Application of Type 4 Wind Turbine Harmonic Model for Wind Power Plant Harmonic Study

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Abstract— **the application of a harmonic model representing Type 4 wind turbines for system-level studies of large wind power plants is presented in this paper. Based on detailed studies the challenges of harmonic modelling such as the sources of the harmonic emission and the resonances are identified. It is shown that wind power plant components such as the AC array power cables and the offshore transformers can introduce significant low-frequency resonances which can cause a significant harmonic distortion at the point of connection. Furthermore, a comparison of different harmonic models is presented showing the importance of careful modelling as well as validation. The studies are done using as an example the biggest Danish wind power plant – Anholt Offshore Wind Farm. Simulation results are compared with measurements showing that only validated models and data can be used for reliable and accurate prediction of harmonic behavior in such complex systems.**

Keywords-harmonic emission, model validation, wind power plant, wind turbine harmonic model

I. Introduction

As a consequence of the increasing grid connection requirements for Wind Power Plants (WPPs), especially for offshore WPPs, the Type 4 Wind Turbines (WTs) with full-scale power converters [1] are commonly deployed, due to the decoupled interaction between the generation side and the grid-connection side, and the excellent dynamic control response. The concern with regards to harmonic compliance has been increasing along with the increasing size of WPPs because grid-connected converters contribute to harmonic emission. In order to mitigate the risk of violating harmonic limits, a WPP harmonic study is often requested at an early stage to facilitate an appropriate electrical design of WPPs from both technical and economic perspective.

A. Harmonic Propagation Studies

Analysis of the harmonic distortion level at the Point of Common Coupling (PCC) or Point of Connection (POC) in a WPP not only requires an adequate WT harmonic model but also an appropriate harmonic propagation study methodology when there are multiple WTs in a WPP. An adequate WT harmonic model requires a few essential elements to precisely represent the WT harmonic emission and its interaction with the external electrical network considering the frequency-dependent converter impedance. This has been investigated and recommended in literatures and IEC standard [2], [3].

However common understanding of how the harmonics flow in a WPP and aggregate at PCC or POC when there are multiple WTs has not been reached due to general lack of knowledge of the converter-generated harmonics behavior. A common practice is to use the summation rule from the existing standards IEC 61000-3-6, which was developed for classical power systems, when power converters were still not widely employed in the power generation. It has been reported that in WPPs with WTs using full-scale power converters, the resulting harmonic levels at PCC or POC are generally overestimated when the above existing standard summation rules are applied. This could lead to overdesign of the WPP system and thereby unnecessary investments (e.g. harmonic filters). Therefore, there is a need to investigate harmonic characteristics of converter-based WTs in order to address adequate harmonic summation rules for WPP harmonic studies and to provide guidelines to the industry.

B. Paper Structure

The paper starts with presenting the Type 4 WT harmonic characteristics including the magnitude and phase angle variation of the harmonics as a function of power bins in Section II. Following that a Type 4 WT harmonic model is explained in Section III [2]. Following that in Section IV an actual study case and application of a proposed WT harmonic model is shown based on the 400 MW Anholt offshore WPP harmonic studies and the simulation results are validated against measurements. Furthermore, a detailed harmonic model and its application are compared to the typical practice of using the IEC ideal current approach. In Section V conclusions are drawn from comparisons with measurements and possible deviations are explained based on the presented understanding of harmonic characteristics and practical factors in measurements used. At the end practical considerations of conducting WPP harmonic studies are discussed and presented.

II. Type 4 Wind turbine Harmonic Characteristics

A. Basics of Studied Type 4 Wind Turbine

The studied wind turbine is a Type 4 WT with nominal active power 3.6 MW as shown in Figure 1. A full-scale back-to-back Voltage Source Converter (VSC) is employed to safely convert wind energy to electrical power meeting specified power quality requirements. A WT transformer is used to step up the voltage level from 690 V to 33 kV before it is connected to the power grid.

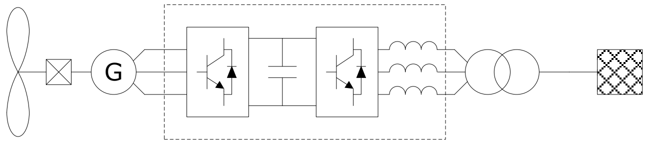

Figure 1. Schematic of studied Type 4 Wind Turbine.

According to IEC 61400-21:2008, the harmonic emissions shall be assessed during continuous operation with at least 10-minute measurement at each phase. Active power bins in the range from 0% to 100% are required to show the dependency of operating points on harmonic emissions whilst maintaining reactive power close to zero. The measurement points of WT voltages and currents are located at the LV side of the WT transformer. Additional measurements of current are made at the converter terminals, PWM filter terminal, and auxiliary supply terminal for supplementary assessment as shown in Figure 2.

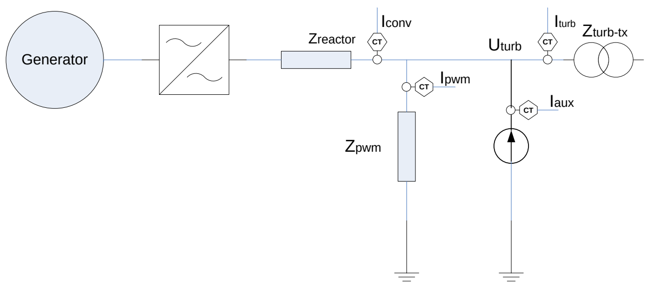

Figure 2. Diagram of measurement locations in Wind Turbine.

The measured voltages and currents are post-processed according to IEC 61000-4-7, which specifies that 10 consecutive cycles shall be used for the time window of frequency analysis in a 50 Hz power system. As a result 5 Hz-resolution harmonics are obtained with magnitude and phase, which are presented in the following.

B. *Active Power-Dependent Harmonics Spectrum*

WT voltage harmonics and current harmonics are presented as box plots[1]. To get a holistic picture the representative harmonics are carefully chosen to include non-multiples of 3 odd harmonics (i.e. the 5th, 7th, 17th), even harmonics (i.e. the 8th, 16th), multiples of 3 harmonics (i.e. the 9th) and switching related harmonics (i.e. the 47th, 48th, and 49th). The peak value of phase-to-ground harmonic voltage magnitudes are shown for power bins 0% to 100% while the harmonic current magnitudes are presented as the peak phase value. The phase angles are directly extracted from raw FFT results using a 200ms rectangular time window without any averaging. This is to avoid introducing a misleading picture by using averaging methods.

[1] Red line is mean value with 25 percentile and 75 percentile on lower and upper box boundary. Default whisker 1.5 is used with corresponding approximately +/- 2.7σ

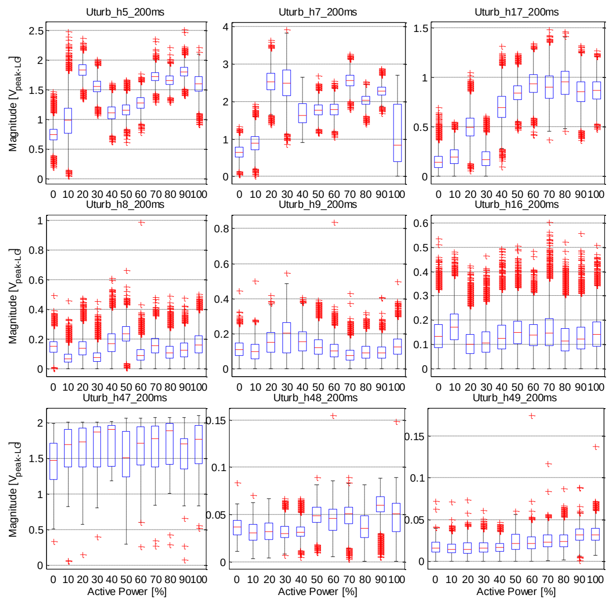

Figure 3. Selected harmonics magnitudes of Wind Turbine voltage in box plot.

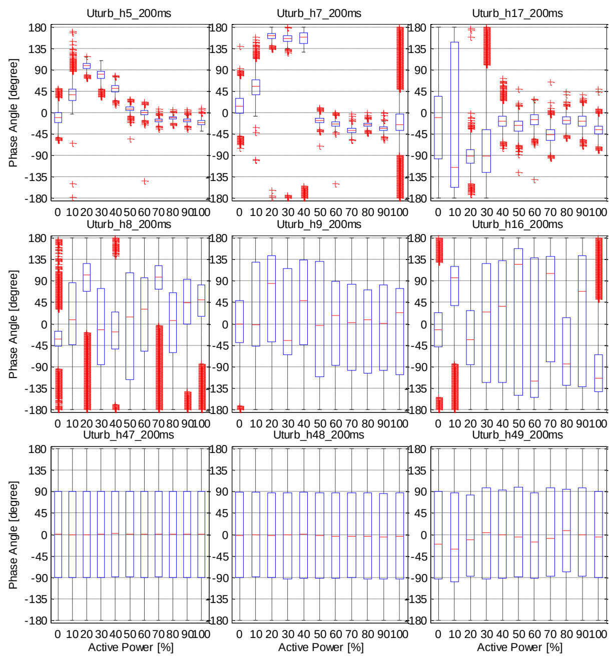

Figure 4. Selected harmonics phase angles of Wind Turbine voltage in box plot.

The harmonic magnitude has traditionally been addressed for harmonic compliance studies. But the distribution of phase angles of harmonics has not been given much attention in the literature yet, although the phase angles of harmonic is an important factor for aggregation studies with multiple WTs in WPPs. From Figure 3. and Figure 4. characteristic harmonics such as h5 and h7 remain the biggest contribution of total harmonic voltage distortion. The magnitudes of all harmonics are generally varying with active power production. But narrower variation of magnitude appear in each power bins for h5, h7 and h17 compared to other harmonics. The same observation can be made for the corresponding phase angles that are concentrated in a relatively narrow range compared to even or multiple of 3 harmonics. It can be seen that the non-multiple of 3 odd harmonics have a strong relation to the fundamental frequency as the phase angle is related to the power system fundamental frequency. On the other hand, magnitudes of h8, h9 and h16 are much lower with mean value under 0.2 V, and their phase angle distribution is much wider than for the non-multiple of 3 odd harmonics. It is even more interesting to look at the phase angle of the switching related harmonics h47, h48 and h49 that are uniformly distributed from -180 degree to +180 degree with mean value at ~ 0 degree. This is due to the fact that the PWM harmonics (i.e. power converter characteristic harmonics) are related to the converter carrier signal instead of the power system fundamental component. Furthermore, the PWM (i.e. carrier signal) fundamental component phases for each of the WTs are not linked between each other causing random angle displacement among WTs in the system.

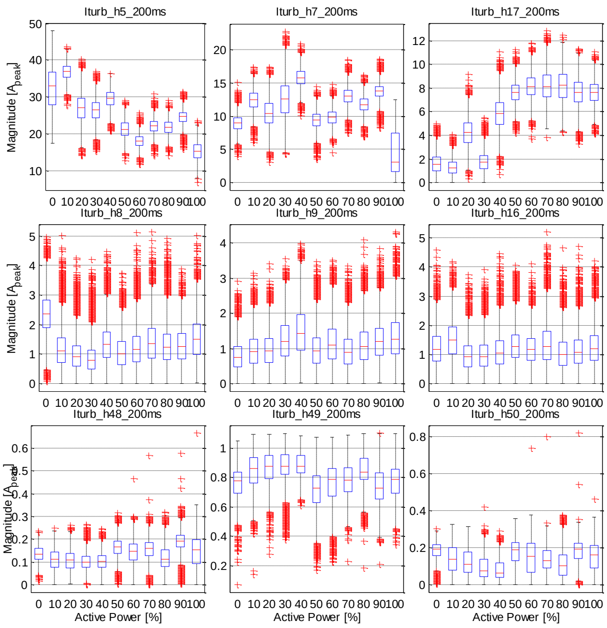

Figure 5. Selected harmonics magnitude of Wind Turbine current in box plot.

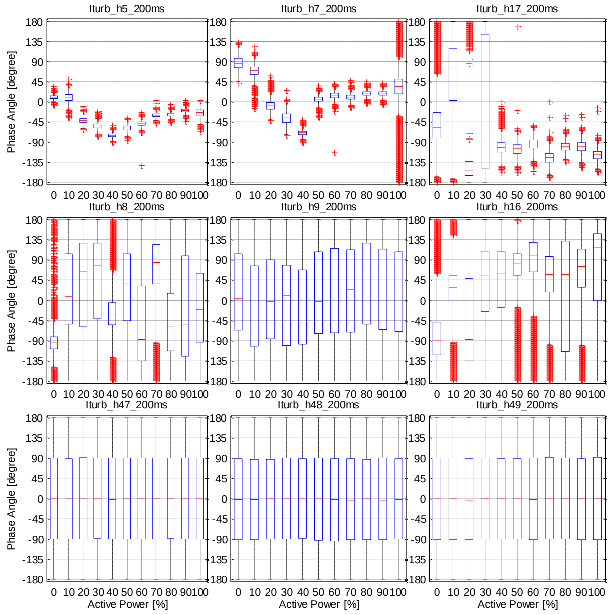

Figure 6. Selected harmonics phase angles of Wind Turbine current in box plot.

Similar conclusions can be drawn from WT current harmonics shown in Figure 5. and Figure 6. One thing to bear in mind is that the power grid to which the WT is connected typically have background harmonics, hence the mentioned WT voltage harmonics and current harmonics are actually combined results of emission from the WT and background harmonic sources. Therefore, harmonic models need to be able to decouple the harmonic contribution from the WT and from the background sources for the grid compliance study of WPPs, which will be introduced in the next section of the paper.

III. Wind Turbine Converter Harmonic Model

The WT Converter Harmonic Model (CHM) serves as a powerful simulation tool for stakeholders within the wind power industry such Transmission System Operator, WPP Developer, and WT Manufacturer, to conduct harmonic studies and evaluate grid code compliance of a WPP from the power quality perspective, especially during the design phase of the WPP. An IEC working group within Technical Committee (TC) 88 is working on a Technical Report (TR), which provides guidance for WT converter harmonic modelling and outlines the essential elements of a WT CHM, its structure and applications [4]. A detailed description of how to derive a Type 4 WT CHM has been proposed in [2]. The WT CHM is modelled as a series of Thévenin equivalent circuits at discrete harmonic frequencies and the effective impedance of the converter including the control system, which represents not only the harmonic emissions of the WT but also reflects interaction between WTs and background harmonics through the frequency-dependent converter harmonic impedances. One thing worth mentioning is that the converter harmonic impedances not only include physical components, such as the smoothing reactor, but also the effect of the converter closed loop control. The converter closed loop control actually has a big influence on the converter harmonic impedances and it should not be neglected. The difference with or without the control impact can be seen in Figure 7.

In Figure 7. that the impact of the converter control on the converter harmonic impedance is clearly visible in low frequency range, especially below 600 Hz, which is the typical range of the current control bandwidth. As the frequency increases, the converter harmonic impedance converges to the smoothing reactor impedance as the smoothing reactor dominates in the frequency range above the converter control bandwidth. The aggregation effect of multiple WTs in a WPP amplifies the deviation of converter harmonic impedance from the smoothing reactor within a single WT which can be even more pronounced at resonance frequencies. Hence, it is important to include the converter control impact in the converter harmonic impedance.

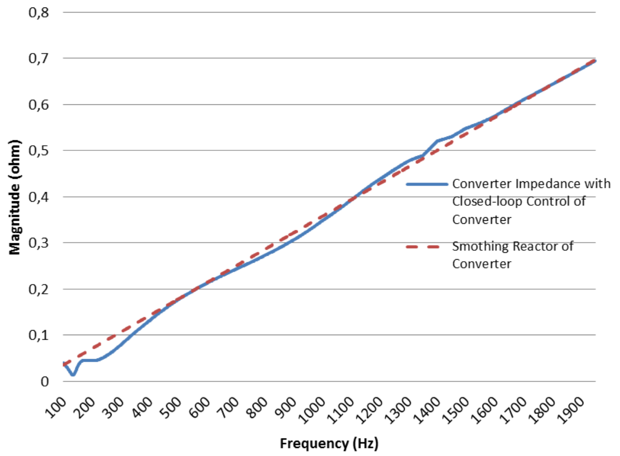

Figure 7. The difference between an example Wind Turbine converter harmonic impedance and the smoothing/series reactor.

Besides converter harmonic impedances, WT voltage and converter current measurements are additionally needed for calculation of the voltages for the converter harmonic model. They can be directly measured in a laboratory or on an operating WT.

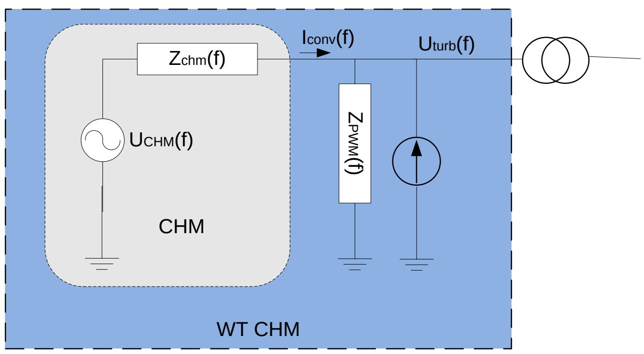

Figure 8. Deriviation of Converter Harmonic Voltage Sources.

According to the below equation the converter harmonic voltages *Uchm* are obtained at individual frequencies.

$$Uchm(f)=Uturb(f)+Iconv(f)*Zchm(f)$$

The converter harmonic voltages *Uchm* are now obtained to represent harmonic sources of WT converter excluding the impact from the grid background harmonics. The CHM for a Type 4 WT is constructed as series of Thévenin equivalent circuits, which consist of both harmonic voltage sources Uchm, and harmonic impedances *Zchm*, and the elements representing the other electrical components inside of the WT. The WT CHM formed can be used directly for complete WPP harmonic propagation studies.

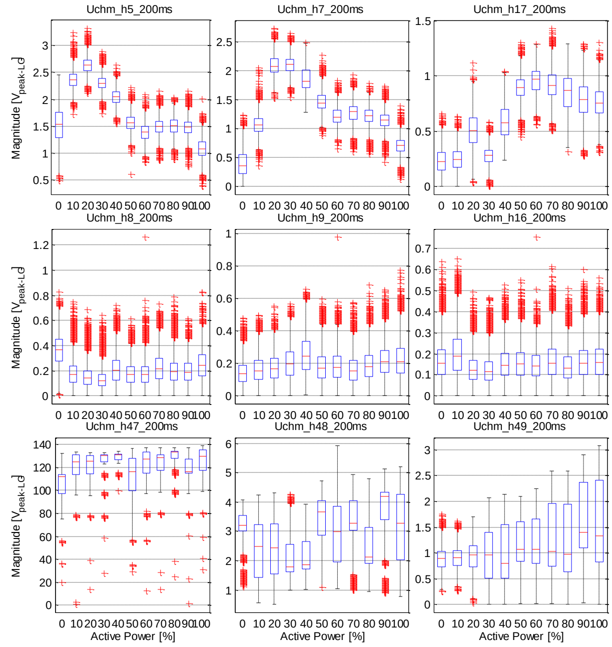

Figure 9. Selected magnitudes of converter harmonic voltage sources in box plot.

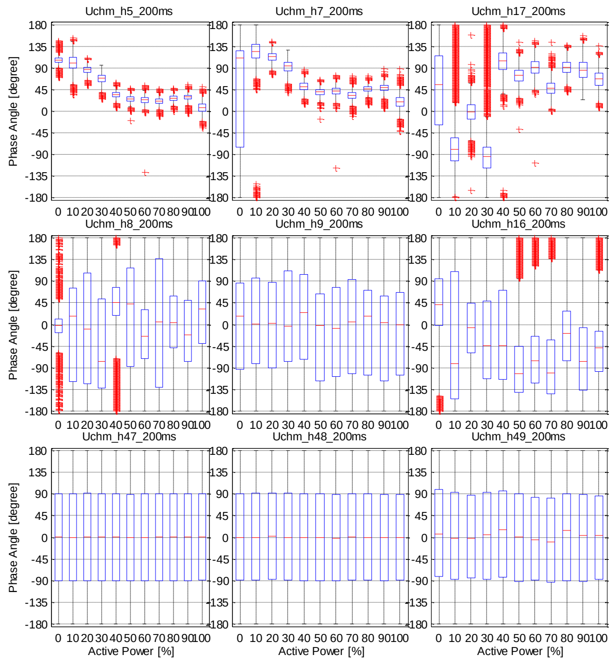

Figure 10. Selected phase angles for converter harmonics voltage sources in box plot.

In Figure 9. and Figure 10. *Uchm* are plotted for each power bin. Non-multiples of 3 odd harmonics h5, h7 and h17 show quite determined phase angles while odd or multiples of 3 harmonics are rather scattered. Outstanding h47 with mean value of over 100 V is caused by the converter switching pattern. Therefore, PWM filters are designed to suppress switching-related harmonics at the LV busbar. Thus h48, as presented in Figure 3. , is of low value in the WT voltage *Uturb* measured at the LV side of the WT transformer. The distinctive distribution of phase angles at individual harmonics provides the evidence that different harmonics should be carefully treated in aggregation calculations when a WPP harmonic propagation study is conducted. This will be discussed in the next section of the paper.

IV. Harmonic Studies on Anholt Offshore Wind Power Plant

It was decided to investigate and compare different types of harmonic models on the Anholt Offshore WPP [5]. The whole series of system-level studies was done and is presented in this paper. Having trustworthy and accurate power quality measurements acquired at POC gives a unique opportunity to compare with simulation results and evaluate the accuracy of harmonic models representing Type 4 WTs behavior.

A. Introduction to Anholt Offshore Wind Power Plant

Anholt Offshore WPP is located in Denmark approximately 21 km of the eastern coast of Jutland. The installed capacity of the WPP is 400MW, with 111 SWT-3.6-120 WTs [6], which together with the array cables were installed by DONG Energy Wind Power. The 111 WTs are equipped with a full-load converter. The export AC system, including the offshore substation, is designed and constructed by the Danish TSO, Energinet.dk. There are three 140 MVA main transformers on the offshore substation, each connected to a group of 37 WTs. The POC is defined on the LV-side of each of the main offshore transformers (i.e. MV level) as illustrated in Figure 11. The 220 kV export system consists of one 24.5-km aluminium 3x1600 mm^2 submarine and one 58-km aluminium 3x1x2000 mm^2 underground cable with 120 MVAr reactor compensation placed in-between and it is connected to the 400 kV grid at the onshore substation via two 450 MVA autotransformers. Furthermore, 4x60 MVAr shunt reactor compensation is also installed in the onshore substation as presented in Figure 11. [7].

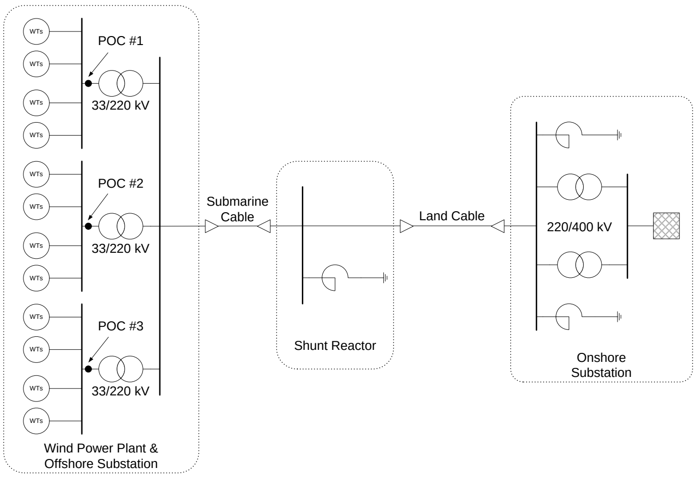

Figure 11. Single line diagram with the main electrical components of Anholt Offshore Wind Power Plant.

150 mm^2, 240 mm^2 and 500 mm^2 copper cables are used in the MV array cable system to connect the WTs to the offshore substation.

Table 1 MV array cable network

Connected to	WTs	Arrays	Total length of array cables	Total capacitance of array cables
POC #1	37	4	50km	14μF
POC #2	37	4	48km	13μF
POC #3	37	4	54km	15μF

B. Frequecy Sweep

In order to define possible resonance within the electrical system under consideration the frequency sweep method is very useful. Combined with harmonic propagation studies is a powerful way of performing harmonic studies and gives a good overview of the system behavior from a harmonic perspective. Commercial tools were used to calculate the impedance frequency sweeps.

The layout of the WPP is not uniform; this leads to a different total length of the array cables of each of the WT groups (Table 1). Since the resonance at POC is mainly caused by the array cables and the offshore main transformers, the difference in length of the array cables also has an impact. The results presented in Figure 12. and Figure 13. is obtained for one specific external grid frequency-dependent characteristic with the WPP in normal operation.

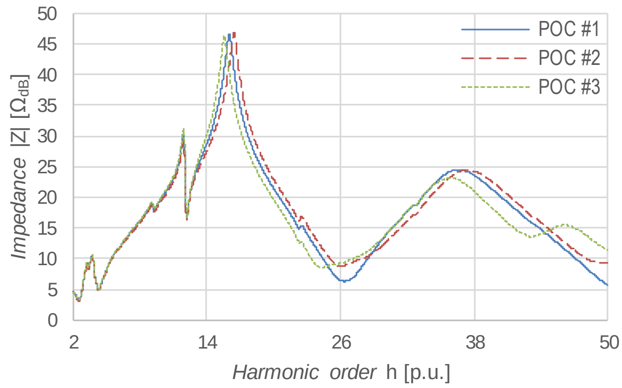

Figure 12. Impedance plots from POC #1, #2 and #3 (2nd – 50th harmonic order).

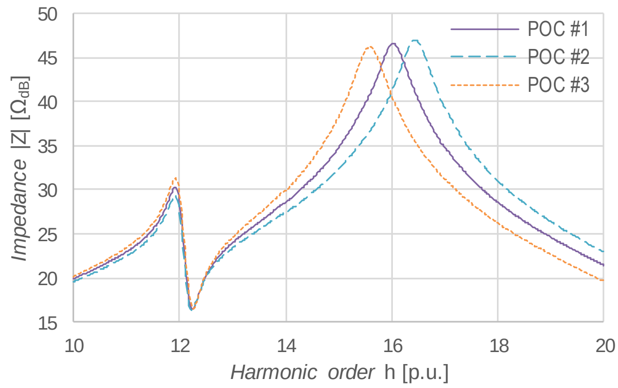

Figure 13. Impedance plots from POC #1, #2 and #3 (10th – 20th harmonic order).

In Figure 13. it can be clearly seen that depending on the offshore electrical infrastructure the resonance frequencies can shift. Keeping in mind that all offshore transformers are identical this is mainly caused by the total equivalent array cable capacitance which is dependent on the MV cable length imposed by the WT physical locations.

The frequency sweeps add useful information to the impedance profile for Anholt Offshore WPP, subject to modelling uncertainties. This allows for a more qualified interpretation of the harmonic propagation studies and also constitutes a useful input to the control stability studies [7] [8].

C. Harmonic Propagation Studies

The harmonic emission level of POC in the Anholt offshore WPP needs to be evaluated with regards to grid code compliance. Besides the impedance frequency sweep shown above, two different WT harmonic models and approaches are used for comparison.

The first one is using the Ideal Current source Model (ICM) of WT where the harmonic current values are extracted from the power quality report of the WT according to IEC 61400-21. The ideal current source is directly connected to the WT transformer before multiple WTs are joined together via array cables. The aggregation calculation of harmonics at POC is made employing the second summation law of IEC61000-3-6 due to lack of information of phase angles. This is currently a widely-used practice in the industry.

The second approach is to use the WT CHM presented above for the Type 4 WT. Each WT is modelled separately within the WPP electrical infrastructure to make sure to get the best replication of the actual WPP system. Therefore, the appropriate phase angle distribution needs to be taken into consideration when the relative phase angles are set in multiple WTs. Based on the presentation of harmonics magnitude and phase angle distribution in Section II, it is of importance that the phase angles of harmonics in each WT CHM should be treated differently in the WPP harmonic propagation study. All non-multiples of 3 odd harmonics are set to have the same phase angle because of their strong link to the power system fundamental frequency. Due to the large variation of phase angles for multiples of 3 and even harmonics, harmonics are likely to be cancelling out to some extent at POC. Therefore the phase angles from individual WTs are generated by a random function to represent the behavior seen from the measurements.

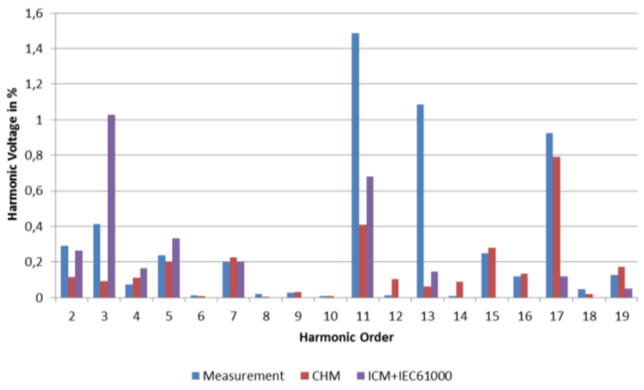

Figure 14. Harmonic results comparison between Converter Harmonic Model, Ideal Current Model and measurement at POC #2.

Since any current harmonic lower than 0.1% is disregarded in the power quality report, not all harmonics are present in the ICM approach. The ICM approach shows over-estimated harmonics at h3, h4 and h5, particularly at h3, which could cause unnecessary investment in filters.

Another outstanding observation is that ICM fails to predict high h17 harmonics while CHM is able to match the measurement within a tolerance of 10%. Considering the impedance frequency sweep shown in Figure 13. it appears that the extraordinary voltage harmonics of h17 is due to the resonance, formed between WPP and offshore transformer. The resonance at h17 is missed with the ICM approach as the ICM is modelled without the converter harmonic impedances. This demonstrates the importance of employing a harmonic model with correct converter harmonic impedance representation to replicate the resonance points in harmonic propagation studies.

High h11 and h13 harmonics are present in measurement but not even close in the simulation results. It has been found out that this it is because of background harmonics. 10-minute averaging of h11, h13 and h17 from measurement are shown given by percentage of voltages in Figure 15. The active power-dependent h17 in green is clear evidence of emission from WPP. But the randomness of h11 and h13 indicates that the harmonic sources are in the external grid, which explains the deviation of simulations results from measurement. In the studies the external network harmonic contribution was not modelled and therefore it was not possible to represent the behavior of harmonics from the grid such as h3, h11 or h13.

Furthermore, it can be clearly seen from Figure 10. that the h16 phase is very random for every active power bin. Therefore random distribution of such harmonics in the WT harmonic model can allow more precise harmonic distortion level estimation at the busbar of interest. In Figure 14. it can be seen that applying the harmonic random angle distribution for h16 allows quite accurately estimation of the system behavior given by the measurements. This is especially important for the resonance points which in this case are around the 16th harmonic (see Figure 13.). Assuming fixed angle or even using the IEC 61000-3-6 summation formula would lead to h16 overestimation.

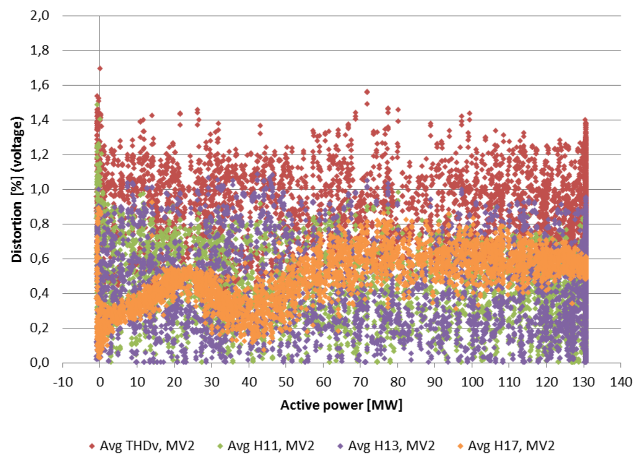

Figure 15. The measurements of h11, h13 and h17 at POC #2showing the dependency (or lack of dependency) on Wind Power Plant active power production.

In a summary the CHM approach gives a much better match to measurement compared to ICM. With the CHM approach the resonances can be precisely captured because of the representation of the converter harmonic impedance included in the model while ICM does not. Background harmonics can play an important role as seen in the Anholt offshore WPP case for h11, h13 which adds to the difficulty of getting aligning between the simulations and measurements. Therefore in this study case the simulation results need to be carefully interpreted as only representing the harmonic emissions from WPP, excluding any background harmonics.

V. Conclusions

Type 4 WT harmonic characteristics have been presented and discussed in the paper. The time-varying characteristics of phase angle for each harmonic poses difficulties to harmonic propagation studies for a WPP, where the relative phase angles among WTs cannot be completely determined based on WT operational status. However the distribution of phase angles with time varying at individual harmonics offers useful information to distinguish the way of conducting calculation from harmonic order to harmonic order. A Type 4 WT harmonic model is explained and essential elements of the model are presented. It was pointed out that converter closed-loop control shall be included in the calculation of the equivalent converter harmonic impedance especially within the bandwidth of converter controller. A real project Anholt offshore WPP is used for comparison studies, where CHM and ICM approaches are compared and validated against measurement results. The conclusion is that the ICM approach generally overestimates low order harmonics and has a risk of missing resonances prediction because the converter harmonic impedances are not considered. Furthermore, the higher order harmonics using a combination of ICM and IEC 61000-3-6 summation formula can lead to underestimation if assuming too pronounced harmonic cancellation. The proposed CHM for Type 4 WT is shown to give a much better prediction of harmonics at POC. The resonances are well replicated and the amplified h17 is successfully predicted in the study. The offset of the phase angle among WT harmonic models in a WPP are categorized based on the distribution characteristics of phase angles. The impedance frequency sweep offers an overview of studied network impedance characteristics.

Acknowledgment

The authors would like to express their appreciation to Troels Stybe Sørensen from DONG Energy Wind Power for the valuable feedback.

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