTs connected, (shown in Fig. 13), different SC fault levels do not influence the reduction ratio of THD when one more string/row/diagonal WT is disconnected. Since the scaling factor $K1$ represents cases when all WTs are connected, a set of scaling factors $K2$ can be derived to represent the WT string/row/diagonal WT unavailability, suitable for any external grid SC fault level. Thus, assuming there are n string/row/diagonal of WTs disconnected from WF, the corresponding scaling factor $K2$ should be $1-0.125*n$, $1-0.167*n$ and $1-0.770*n$, respectively for parallel, star and T configuration.

Fig. 13. WF Normalised 95th percentile THD combined cases with (a) 1300 MVA and (b) 2000 MVA external grid SC fault level (parallel configuration)

Finally, when the wake effect is considered, the calculated 95th percentile of THD for three different wind directions decreases by approximately 30%. Therefore, the aggregate WF harmonic injection can be determined by using a scaling factor of 0.7 to account for the wake effect, regardless of the wind direction. For star and T configuration, the normalised curves have roughly in the same trend as those shown in Fig. 13 for parallel configuration. A group of scaling factors, $K2$, accounting for the WT unavailability, and wake effect scaling factors for all three configurations are summarised in Table IV.

TABLE IV

SCALING FACTOR $K2$ REPRESENTING WT DISCONNECTIONS AND WAKE EFFECT

	String Disconnection	Row Disconnection	Diagonal Disconnection	Wake Effect
Parallel	$1-0.125*n$	$1-0.167*n$	$1-0.770*n$	0.70
Star	$1-0.167*n$	$1-0.333*n$	$1-0.050*n$	0.67
T	$1-0.500*n$	$1-0.042*n$	$1-0.040*n$	0.77

F. Effect of Non-ideal External Grid on WT Disconnection

In this case, the external grid harmonic voltage distortion has been considered and modelled in the case of parallel configuration with 1300 MVA and 2000 MVA SC fault level. The WT string disconnection cases are simulated to study the effect of the non-ideal grid on THD. The results are compared with the IEC 61000-3-6 standard in Fig. 14.

Fig. 14. WF 95th percentile values of THD for sting cases with ideal and non-ideal external grid (parallel)

It can be seen that the presence of harmonics in the external grid increases the THD values while reducing the rate of decrease in THD as more WTs are disconnected. Similar conclusions are obtained for star and T configurations. The worse cases are the cases with 1300 MVA SC fault level and non-ideal external grid together. The corresponding THD is 2.7%, which is within the THD limit (3%). Under the same SC fault level, the equivalent impedance of external grid (Z_2) is constant. Meanwhile the equivalent impedance of internal WF (Z_1) is also constant since the WT disconnection only affects the value of harmonic injection but not the structure of WF. Hence, according to equation (4), along with the absence of harmonic current injection (I_h) caused by WT unavailability, the values of each harmonic voltage on PCC bus (U_{PCC}^h) drop. Consequently, under the ideal external grid, the THD curve declines as more WTs are disconnected. However, according to equation (5), when the external grid is non-ideal, the harmonic current injection (I_h) contributes less and less to the U_{PCC}^h with more WTs unavailable, which in turn amplifies the influence of external grid harmonic voltage distortion (E_h) on U_{PCC}^h . Consequently, in a WF with non-ideal external grid, the THD at PCC bus remains at about 2% and is not affected by the disconnection of WTs.

The results of individual harmonic distortion for PC 0 are plotted and compared with the IEC 61000-3-6 Standard in Fig. 15. As discussed before, the 19th harmonic contributes the

Fig. 15. Individual harmonic distortion values for cases with ideal and non-ideal external grid (parallel)

most to the overall THD with ideal external grid. However, when considering the WF with non-ideal external grid, the

other harmonics contribute as well to the overall THD. In the cases with 1300 MVA SC fault level, the 19th harmonic presents a severe problem, due to the resonance, and the corresponding harmonic distortion at PCC exceeds the IEC Standard levels.

G. Wind Farm Configurations

Comparison of three considered WF configurations, connected to the PCC with 2000 MVA SC fault level, showed that the star configuration results in the lowest THD at PCC. It should be noted though that the star configuration may be more costly given the extra length of cables and switchgear required. There is clearly a trade-off between capital investment in WF design and potential cost of power quality mitigation.

H. Effects of Cable Disconnection

In this set of simulations, the cables are disconnected by switching off the circuit breaker. These scenarios represent cable disconnection either due to cable fault or maintenance. Once the cable is disabled from the WF, all the WTs located downstream would be excluded from the equivalent impedance. In the meantime, the harmonic current injection from the WTs located downstream would be zero. The simulation results of 95th percentile THD at PCC bus with 1300 MVA SC fault level (all configurations) and with 2000 MVA SC fault level (parallel) are shown in Fig. 16. As can be seen from the

Fig. 16. WF 95th percentile THD combined cases for parallel (a), star (b) and T (c) configuration with 1300 MVA SC fault level, and for parallel configuration with 2000 MVA SC fault level (d)

figure, the variations of THD curve are no longer linear in this case. For example, in the string disconnection cases for parallel configuration with 1300 MVA SC fault level, Case 0, Case 4 and Case 5 result in higher THD. According to the frequency scan (shown in Fig. 17), the resonant impedance of these cases are located near the characteristic harmonics, namely 19th, 23rd, and 25th respectively, where a large amount of harmonic current is injected from the WF, resulting in excessive THD at

PCC. The other cases with high THD are also consequence of the resonance. It should be noted that the equivalent impedance of the WF seen from PCC bus changes with the disconnection of cables. The more cables are disconnected, the larger equivalent impedance (Z_I) and the lower the amount of harmonic current (I_h) injected into the WF. According to equation (4), the harmonic voltage at PCC (U_{PCC}^h) no longer varies linearly. As a consequence, it is not easy to identify a general scaling factor representing the cable disconnection cases to model the entire WF as a single harmonic source. However, it can be noted that among all the frequency scans, the resonant frequency is always above 19th harmonic for parallel and star configuration and above 23rd harmonic for T configuration. Hence, it may be possible to deduce linear coefficients if only the lower harmonics (up to 17th) are considered.

Fig. 17. Frequency scan of string cable disconnection cases for parallel configuration with 1300 MVA SC fault level

Fig. 18 shows the 95th percentile THD with total and individual harmonic distortion values considering string cable disconnection cases for parallel configuration with 1300 MVA SC fault level. The THD curve is approximately a combination of the curves formed by specific resonant frequencies, in this case, the 19th, 23rd and 25th harmonic. Similar behaviour can be found for all the cable disconnection cases. This suggests that the non-linearity of the THD at PCC bus is mainly determined by the resonant frequencies, which could be 19th/23rd/25th harmonic for parallel and star configuration and 23rd/25th harmonic for T configuration.

Fig. 18. WF 95th percentile THD with total and individual harmonic distortion values considering string cable disconnection cases for parallel configuration with 1300 MVA SC fault level

Therefore, it is feasible (in this particular case) to study the influence of harmonics below 17th and above 19th on THD separately. Afterwards, in order to model the WF as a single probabilistic harmonic generator, a group of scaling factors could be developed by combining the linearity and non-linearity features of the THD caused by resonance. The identified resonant frequencies would clearly be different for different WFs and they should be determined on a case by case basis.

IV. CONCLUSION

The paper presented exploratory study to inform equivalent harmonic modelling of wind farm for large transmission system probabilistic harmonic propagation studies. Different plant configurations, wake effect, harmonic cancellation, individual generator availability, cable availability, external grid voltage distortion and short circuit fault level are considered. It is shown that the WF can be modelled, in a first approximation for exploratory studies, as a single probabilistic harmonic generator with appropriate scaling factors to account for different configurations and harmonic cancellation, and to represent WT disconnections and wake effect. The procedure and approach described in the paper can be used to develop (and validate) sufficiently accurate equivalent models of wind farms or equivalent models of other converter connected generation based plants, once appropriate sets of measurements (at PCC and individual harmonic sources) are available.

It is recognised that harmonic resonance may occur with the variation of external grid short circuit fault level for different configurations. The non-ideal external grid, however, does not affect the resonant frequency but only contributes to the total harmonic distortion at PCC bus. The importance of accounting for harmonic resonance and individual characteristic harmonics on the equivalent modelling of WF has been clearly established.

The equivalent models of WFs or other PE connected renewable energy sources (e.g., PV generation or large battery energy storage systems) could be used in large transmission system probabilistic harmonic propagation studies with a great efficiency and confidence to identify potential harmonic issues in the network. If those are identified then more detailed modelling of individual plant and network conditions is required for harmonic mitigation, however, in such cases the extent of network modelling can be substantially reduced.

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