Analysis of Harmonic Behaviour in Wind Power Plants Based on Harmonic Phase Modelling and Measurements

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***Abstract*—This article aims to examine the harmonic emission assessment methods in the application of high-power converter-based wind power plants, where the harmonic amplitude and phase are considered. The IEC 61000-3-6 summation rule could lead to incorrect results due to the assumptions made with respect to the harmonic phase and assumptions from conventional power system harmonics. It has been shown in this paper that the amplitude and phase of low-order odd voltage harmonics (converter generated) dependents on the wind turbine operating point and the thereby phase of the fundamental component of current. Harmonic emission assessment for grid code compliance should be more accurate and the harmonic phase and wind turbine operating point needs to be considered. This paper presents sophisticated phase-aligned measurement results using GPS-disciplined time-base.**

***Keywords*— Background harmonic distortion, Grid code compliance, Harmonic modelling, Harmonic phase modelling Harmonic summation.**

I. Introduction

Nowadays, the number of wind turbines (WTs) in offshore wind power plants (WPPs) is growing. Furthermore, the complexity of offshore electrical infrastructure is also increasing. This potentially creates challenges in relation to harmonic generation from WTs, propagating through resonance circuits and distortion at the point of common coupling (PCC) [1], [2], [3]. Therefore, the assessment of harmonic disturbance from offshore WPPs is becoming an important task.

The estimation of harmonic current and voltage levels at the PCC is typically performed in harmonic studies. This requires detailed and accurate modelling of each WPP component such as cables, transformers, converters. The studies are done to assess the level of harmonic distortion for compliance with harmonic limits imposed by grid operators at PCC, and to assess the harmonic distortion to ensure harmonic compatibility within the WPP electrical infrastructure. Therefore, it is important to assess the harmonic emission as accurately as possible to avoid harmonic underestimation leading to power quality and grid code compliance issues as well as harmonic overestimation leading to unnecessary filtering and capital expenditure.

Typically, the harmonic assessment is performed based on the general summation rule given in IEC 61000-3-6 [4], where assumptions are made about the phase through a summation factor. However, the actual harmonic phase of the individual harmonic is not considered in the standard, which is necessary for accurate assessment of the harmonic level at the PCC. Particularly, when several WTs are connected in parallel to the PCC, the harmonic phase information indicate whether the resulting harmonic contribution may add or cancel. Harmonic summation considering the harmonic phase is discussed in [5], [6]. The pre-calculation of the harmonic emission summation is based on the summation law given in IEC-61000-3-6 for both voltage and current. The summation law can be described with the following equation:

$$\mathrm{U}_{\sum h} = \sqrt[\alpha]{\sum_{i=1}^{N_{WT}} {U_{h,i}}^{\alpha}} \qquad (1)$$

$$\alpha = \begin{cases} 1;\ if\ h\ <\ 5\ arithmetic\ summation\ terminology \\ 1.4;\ if\ 5\ \le\ h\ \le\ 10\ relaxed\ vectorial\ summation\ terminology \\ 2;\ if\ h\ >\ 10\ orthogonal\ summation\ terminology \end{cases}$$

Where:

- U_h is the amplitude of the resulting harmonic voltage for the h^{th} order harmonic, the value refer to 95 % quantile non-exceeding probability value.
- $\mathrm{U}_{h,i}$ is the amplitude of the individual harmonic voltage for the h^{th} order harmonic, the value refer to 95 % quantile non-exceeding probability value.
- α is called the summation factor coefficient for the h^{th} order harmonic.

Typically, the WPP harmonic performance evaluation is done by measurements procedures as recommended in IEC 61000-21 [7], 61000-4-7 [8] and 61000-4-30 [9]. The harmonic evaluation checks WPP compliance with the grid code and / or IEC 61000-3-6 [4] with respect to the harmonic planning or compatibility limits. Therefore, it is important that accurate guidelines to estimate the harmonic emission level in WPPs as well as transmission systems are developed. These guidelines and their outcome could have a great impact on the decision making during the design process, by indicating whether filtering is needed or not, in order to improve the design of the WPP.

The state-of-the-art knowledge about the harmonic phase of harmonic emission from WTs is quite limited. Therefore, extensive phase-aligned measurements using GPS-disciplined time-base were done at Avedøre Holme offshore wind power plant (AHOWPP) in Denmark. This creates a foundation for investigating harmonic summation considering the harmonic phase information when modelling WPPs. The sampling rate of 44.1 kHz and precise GPS synchronization of the presented one-minute dataset is the first of its kind presented in the literature.

This paper presents the state-of-the-art results and a review of the harmonic behaviour considering Type-4 WTs. The harmonic emission phase data from the GPS-synchronized measurements are utilized to analysis the harmonic behaviour in wind power plants based on harmonic phase. Finally, the paper suggests an alternative approach for harmonics procedures to further improve the IEC summation method.

II. Measurement Campaign at Avedøre Holme Offshore Wind Power Plant

A measurement campaign was performed on AHOWPP and extensive phase-aligned measurements using GPS-disciplined time-base were done, which is the foundation for this study.

A. *System Description*

AHOWPP is located in the south of Copenhagen, Denmark, and consists of three identical 3.6 MW Type-4 full-scale converter (FSC) WTs (yielding 10.8 MW) located less than 10 metres from the shore, as shown in Figure 1, which allows access to the offshore WTs by means of a footbridge [1], it has to be noted that AHOWPP is classified as an offshore WPP.

Fig. 1: AHOWPP location in Denmark from [1].

Each of the three WTs has a Dyn11 step-up transformer 0.69/10 kV for connection to the grid. The WT transformer is connected by means of a circuit breaker to the medium voltage (MV) array cable system (240 mm^2 10kV aluminium cables). The 10 kV array cable system has a combined length as presented in Table 1.

TABLE 1: AHOWPP array cables details

WTs	Array cable length [km]	Array cable impedance [Ω]	Array cables capacitance [μF]
(M1)	2.31	0.361-j0.17	1.23
(M2)	2	0.312-j0.15	1.06
(M3)	1.4	0.218-j0.11	0.74

It should be noted that the array cable system layout is non-uniform leading to differences in the length of the MV cables connected to PCC as presented in Table 1. The installed off-shore WTs are fortunately around 300-600 metres from each other, leading to almost the same active power production disregarding the wake effect, thus, no different power bins considering the wake effect are needed in the studies. A simplified diagram of AHOWPP is shown in Figure 2. The specification of the system is shown below:

- 50 kV AC grid voltage
- 0.69 kV WT rated voltage
- 10 kV AC array cable voltage
- Three 3.6 MW WTs

B. *Measurement System Setup*

The voltages and currents were measured at several measurement points in AHOWPP as presented in Figure 2. The low voltage (LV) probes were installed at the WT transformer LV-side terminals and the current through the converter inductance were measured using Rogowki coils installed after the converter reactor according to Figure 2. For brevity the pulse width modulation (PWM) filters and cables have been omitted from Figure 2.

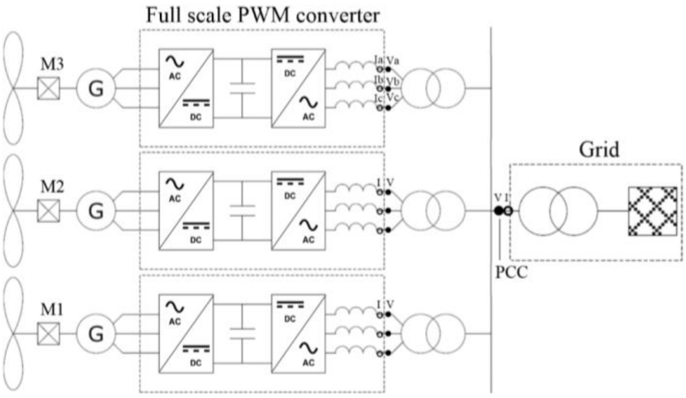

Fig. 2: AHOWPP installed measurement point locations.

All the measurement systems are synchronized by the disciplined clock and digital trigger using GPS-synchronized phase-aligned time-base, which means the number of samples for both the voltages and currents will be exactly the same for all measurement locations in the three WTs and at the PCC [10], [11]. The measurement system GPS-synchronization and accuracy considerations are elaborated in [12]. A more detailed explanation of the measurement system measurement software and GPS-synchronization system can be found in [10]. The measurement accuracy and precision are described in [12]. The employed harmonic data processing algorithm applied for the measured data was based on [4] and [7] are summarized in [12].

III. Results from Avedøre Holme wind farm

The measurement procedure given in IEC 61000-21 [7] recommends zero reactive power injection during the power quality (PQ) assessment of WTs. The measurement campaign was conducted throughout year 2012, where the AHOWPP was operating normally including reactive power injection as well. This is a challenge for harmonic evaluation of AHOWPP that makes the study more complex. However, the obtained measurements can still be considered as sufficient for the validation of the harmonic behaviour, which will be elaborately described in the following section.

A. Harmonic Measurement Results

The selected aggregation interval of the harmonic spectrum study is 10 cycles. The output active power production from all three WTs during one minute of measurements is calculated according to [8] and can be considered as constant 30% of nominal power. However, Figure 3 shows that the reactive power variation is different for the three WTs. The presented active and reactive power during one minute of measurements will be used for the analysis of harmonic behaviour in the WPP.

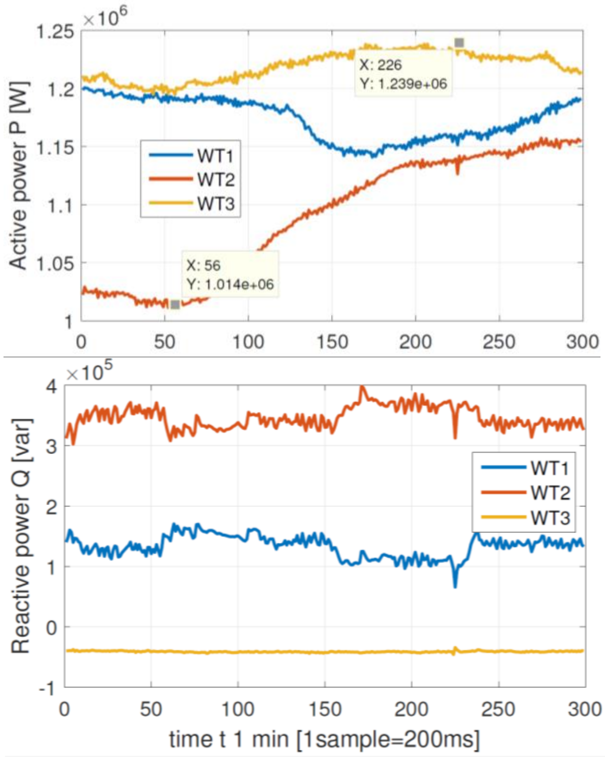

Fig. 3: The reactive power injection for all three WTs during 1 minute of operation, when PWM synchronizations feature is enabled and the active power operating point is approximately 30%.

Moreover, a converter PWM synchronization feature is activated for all three WTs during the measurements [13], which allows the carrier signals in wind turbines to be shifted with respect to each other by synchronizing to the fundamental voltage component. This allows more accurate estimation of PWM (sideband, carrier group) harmonics as the power system fundamental component phase is linked with the carrier signal in the PWM scheme, i.e. the switching frequency is synchronized to the grid frequency. Therefore, it is expected that the displacement angle is fixed 120◦ for the sideband harmonic from all three corresponding WTs [14].

B. Prevailing Angle Ratio

The prevailing angle ratio (PAR) can be employed for aggregation and summation of harmonic phasors. Aggregation (as in IEC 61400-21) in this context means data processing to obtain a combined representation of a number of harmonic components from 10-cycle DFT into one value for a longer period (e.g. 10 second, 1 minute) and summation (as in IEC 61000-3-6) means the total impact of all harmonic sources at a busbar of interest in the power system (e.g. harmonic distortion at the PCC). The harmonic phase information and behaviour can be retained by the aggregation of harmonic phasors based on the prevailing angle. Hence, only the PAR is used to estimate the randomness of the prevailing angle. The PAR can be determined based on:

$$\mathrm{PAR} = \frac{\left|\sum_{i=1}^{n} C_{h,i}\right|}{\sum_{i=1}^{n}\left|C_{h,i}\right|} = \frac{\left|\sum_{i=1}^{n} a_{h,i}+jb_{h,i}\right|}{\sum_{i=1}^{n}\left|a_{h,i}+jb_{h,i}\right|} \qquad (2)$$

where $C_{h,i}$ is the harmonic component complex phasor, $a_{h,i}$ and $b_{h,i}$ represent the real and imaginary part of the i^{th} window, respectively.

Generally, a PAR result higher than 0.5 indicates a higher degree of deterministic behaviour of the harmonic phase according to [7], whereas a PAR result less than 0.2 indicates a degree of variability resulting in random characteristic of the harmonic phase. This can be used to identify, classify and verify whether the measured data is trustworthy or not.

The current harmonic spectrum plot is presented in Figure 4 (top) and PAR (bottom). It can be clearly seen that the low-order harmonics with relative high amplitude have PAR > 0.6 as shown by the dotted line in Figure 6 (bottom). On the contrary, PAR < 0.6 is mainly related to the converter generated high-frequency harmonics due to the PWM scheme. The PAR for switching harmonics is in general low as shifting with respect to the rectangular window being synchronized to the fundamental frequency. However, for carrier phase interleaving between WTs could fix the phase offset and assure deterministic (rather than stochastic) cancellation [14].

The observations with respect to the voltage are presented in Figure 7. By comparing Figure 6 and 7 (bottom) it can be seen that the number of harmonics with PAR > 0.6 for higher orders is decreasing due to the measurement accuracy [12].

The voltage and current harmonic spectrum plots show that the low values of PAR < 0.6 is related to the very low harmonics amplitude, especially for non-characteristic power system harmonics (e.g. 6^{th}, 8^{th}) and higher-frequency harmonics disregarding the harmonics emissions up to the 5^{th} harmonic order due to the relatively low measurement accuracy for very low harmonic amplitudes. On the contrary, the lower-frequency harmonics have high values of PAR, particularly the power system characteristic harmonics (e.g. 5^{th}, 7^{th}).

Moreover, the PAR can provide some information about the harmonic phase behaviour [14], in order to improve the understanding of the harmonic emission in WPPs. However, it is worth mentioning that non-ideal converter behaviour caused by e.g. dead-time [2], [15], semiconductor voltage drop [16] and background harmonic distortion [17] may influence the harmonic phase and make the analysis more complicated in relation to the harmonic phase characteristic due to the large variety of technologies (PWM switching pattern, dead-time, control schemes, etc.).

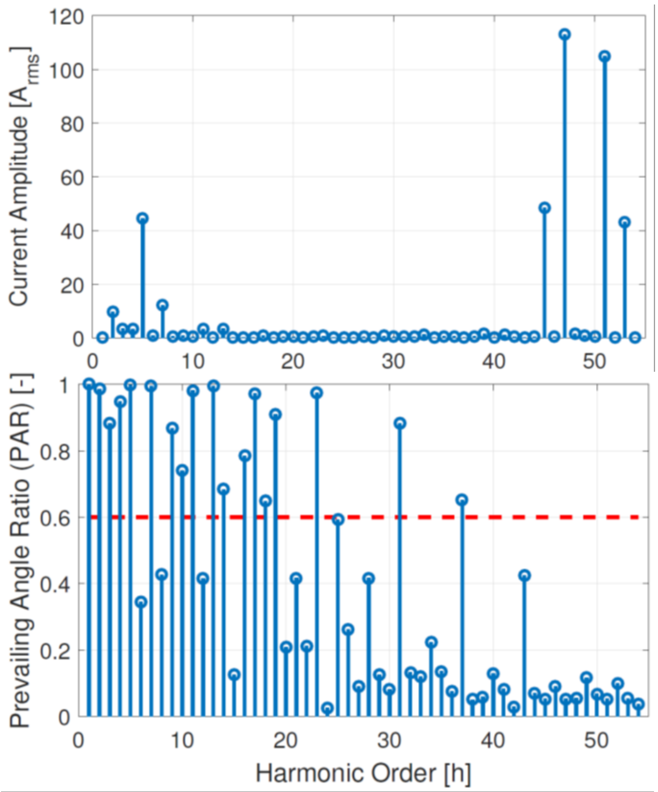

Fig. 4: Current harmonic spectrum for WT 1 (M1) (top) and the respective PAR (bottom) for 1-min period when the carrier signal synchronization feature is enabled

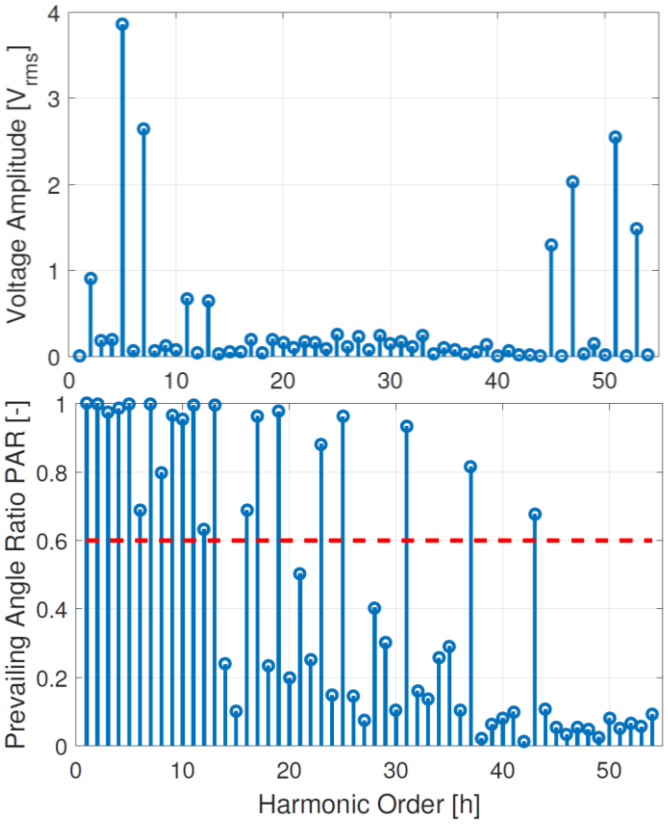

Fig. 5: Voltage harmonic spectrum for WT 1 (M1) (top) and PAR (bottom) for 1-min period when the carrier signal synchronization feature is enabled.

Harmonic emission assessment based on the IEC 61000-3-6 summation rule, where only the harmonic amplitude is known can lead to incorrect results since assumptions are made about the harmonic phase based on choosing a summation factor [18]. It is shown in [12] that this assumption cannot be used and can lead to incorrect harmonic emission assessment with respect to the IEC planning / compatibility levels and grid code compliance. The PAR reflecting the harmonic phase behaviour, which can be used to simplify the harmonics summation approach by simply dividing the harmonics into two groups: (i) those which tend to have a deterministic phase and (ii) those which tend to have stochastic phase characteristic.

IV. Evaluation of the Harmonic Behaviour

Again, it should be noted that only the harmonics with relative high amplitude will be considered in the following, due to the measurement accuracy.

The current (top) and voltage spectrum from WT1 (M1) measured at the transformer LV-side are shown in Figure 4 and 5, respectively.

The low-order even and triplen harmonics phase behaviour tend to have uniform phase distribution from 0 to 2π according to the observations given in [2] and [16]. As an example of a low-order even harmonic characteristic the phase for the 2nd order harmonic for the three turbines are shown in Figure 6.

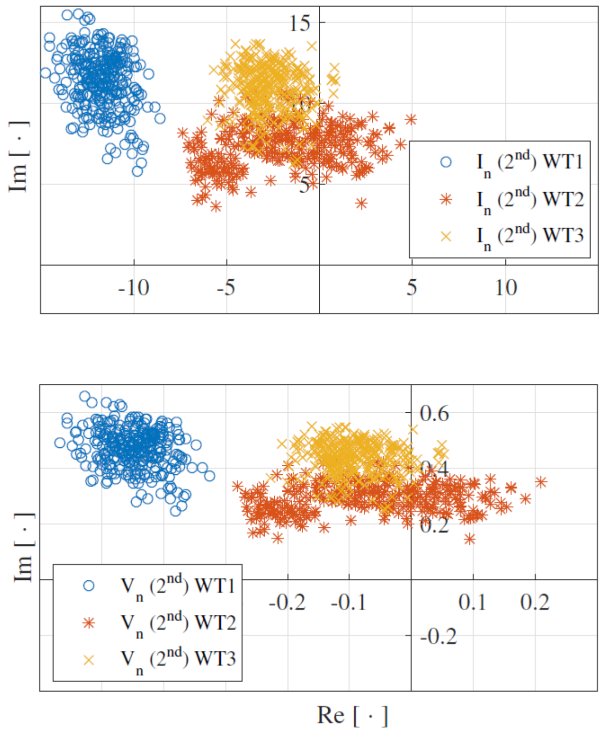

Fig. 6: Phasor diagram of the 2nd harmonic order, current and voltage based on the sequence domain (SD) harmonic model during the operating points shown in Figure 3.

It can be observed from Figure 6 that the 2nd harmonic order phase distribution does not vary between 0 to 2π. It can be clearly seen that the 2nd order phase is scattered mainly scattered around specific angles and varies due to the active power variation. The same observation was made for the 4th harmonic order current and voltage (not shown).

Also, the low-order triplen harmonic shown in Figure 7 phase angle distribution trends to be relatively fixed. The same observation can be made based on the PAR. In fact, the phase angle distribution is not uniformly distributed from 0 to 2π as observed in [15].

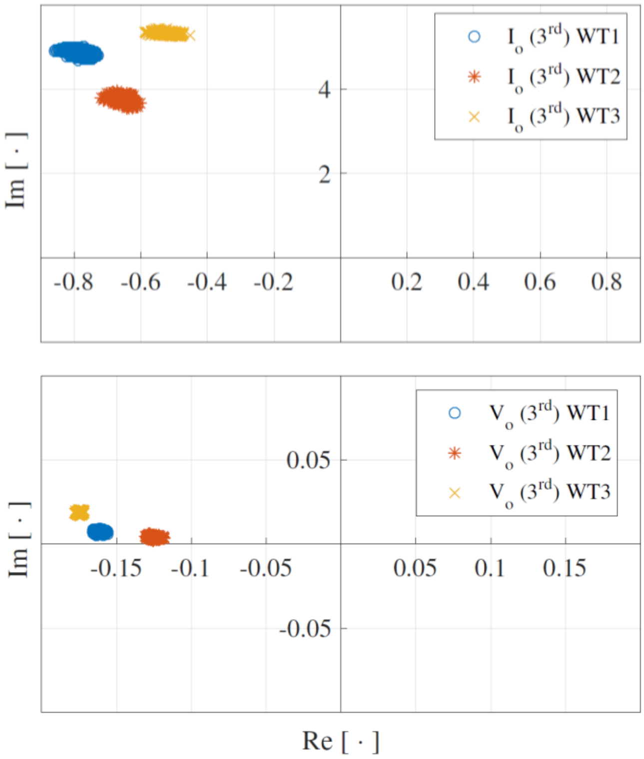

Fig. 7: Phasor diagram of the 3rd harmonic order, current and voltage based on the sequence domain (SD) harmonic model during the operating points shown in Figure 3.

The low-order odd (non-triplen) harmonic characteristic is lineally related to the phase angle of the fundamental current component according to the observations in [2] and [15] with narrow band phase angle distribution characteristics. The amplitude and phase of low-order odd harmonic characteristic are shown in Figure 8.

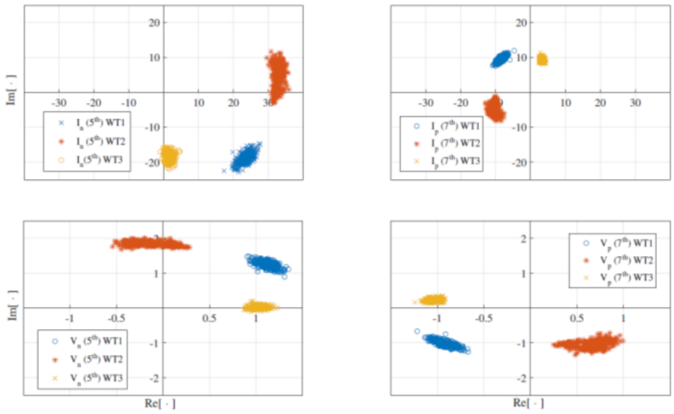

Fig. 8: Phasor diagram of the 5th and 7th harmonic order, current and voltage based on the sequence domain (SD) harmonic model during the operating points shown in Figure 3.

By comparing Figure 3 and Figure 8, it can be clearly seen that the 5th and 7th harmonic order the phase angle is scattered mainly due to the active power variation and partly due to measurement uncertainty.

It can also be observed that the active and reactive power operating points in a WT determine the amplitude and phase of the current fundamental component. Consequently, the low-order odd voltage harmonics that may be caused by the dead-time error-pulses and semiconductor voltage drop will change with the WT operating point. Moreover, it is observed that the phase of the low-order odd voltage harmonics is linearly related to the phase of the current fundamental component, as shown in Figure 8 depending on the change in the reactive power for each WTs. The impact of the power setpoint on harmonic phase and amplitude is only valid by employing the sequence domain (SD) harmonic model [15] and assume that there is no change in the grid, i.e. impedance or background distortion, especially for low-order power system characteristic harmonics.

Again, by comparing Figure 3 and Figure 8, it can be clearly seen that the voltage 5th and 7th harmonic order phase will vary with the WT operating point in this case due to reactive power variation.

The same observations can be made from Figure 9 for the harmonic voltage 11th and 13th harmonic order.

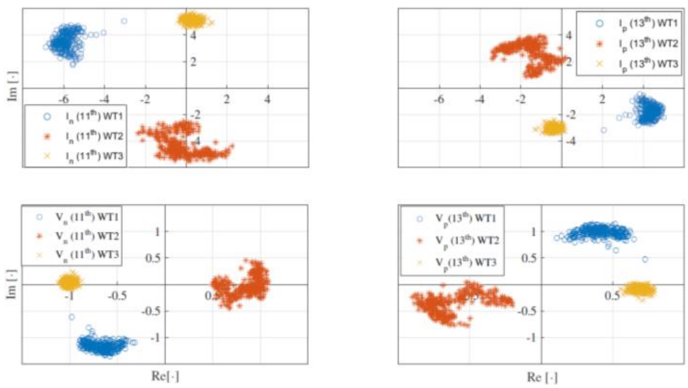

Fig. 9: Phasor diagram of the 11th and 13th harmonic order, current and voltage based on the sequence domain (SD) harmonic model during the operating points shown in Figure 3.

The harmonic summation can thereby occur differently depending on the harmonics phase characteristic. In other words, depending on the type of phase distribution. Particularly, the low-order odd voltage harmonics (non-triplen), that are different compared to even and triplen harmonics with a certain phase distribution.

In case of harmonics within the "grey zone" that are a mixture of baseband dependent mainly on power system fundamental frequency and sideband dependent on carrier signal fundamental frequency. It may be some sideband interaction; that may be identified due to the sequence decomposition as shown in Figure 10. Therefore, the non-predominant sequence can be neglected in order to simplify the studies and reduce the complexity. The sequence domain separates the characteristic ones from the non-characteristic ones and is useful to evaluate the harmonics.

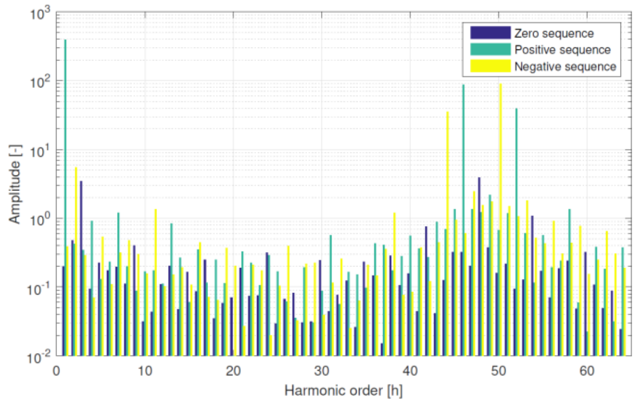

Fig. 10: Harmonic voltages spectrum in sequence component form at WT3 converter-side.

The higher-order harmonics (e.g. from PWM) in reality tend to behave randomly and tend to have a random phase distribution.

V. Discussion

A sensitivity analysis of the transformer tolerance can be performed to verify the impact of the component uncertainties to conclude the impact and the need of modelling. The performed analysis in this paper has some other limitations which must be mentioned such as the limited aggregation time for PAR results needs to be extended with more than one minute of data. To sum up, the following limitations were observed which can be covered in future studies.

Harmonics with deterministic or stochastic phase characteristics for some Type-IV WTs be calculated as presented in [15] and [2], however, the phase behaviour can change depending on the WT control, modulation scheme, etc.

Furthermore, more measurement data need to be analysed to provide general conclusions applicable to large WPPs including active and reactive power variation.

The study can be useful to represent similar WTs with the same control and modulation scheme. However, changes in the control algorithm, dead time scheme, modulation technique, etc. can lead to different conclusions and the WT harmonic performance is significantly affected by the factors mentioned above.

VI. Conclusions

The analysis of harmonic behaviour in WPPs based on detailed phase modelling and measurements was presented in this paper. The harmonic phase behaviour for single WTs was presented and the limitations were discussed.

The analysis presented in this paper brings better understanding regarding offshore WPP harmonic phase behaviour. The presented power quality measurements results showed that amplitude and phase of the odd low-order voltage harmonics depends on the WT operating point including both the active and reactive power. This should be considered for accurate assessment of the harmonic emission level in the future. Moreover, the PAR was applied and gave an indication of whether the harmonic phase tends to behave deterministic or stochastic. It was observed that the harmonics can be divided into two groups: (i) with deterministic phase and (ii) with stochastic phase.

The results from this study, in general, give an overview of harmonic behaviour on a system level and it creates a basis for further advanced studies on harmonic propagation of such complex systems as offshore WPPs. The presented analysis creates a basis for more advanced in-depth studies.

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