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VALIDATION OF THE EQUIVALENT MODEL OF WIND FARM FOR PROBABILISTIC HARMONIC PROPAGATION STUDIES

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Abstract

This paper develops and validates an equivalent model of a wind farm for probabilistic harmonic propagation and mitigation studies in power electronics rich transmission or distribution networks. The methodology is based on Monte Carlo simulations and probabilistic distributions. Field measurements from a single wind turbine and PCC bus are used for the validation of the equivalent model. It is found out that the simulated results using developed model are in good agreement with the available field measurements. This equivalent model is therefore deemed to be suitable for the first level approximation of harmonic propagation and the identification of potential harmonic issues in the power electronics rich networks.

1 Introduction

Power systems are increasingly undergoing a transition towards the decarbonisation of electricity production through replacing the conventional thermal plants with large-scale renewable energy sources (RES) generation. Wind power is one of the fastest-growing renewable energy technologies. According to [1], electricity generated by wind farm (WF) is doubled between 2009 and 2013. In 2019, the 60.4 GW of new WF installations brought global cumulative wind power installed capacity to a new milestone of 651 GW, with strong continued growth foreseen across Asia, the Americas and Europe. Meanwhile, investment in wind energy globally has risen to USD 142.7 billion in 2019, compared to USD 97.8 billion in 2010 [2]. To achieve the Paris Climate Goals, the wind energy should generate more than one-third (35%) of total electricity needs, becoming the prominent generation source by 2050. This would imply increasing global average annual onshore WF investment by more than three-fold and offshore WF by more than five-fold over the remaining period to 2050 [3].

Considering that the WF connection to the network is mainly achieved by using non-linear power electronic (PE) devices, which are potential source of harmonic distortion, the studies of the effect of the PE based generation on harmonic levels in power systems have been gaining significant attention in recent years. The harmonic pollution could result in amplified voltage distortion, current distortion, additional power losses and overheating of electric equipment, etc., thus leading to severe financial losses. In order to accurately assess the harmonic propagation through the network, it would be ideal to be able to represent all network components in detail. However for many studies, the level of detail of wind farm model may be insufficient to perform detailed technical studies due to reasons such as constraints of software tools, unavailability of component datasheets, confidentiality of wind turbine (WT) data, very large size of WFs, etc. It is therefore a practical requirement to reduce the large wind farm model to a suitable equivalent to facilitate harmonic propagation studies. The traditional approach is to represent harmonic generation devices as ideal (constant) source. However, with the increasing penetration level of PE devices connecting at all voltage levels, it is necessary to represent the harmonic WF model more accurately considering not only harmonic source but also harmonic impedance of the device i.e., Norton/Thévenin equivalent circuit [4,5].

Moreover, in practical applications, due to spatial and temporal uncertainties associated with WF operation (e.g., different weather conditions, different topologies, wake effect) the probabilistic harmonic modelling method becomes more appropriate than the conventional deterministic approaches when considering harmonic propagation and mitigation studies in PE rich transmission networks [6].

A recent study [7] proposed procedure and approaches that can be adopted to develop sufficiently accurate equivalent models of WF (or other PE interfaced generation), i.e., a single probabilistic harmonic generator, for harmonic analysis using commercial software package for power system analysis. Against this background, this paper first proposes appropriate modelling ranges and distributions of the equivalent model parameters, according to simulation results and field measurements form single wind turbine generator (WTG), and then validates the equivalent model of the WF based on field measurements at the PCC bus.
2. Methodology

2.1 Modelling of Wind Farm
Software DigSILENT/ Power-Factory 2018 SP6 is utilised in this study for WF modelling and simulations. The wind plant model consists of 48 Doubly Fed Induction Generators (DFIG) each of 2 MVA rated power. The wind turbines (WT) are connected through individual step-up transformers in strings to a medium-voltage bus (33 kV) and then each string is connected to the point of common coupling (PCC) bus (138 kV). As one of the most popular topologies used in existing WFs, the parallel configuration (see Fig. 1) is adopted in this study for majority of the simulations [7]. In order to analysis the effect of different WF topologies, the star and T configurations [7] are also modelled for comparative harmonic assessment.

![Wind farm model](Image 1)

Fig. 1 Wind farm model

Considering the uncertainty of weather conditions, probabilistic Weibull distribution is utilized to model the wind speed variation throughout the year [8]. The power output of each WT is first generated in MATLAB as 500 random values (500 iterations), independently for each generator, and then assigned to the power output of individual WT in DigSILENT.

Cables are modelled as π equivalent. In order to account for the current generated from the downstream WTs in one string, the cross section of upstream cables is assumed to be larger. The distance between the collector bus and medium-voltage bus is set as 2 km, while that between individual WTs is 0.5 km. Since the skin effect also changes the harmonic load flow through the network, it is represented using (1) and (2) when modelling the impedance of cables (Zc) and transformers (Zt), respectively [9]. R, X and h in (1) and (2) refer to the resistance, reactance and harmonic order, respectively.

\[ Z_c(h) = \sqrt{h}R_c + jX_c \]  
\[ Z_t(h) = \sqrt{h}R_t + jhX_t \]

2.2 Modelling of Probabilistic Harmonic Source
Each generator in the WF is represented as Norton equivalent (i.e., independent harmonic current source in parallel with the admittance) as shown in Fig. 2. The parameters of the Norton equivalent harmonic source are harmonic current injection magnitude [\(i_h\)], harmonic current injection phase angle [\(\theta_h\)] and source impedance [\(Z_o\)].

In order to evaluate the importance of different parameters of the equivalent harmonic source, these parameters are set as either fixed values or random values within different ranges. The predefined ranges of harmonic injection magnitudes from 2nd to 25th order are determined by probabilistic distributions of documented harmonic performance of individual PE device involving different operating conditions or alternatively from simulation studies using appropriate device models. In this study, there are three types of harmonic current injection magnitudes, which are fixed mean value (represented as study case FI), randomly selected from the range between the minimum and maximum values (represented as RI), and randomly selected from the range between the minimum and mean values (represented as RI.2).

![Norton equivalent circuit](Image 2)

Fig. 2 Norton equivalent circuit

Several values/ranges of harmonic injection phase angles were considered, namely, fixed 0° (represented as study case FA), randomly selected from the range [0°,180°], [0°,90°], [90°,270°] and [0°, 360°], represented as study cases RA.1, RA.2, RA.3 and RA.4, respectively.

The resistance R and reactance X of source impedance are considered separately in this study. They are either both fixed values (represented as FZ.1-4 in study cases), both random values varying from 0 to infinity (9999 p.u.), represented as case RZ.1-6, or combined fixed R and random X (represented as study cases RZ.7-8). Apart from parallel configuration of WF, the star and T configurations (differentiated by letter P, S and T before the name of the case, respectively) are also considered to analyse the effect of Norton equation impedance.

The probabilistic harmonic propagation simulation approach is based on the Monte Carlo simulation technique where in each of 500 iterations, harmonic current injection (magnitude and angle) and impedance (R and X) of individual 48 wind generators are sampled randomly using uniform distributions within given ranges. Since the input and output data are random variables they are characterized by probability density functions (PDF) [10]. Therefore, the resulting total harmonic distortions (THD) at PCC bus are also presented and compared in the form of fitted PDFs.

3. Results

3.1 Effect of Harmonic Injection Phase Angle
Fig. 3 shows the fitted PDFs of THD at PCC bus for cases with the same fixed harmonic injection magnitude and same fixed impedance, but with various random angle injections. When the span of injected phase angle range is getting narrower, the mean value of THD increases. The cases with a phase angle span of 180° (Case FIRA.1FZ.4 and Case FIRA.3FZ.4) result in similar distribution of THD and thus, their PDF curves are overlapped. If the injected phase angle is randomly selected from a wider range from 0° to 360° (Case FIRA.4FZ.4), the
range of data distribution significantly reduces, and the mean value of THD also will significantly decrease (higher cancellation of harmonics). Thus, the harmonic angle range span of 360° is not recommended as it leads to unrealistically high harmonic attenuation.

Fig. 3 Fitted PDFs of THD at PCC bus for FIRAFZ cases

Results of the cases with random injection magnitude, fixed angle 0° and different fixed equivalent impedance values are shown in Fig. 4. Compared with all the cases in Fig. 3, Case RIFARZ.4 uses the same impedance, but different phase angle injection (fixed 0°). However, this case has the same distribution of THD as the case with 90° angle span and fixed injection magnitude (FIRA.2FZ.4) whose mean value is larger than the cases with 180° angle span. Hence, the angle range span of 90° and fixed value of the angle are not suitable for modelling harmonic phase angle as they do not account adequately for harmonic cancellation.

Fig. 4 Fitted PDFs of THD at PCC bus for RIFAFZ cases

Therefore, the PDFs which correspond to the case with harmonic angles varying randomly from 0° to 180° or any other range with a span of about 180° are recommended when modelling WTG harmonic injection using a Norton equivalent.

3.2 Effect of Norton Equivalent Impedance for Parallel Configuration

Fig. 4 also shows that the mean value of THD varies depending on the equivalent impedance. When the impedance is extremely large (Case RIFAFZ.2-4), corresponding fitted PDF curves overlap, with larger mean value and wider distribution. This can be explained by considering the equivalent circuit combining of internal and external grid p [11]. The harmonic distortion at PCC \(U_{\text{PCC}}\) can be calculated using (3). When the equivalent impedance of the external grid \(Z_2\) stays constant, a larger internal impedance \(Z_1\) will cause higher THD at PCC bus. Depending on the impedance value, the observed THD can vary in reasonably large range, i.e., an increase of up to 115% (\(\Delta= (0.0456−0.0983)/0.0456=115\%\)) in mean value is seen.

\[
U_{\text{PCC}}^2 = \frac{1}{Z_1 + Z_2} I_h
\]

(3)

Fig. 5 investigates how the 95th percentile THD at PCC bus varies with the increasing of only resistance R or only reactance X in Norton equivalent. It can be seen that the variation of R does not influence THD much, however the variation of X has significant impact on THD.

Fig. 5 95th percentile THD at PCC bus when vary R and X

Therefore, Fig. 6 compares the cases employing different ranges of both R and X (Case RIRA.1RZ.1-8). When the maximum boundary of impedance varies beyond 100 p.u., their corresponding PDF curves are roughly the same. If the range of R and X become smaller (less than 10 p.u.), their PDF curves move to the right with a larger mean value. It can be noticed that when modelling the Norton equivalent impedance as a range of values, there is less influence on THD at PCC, i.e., the mean value of THD varies only up to 28% (\(\Delta= (0.09−0.07)/0.07=28\%\)) compared to 115% when modelling the impedance as fixed value.

Fig. 6 Fitted PDFs of THD at PCC bus for RIRARZ cases

Therefore, for the purpose of probabilistic harmonic analysis with intention of capturing possible worst-case scenario of harmonic injection by the source, the values of R and X in Norton equivalent model should be both sampled randomly within a reasonably narrow range, for example (0, 1) p.u. for parallel WF.
3.3 Effect of Norton Equivalent Impedance for Different Configurations

For all three configurations, the corresponding fitted PDFs of THD at PCC are plotted in Fig. 7. Compared with modelling the harmonic impedance as random between (0, 9999) p.u., the random variation between (0, 1) p.u. results in higher mean value for both parallel and star configurations, i.e., an increase of about 28% ($\Delta = (0.09 - 0.07)/0.07 = 28.5\%$ for parallel and $\Delta = (0.1 - 0.078)/0.078 = 28.2\%$ for star configuration). However for T configuration, the random harmonic impedance variation between (0, 9999) p.u., results in relatively larger mean value and wider distribution, i.e., an increase of around 73% ($\Delta = (0.135 - 0.078)/0.078 = 73.1\%$). This is because of the resonance in case of parallel/star configurations that occurs at/around characteristic harmonic orders when the WTG impedance is modelled as random value between (0, 1) p.u.. For T configuration, however, there are many more WTGs connected to one string. If the WTG impedance is still randomly selected from a range less than 1 p.u., the resonance point moves to other harmonic orders (those with lower harmonic injections), thus, the distribution of THD is no longer concentrated on a large value anymore.

Therefore, for a WF with parallel/star configuration, the R and X in Norton equivalent model can be both sampled randomly within a range of (0, 1) p.u. However, for T configuration, the range of (0, 9999) p.u., or similarly large range, e.g., (0, 9999) p.u., is more suitable to capture possible worst-case scenario. Considering that the parallel configuration is mostly utilised in current industry practice, the range of (0, 1) p.u. is recommended in this study.

3.4 Effect of Harmonic Injection Magnitude

In the modelling of Norton equivalent harmonic injection magnitude (from 2nd to 25th orders) of each WTG, both fixed (mean values) and random values from different ranges are considered. Meanwhile, two different values of impedance are taken into account. Fig. 8 shows the fitted PDF curves of THD at PCC. It can be seen that there is very small variation in the mean value of THD. And it is also true for different types of impedance modelling methods. According to IEC 61400-21 [5], harmonic measurement provided by manufacturers are tested for a long period, which means it is more practical and convenient to use a magnitude range, instead of fixed mean value, to model the harmonic injection. Moreover, when modelling a WF with more than one type of WTGs, harmonic injection in ranges is useful for collecting measurements involving different WTGs’ operating conditions.

Therefore, the harmonic injection magnitude in Norton equivalent model of WTG is recommended to be sampled randomly within completely available range. In the absence of these measurements, however, the short-time data could also be used at the expense of the accuracy.

3.5 Combination of the Cases

If all the fitted PDF curves mentioned above are combined together, Case RIRA.1RZ.6 results in largest mean value of THD. Fitted curves of the cases with high impedance injection (more than 10 p.u.) are overlapped. Also, the cases with lower impedance injection (less than 10 p.u.) are overlapped and result in higher mean value. This highlights the importance of the harmonic impedance modelling for establishing the exact injection by the source, the nature of the behaviour of the source remains the same and the source can be represented as a single PDF of harmonic injections at PCC.

3.6 Distribution of Norton Equivalent Parameters

Field measurements of harmonic distortion (in both current and voltage) form a 3.2 MW wind turbine is tested according to standard IEC 61400-21 [5]. Among different types of distributions tested to represent the measurement data, the Normal distribution fit the histograms best.

Theoretically, if the WTG is modelled as a probabilistic harmonic source using Norton equivalent, the harmonic voltage distortion can be calculated through multiplying the equivalent impedance by harmonic current injection. Therefore, based on the recommended modelling method of Norton equivalent parameters discussed before, the harmonic voltage distortion is calculated in MATLAB using field measurements under following conditions. Harmonic current injection magnitude: Randomly sample 500 values following Normal and Burr distribution. From the field measurements of harmonic current distortion, their average value is considered as mean value (µ). Then the standard derivation (σ) is calculated by considering $\mu \pm 3\sigma$ confidence within measurement range (i.e. approximately 99.7% of the points.

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**Fig. 7** Fitted PDFs of THD at PCC bus for cases with different configurations

**Fig. 8** Fitted PDFs of THD at PCC bus for cases with different harmonic injection magnitude
from probability distribution within measurement range are captured in simulations). Harmonic current injection angle: Randomly sample 500 values from (0°, 180°), following uniform distribution. Equivalent impedance: Randomly sample 500 values of both R and X from (0, 1) p.u. following uniform distribution.

The harmonic voltage distortions calculated considering Normal and Burr distributed |Ih| are fitted and compared with field measurements. The corresponding mean value (μ) and standard derivation (σ) are shown in Table 1. It can be seen that the Normal distributed |Ih| results in much similar mean value to field measurements. Therefore, when modelling the harmonic injection magnitude of Norton equivalent, the Normal distribution is more suitable for probabilistic analysis.

Table 1 Comparison of Normal distribution parameters

<table>
<thead>
<tr>
<th></th>
<th>Field measurements</th>
<th>Normal</th>
<th>Burr</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ</td>
<td>1.721</td>
<td>1.712</td>
<td>1.602</td>
</tr>
<tr>
<td>σ</td>
<td>0.056</td>
<td>0.628</td>
<td>0.332</td>
</tr>
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3.7 Validation of WF Model

The filed measurements of THD at PCC of a parallel-configured WF are compared with the results obtained using the proposed Norton equivalent model. It is found that the 95th percentile of THD obtained by simulating the equivalent model is 1.05%, and that from the available measurements is 1.02%, which are approximately the same. Meanwhile, Fig. 9 compares the fitted Normal distribution of THD at PCC. It can be seen that their mean values (0.6 for field measurement and 0.56 for simulation results, i.e., error of 6.67%) and variance (0.04 for field measurement and 0.06 for simulation results) are also very similar. The errors are acceptable since there exists discrepancy of the network topology (e.g., wind generators separation, cable length, component type, weather condition etc.) between the practical wind plant and the WF model used in this study.

![Fig. 9 Normal distribution of field measurements and simulation results](image)

4 Conclusion

The analysis described above confirmed that for the purpose of global assessment of the effect of large penetration of PE connected WFs, i.e. harmonic sources, on harmonic performance of the transmission network, the WTG/WF can be modelled as a Norton equivalent with following parameters:

- Harmonic current injection magnitude: sampled randomly within the completely available range, following Normal distribution. The ranges of these harmonic distributions are most accurately determined by long-term measurements involving different operating conditions.
- Harmonic current injection angle: sampled randomly within the range of (0°, 180°), following uniform distribution.
- Harmonic impedance: sampled both resistance R and reactance X randomly within the range of (0, 1) p.u. for parallel/star configuration and within the wider range, e.g., (0, 100) p.u. or above, for T configuration, following uniform distribution.

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6 References