Harmonic Analysis of Offshore Wind Farms with Full Converter Wind Turbines

Łukasz Hubert Kocewiak, Jesper Hjerrild, Claus Leth Bak

***Abstract*--This paper presents the harmonic analysis of offshore wind farm (OWF) models with full converters represented as harmonic sources and measurement data on the point of common coupling (PCC) during normal operation. The model describes a wind farm (WF) with full rated converters installed connected to a shore with a long HV cable. The way of propagation and effects of harmonics are presented for different study cases. Modeling strategies of harmonic sources for harmonic analysis are described and compared. Different results dependent on applied harmonic models are shown and discussed in this paper.**

Simulation results are compared with representative measurement data obtained from measurement campaign done in an OWF situated in United Kingdom. The problems and limitations related to present standards and practice will be discussed based on measurements from offshore wind farm.

***Index Terms*--full-rating converters, harmonic analysis, offshore wind farm, wind turbine, validation with measurements**

I. INTRODUCTION

THE tendency to rapid increase in grid-connected, especially, in onshore located coastal areas, and offshore located open seas, WFs has made it necessary for manufacturers and transmission system operators (TSO) to investigate in large OWFs from a power grid operation, harmonic emission, stability and control point of view. Nowadays wind turbines are often grouped in large wind farms, installed offshore and connected directly to the high voltage network via long AC cable lines [9]. The electrical conditions present in the collection grids for large offshore wind farms are not similar to any other industrial application and should be investigated separately.

The number of wind turbines with full converters used in large offshore wind farms is rapidly increasing. Most frequently they are connected through a widespread MV cable network and connected to the transmission system by long HV cables. This generates advantages such as higher power system reliability and dispersed generation of electricity but also represents new challenges to the industry in relation to understanding the nature, propagation and effects of harmonics [18].

A. *Summary of a problem*

Mainly wind turbines in large offshore wind farms are equipped with induction generators, connected to the grid through full-scale frequency converters. The concept of such configuration is shown in Fig. 1

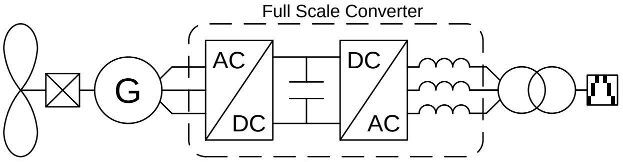

Fig. 1 Wind turbine configuration with an induction generator and a full-scale converter.

Full-rated power converter applied in wind turbines is used to interface a generator that provides a variable voltage at variable frequency to a supply network operating at fixed frequency and including features that allow the power converter to remain connected to the supply network and retain control during supply network fault and transient conditions. Those features allow the converter to find a broad application in the wind power industry. This kind of power converter includes a generator bridge electrically connected to the stator of the generator and a network bridge. A DC link is connected between the generator bridge and the network bridge. A filter with network terminals is connected between the network bridge and the supply network through the wind turbine transformer as shown in Fig. 1 [15].

Fig. 2 Wind turbines from Burbo Bank Offshore Wind Farm (daylife.com).

In order to investigate harmonic emission of offshore wind farms, measurement campaigns have been conducted.

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In this paper Burbo Bank Offshore Wind Farm (BBOWF) is taken into consideration as an example, where measuring systems were installed and used for simultaneous measurement at different locations within the wind farm. The BBOWF is located on Burbo Flats in Liverpool Bay (see Fig. 3). At its closest point, the site is approximately 6.4 km from the Selfton coastline and 7.2 km from North Wirral. The wind farm consists of 25 SWT-3.6-107 Variable Speed wind turbines [7], each with rated capacity of 3.6 MW. BBOWF is therefore capable of providing a maximum output of 90MW of electricity. The WT has a fully rated power converter IGBT-based power electronic converter.

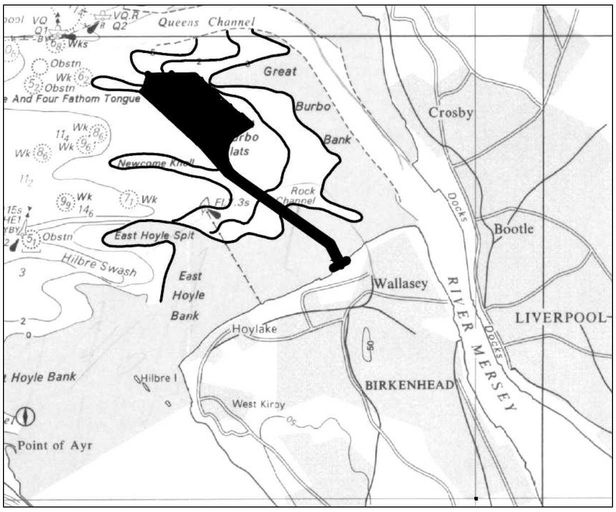

Fig. 3 Location of Burbo Bank Offshore Wind Farm in Liverpool Bay.

The wind turbines are arranged as it is described in Fig. 3. Three 33 kV radials go back to the shore-based substation adjacent to the SP Manweb BSP substation and they are located near the consumption centre. 9, 8 and 8 wind turbines are connected to each radial respectively as presented in Fig. 4. The substation consists of the wind park transformer, a capacitor bank and earthing transformer with is also used for substation supplies.

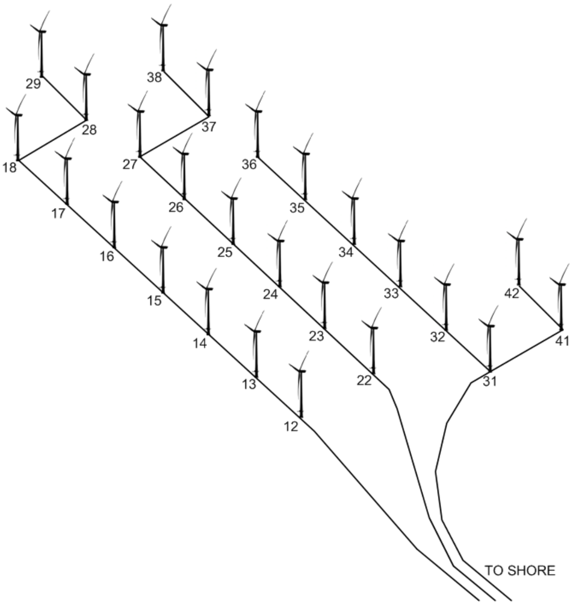

Fig. 4 Layout of Burbo Bank Offshore Wind Farm in Liverpool Bay.

B. *Proposed analysis approach*

The analysed WT conversion system is to be rated at 3.6 MVA output power focusing on a full converter solution for different kinds of generators in order to avoid dealing with slip rings, which is extremely important if offshore wind farms are exposed to truculent environment, and any low voltage ride through (LVRT) difficulties characteristic for demanding grid codes [7].

Modeling strategies of harmonic sources such as power converters for harmonic analysis sometimes give different results which will be shown in this paper.

Resonances may be excited by a relatively small distortion source in the system or by an imbalance in the converter components or control. The resulting amplification of the small source by the resonant characteristics of the system can compromise the normal operation or even lead to instability. That is why power converters from WTs harmonic emission point of view should be deeply investigated [2, 17]. The schematic clarification of this behavior is shown in Fig. 5.

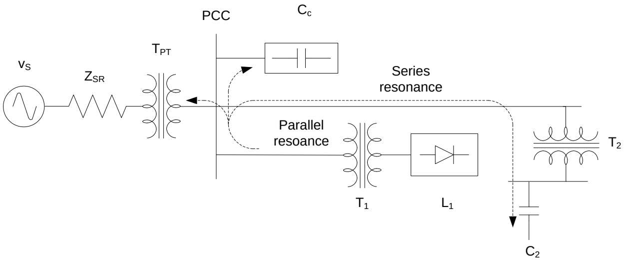

Fig. 5 Simple representation of a WF connected to the network with possible resonances excitation.

An electrical system, which contains capacitance in the form of cables, overhead lines or capacitor banks, will have some frequencies where the reactance of the capacitors and the reactance of the system are equal, opposite and in parallel. This situation becomes very important if large offshore wind farms are connected with a long cable to the network. High long HV cable or capacitor banks capacitances create resonances in a low frequency range, up to 1000 Hz, where harmonic content exists very often. When a parallel resonance appears that harmonic current will be excited to oscillate between the energy storage in the inductance and the energy storage in the capacitance. It affects every WF component negatively and finally it may damage the system [3].

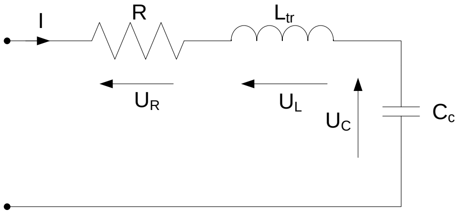

Fig. 6 Series resonance circuit where reactance of the capacitor and the inductor are equal.

A series resonance can also occur where the reactance of the capacitors and the reactance of the system are equal but in series and this would cause a low-impedance path for harmonic current as shown in Fig. 7. Therefore, the amplitude of the current during the resonance can reach very high value. Series resonance can result in high voltage distortion levels between the inductance and the capacitor in the series circuit. During the resonance the inductive reactance of system components such as transformers L_{tr} is equal to the capacitive reactance of cables or capacitor banks C_c as shown in (1):

$$\omega L_{tr} = \frac{1}{\omega C_c} \tag{1}$$

This condition is fulfilled at the resonant frequency described by (2):

$$f = \frac{1}{2\pi\sqrt{L_{tr}C_c}} \tag{2}$$

When system configuration creates harmonic resonance and harmonic excitation exists as well, large current of the resonant frequency will flow through the circuit causing large voltage drop [4, 5].

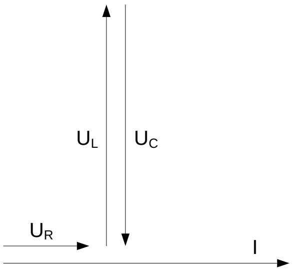

Fig. 7 Series resonance phasor diagram.

In case of series resonance high voltages drop will have opposite signs. Therefore, the sum of the two voltages will be zero, but each of them will have high amplitude as presented in Fig. 6. This kind of problem may occur in OWFs especially from the resonant circuits of cable connections [6].

II. SYSTEM CONFIGURATION

In the simulated system three voltage levels have been taken into consideration. The 0.69 kV on each wind turbine, 33 kV collection grid and extended 132 kV power grid have been included in the model created in DIgSILENT Power Factory 14.0.

In the 132 kV export system the main modeled components are:

- SP Manweb grid,
- overhead line (OHL) with 1.83 km length and 5.78 km cable connection to the substation,
- 33 kV consumption centre,
- 90 MVA park transformer;

in the 33 kV collection grid the main modeled components are:

- three cable radials with different cross-sections,
- earthing transformer with connected loads,
- capacitor bank (PFC) for reactive grid code compliance;

in the 0.69 kV for each WT the main modeled components are:

- 4 MVA wind turbine transformer,
- full scale PWM converter,
- high frequency filter designed to cut-off power converter switching frequency,
- grid converter reactor.

A. *External network configuration*

BBOWF is connected to SP Manweb's Network which is designed to operate substations in interconnected groups with standard transformer and cable sizes. In order to limit effects of distortion of the system voltage waveform, the harmonic content of any connected load complies with the limits set out in Engineering Recommendation G4/5 [10]. The 132 kV and 33 kV networks comprise sections of underground cable or overhead lines or combinations of each. The BBOWF is connected to the 132 kV Wallasey Circuit 1.

The cables and overhead lines in the network could create parallel harmonic resonances dependent on the system configuration characterised by the system impedance. As both factors are difficult to identify from measurement data, the network model configuration for simulation purpose has been chosen based on load profiles from ScottishPower Long Term Development Statement [14].

B. *Subsea cables and transformers*

The submarine cables connect the wind turbines to each other and to the submarine export cables, which in turn connects the wind farm to the onshore substation in Wallasey (34/132 kV). All land and submarine cables have been modeled as long-lines with skin effect approximated as a square-root function against harmonic order [8, 9].

For a precise modeling of high frequency effects of transformers, additional capacitances need to be considered. The high frequency model provides an accurate frequency response with respect to voltages and currents at the transformer terminals as it is implemented in Power Factory [16].

C. *Wind turbine representation*

A voltage sourced converter defines the voltage waveform at the bus-bar to which it is connected, that is why the most accurate harmonic model is a harmonic voltage source. The series reactance in the model represents the coupling reactance that is modeled internally in the full scale PWM converter model. The harmonic voltage is defined by a frequency series used as a look-up table.

In many applications, harmonic injections are given as harmonic current injections at the output of the converter. Therefore to represent the converter in a more realistic way, a harmonic current source has been defined and the amplitude and angle of the harmonic currents have been defined. This approach is only valid if it can be assumed that the coupling reactance is very high compared to other network impedances. In this case, the equivalent voltage source can be transformed into a pure current-source, without internal admittance, with sufficient accuracy. In cases, in which this cannot be assumed, the actual level of harmonic current injections is depends on the network impedance.

For both current source and voltage source the unbalanced representation has been chosen [16].

D. Measuring equipment

The measurements were carried out with a PC equipped with National Instruments data acquisition card, running by a programme developed in LabVIEW. Voltage and currents were sampled at 44.1 kHz, using NI PCI-4472 8-Channel Dynamic Acquisition Board. The dynamic signal acquisition board has analog filter to remove any signal components beyond the range of the analog to digital converters (ADCs). However, in order to cut frequency components above half programmed sampling rate digital anti-aliasing filters are implemented.

III. HARMONIC ASSESSMENT

A range of harmonic analysis studies has been undertaken over a range of network operation conditions. It determines the harmonic impedance which the BBOWF is likely to see and the typical WF harmonic emission in the PCC. The frequency range of interest is 0-1250 Hz.

Analysed measurement data is presented in Fig. 8. During measurements study process it has been observed that mainly 3rd, 5th, 7th, 11th and 13th harmonics have changed depending on production and measurement time. Presented in the paper measurement data frequency analysis has been assumed to be the most common and representative.

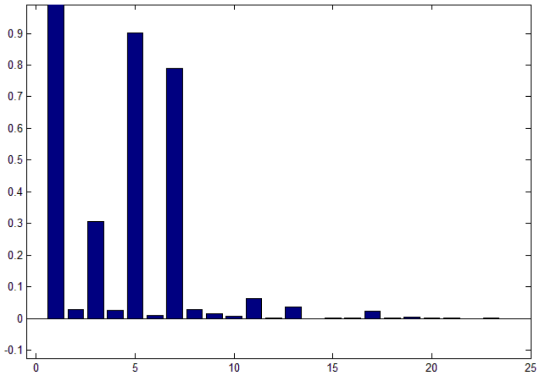

Fig. 8 Harmonic analysis of the voltage waveform measured with 44.1 kH sampling ratio at the PCC. Harmonic voltages are presented in % with harmonic order on the abscissa axis.

Basis of daily and annual load profiles from Distribution Long Term Development Statement [14] typical network configuration has been chosen for simulation purposes. Other possibilities have been taken into consideration as well, but no significant changes have been observed.

Firstly harmonic voltage source has been applied and analysed during simulation process. It should be emphasised that no DC link capacitive impedances have been taken into consideration [11]. This generalization makes impossible to observe interaction between power converter DC side capacitor with the smoothing reactor and the AC system impedance.

Results presented in Fig. 9 show that relations between harmonics are similar in comparison to measurement data but harmonic distortion is much lower than observed in BBOWF. It shows that much lower impedance in case of voltage source causes more impedance damping and shifting when harmonic current source is used for simulations.

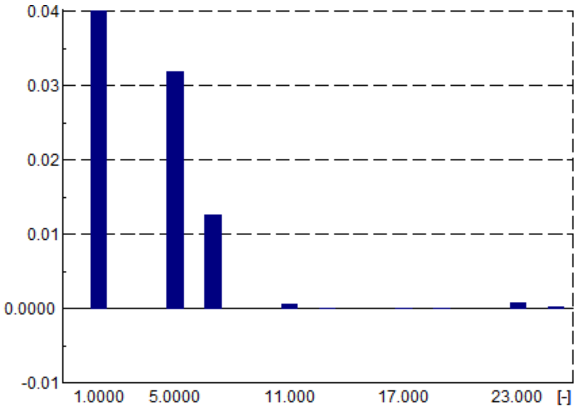

Fig. 9 Harmonic analysis of the BBOWF Power Factory model at the PCC with harmonic voltage source applied. Harmonic voltages are presented in % against harmonic order.

In the next step harmonic current source has been used to analyse BBOWF harmonic emission in the PCC. As it is presented in Fig. 10, results are different in comparison to harmonic voltage source. The first noticeable difference is 7th harmonic domination when for voltage source 5th harmonic is the highest. It has been observed during measurement data analysis that this happens also in real life. This observation raises the question whether the set of measurement data is representative and appropriate to this case study. From impedance plot it will be seen that high resonance peak close to 7th harmonic is the main reason of this amplification.

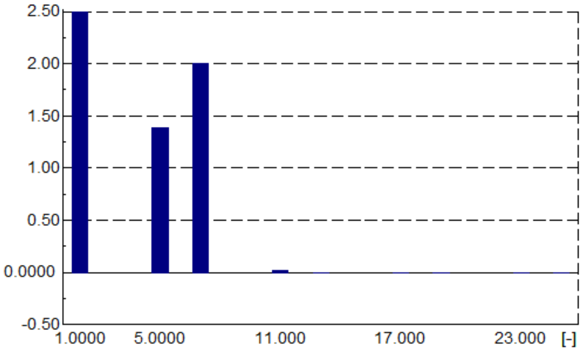

Fig. 10 Harmonics at the PCC obtained from the BBOWF Power Factory model simulation with harmonic current source applied. Harmonic voltages are presented in % with harmonic order on the abscissa axis.

From the harmonic emission analysis in the PCC it can be observed that both models are not able to give satisfactory proper results. Real harmonics level is somewhere between both obtained from calculations. From measurement data analysis of different periods during day and night it has been observed that harmonic level, especially in case of 5th and

7th, had never been so high as in case of current source and as low as it was calculated from simulation with voltage source.

Different power converter modeling for harmonic load flow analysis has also shown that different models have an influence on harmonic impedance in the PCC. This affects harmonic levels and in consequence WF harmonic emission assessment. It has been shown that can play a crucial role in analysis process and power quality assessment.

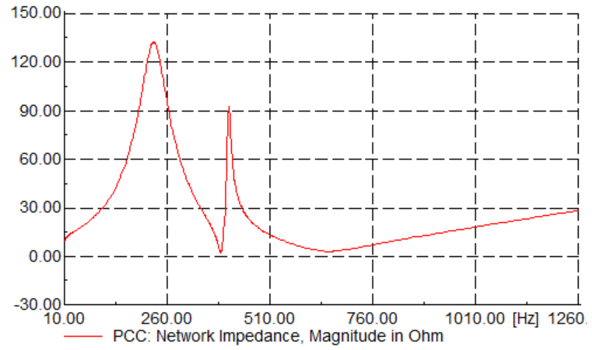

Fig. 11 Magnitude of the network impedance calculated at the PCC with voltage source applied.

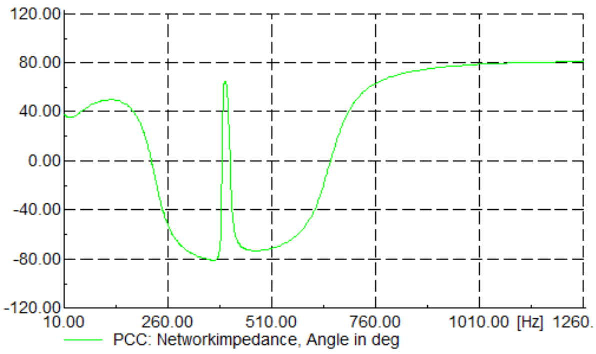

Fig. 12 Angle of the network impedance calculated at the PCC with voltage source applied.

Frequency sweep impedance plots show that for different power converter modeling scenarios different impedances characteristics appear in the PCC as well. It also is reflected in presented above harmonic emission analysis.

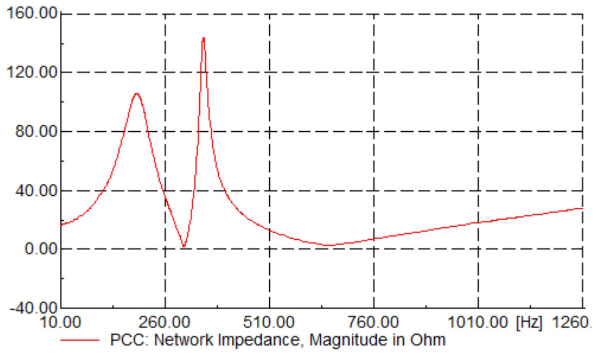

Fig. 13 Magnitude of the network impedance calculated at the PCC with current source applied.

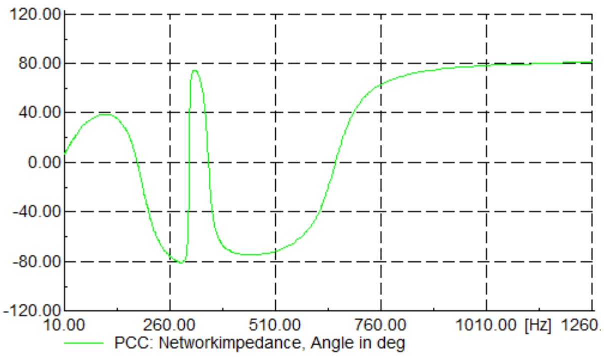

Fig. 14 Angle of the network impedance calculated at the PCC with current source applied.

As it was described previously impedance plot proves (see Fig. 11, 12) that voltage source behaves in a different way for low frequencies in comparison to current source. Unfortunately both models show inaccurate results. In case of harmonic voltage source there is too high damping around 5th and 7th harmonics while for harmonic current source it is too low. The results show that real measurement waveform spectrum is somewhere between two different simulated study cases.

IV. CONCLUSIONS

This paper describes large offshore wind farm harmonic emission assessment obtained basis of different models of full scale power converter. Voltage and current harmonic sources have been taken into consideration in analysis process. Burbo Bank wind farm situated in Liverpool Bay has been used as example. Simulation results have been compared with measurements. Results were presented up to 25th harmonic.

The measurement results have been used for verification of simulation models of the wind farm thereby making it possible to have a more accurate determination of harmonic emission and propagation in a wind farm mainly during steady state operation.

It was shown that different harmonic sources in offshore wind farms modeling techniques give different results. Both harmonic load flow and sweep frequency response analysis in the point of common coupling (PCC) in BBOWF give different results for different models. Analysis has shown that the results obtained in Power Factory are similar but not identical to measurement data. This fact implies that simulation techniques in the frequency, time and harmonic domains and modeling of the wind turbines as harmonic sources should be extended. It is necessary to find a better agreement between theory and experiment.

The comparison of power converter represented as a harmonic voltage source or current source shows that in case of voltage source the impedance is noticeably lower and hence has larger impact on the system. It causes more impedance damping and shifting than when harmonic current source is investigated.

From a general investigation of the external network, it seems not to have any significant resonant conditions that rise suspicions.

The need for accurate simulations is major for OWFs as consequences of faults are more severe in terms of repair costs and lost revenue than for onshore based WFs. The result of simulations can always be questioned depending on the accuracy of the component models used in the simulation programme, and validation of models and simulations with reliable measurements performed in a real large WF, makes it possible to verify and improve the simulations to give more reliable results [18].

Insufficient agreement between simulations and measurements is a premise for future work on models development. Both IEEE and IEC standards consider harmonics in a general sense, without regard to characteristic harmonics generated by certain types of equipment or special operation modes [12, 13]. The above presented analysis shows the need to extend harmonic sources description in standards and to define more precisely power converters more precisely and other wind farm components harmonic models. It has been shown that different modes give different result and in consequence different harmonic emission assessment of OWFs what implies problems with agreement with standards and restricted grid codes.

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VI. BIOGRAPHIES

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Currently he has been employed at Dong Energy. His main technical interest is electrical power systems in general, involving a variety of technical disciplines including modelling of power system including wind power and power system control, stability and harmonics. Furthermore, he also works with designing of the wind farm

From 2002 until 2004 Jesper Hjerrild was employed at DEFU (The Association of Danish Energy Companies R&D).

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