

Harmonic models of a back-to-back converter in large offshore wind farms compared with measurement data

Łukasz Hubert Kocewiak, Jesper Hjerrild, Claus Leth Bak

Abstract—The offshore wind farm with installed back-to-back power converter in wind turbines is studied. As an example the Burbo Bank Offshore Wind Farm with Siemens Wind Power wind turbines is taken into consideration. The wind farm is simulated in DIGSILENT Power Factory software in order to determine and assess harmonic emission in the point of common coupling.

Different modelling methods of power electronic devices installed in wind turbines are presented. Harmonic load flow analysis and impedance frequency characteristics calculation are conducted to present differences between the models.

Simulation results are compared with measurement data from the Burbo Bank Offshore Wind Farm. The delimitations of both power converter models with reference to harmonic analysis are shown in this paper.

Index Terms—back-to-back converter, harmonic analysis, measurement data processing, offshore wind farm, wind power, wind turbine.

I. INTRODUCTION

THE number of variable speed wind turbines (WT) with advanced power electronic converters in the MW range used in large offshore wind farms (OWF) is rapidly increasing [1, 25]. More and more WTs manufacturers such as General Electric (GE) Energy, Siemens Wind Power, Vestas Wind Systems or Gamesa use back-to-back converters in their flagship products. Nowadays, OWFs are connected through a widespread MV submarine cable network and connected to the transmission system by long HV cables. This represents new challenges to the industry in relation to understanding the nature, propagation and effects of harmonics [8, 12].

A. Wind Power Market

In recent years, power systems in the whole world have experienced a significant increase in dispersed generation units (DGUs), and especially wind energy penetration. Presently, the trend is for planning large WFs with a

capacity of hundreds of MVA. This large-scale utilization of wind energy has caused an increasing concern about its influence on the power quality of the power system.

Commonly applied in WTs power electronic devices, transferring power from the generator to the grid, are able to meet with the most demanding grid requirements. The latest achievements in semiconductor technology and control methods of WT converters contribute to improve power quality obtained from modern wind power plants, enhanced voltage stability [6, 14]. Reduced transmission losses and reliability improvement are the most important virtues of dispersed power generation sources. Those advantages create a bright future for the wind power industry.

B. Back to Back Converter

The use of DGUs with voltage source converter (VSC)-based interfaces for controlling the voltage (and for providing other improvements) is commonly applied in modern large OWFs. Large DGUs such as large OWFs are able to operate in a constant power factor mode and allow constant voltage mode operation [3]. This statement, however, seems to refer to rather large units what introduces legitimacy of offshore wind power development.



Fig. 1 Siemens SWT-3.6-107 wind turbine installed in an offshore wind farm (powergeneration.siemens.com).

The performance of WTs is a critical issue in light of increasingly stringent grid requirements [15]. These days, modern WFs provide a sophisticated set of grid code friendly benefits similar to conventional power plants. This is mainly back-to-back power converter merit.

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II. HARMONIC ANALYSIS IN OFFSHORE WIND FARMS

Non-linear characteristics of WF equipment (i.e. transformers) produce harmonics. A transformer operated at higher flux density (i.e. during an overvoltage) will operate in the saturation region making the exciting current a non-sinusoidal waveform containing the fundamental and odd harmonics [2]. This is the important reason of background harmonic existence in the WF point of common coupling (PCC).

The objective of power electronics equipment installed in WTs is to control and to condition the electric power (i.e. voltages and currents). Power electronics use semiconductor non-linear switching devices (i.e. diodes, thyristors, and transistors). During normal operation they produce non-sinusoidal periodic voltages and currents, thereby producing harmonics and characteristic for power converters inter-harmonics [11].

Power electronic devices are widely used in WTs nowadays. They prove benefits such as controlling the frequency of the generator and thereby operating the wind turbine at variable speed, which leads to higher efficiency, reduced loads on the gear box and drive train [29]. The use of power electronics opens the possibility of direct drive wind turbines which have found an application in Enercon and Siemens Wind Power projects [30]. It also allows the control of active and reactive power flow and reduces flickers generated from the WT.

Non-harmonic distortion (inter-harmonics and non-periodic distortion) is much harder to quantify through suitable parameters and it is regularly neglected. For this purpose classical harmonic analysis (i.e. harmonic power flow) becomes insufficient [4]. Another reason for neglecting non-harmonic distortion is that harmonic distortion dominates in most cases. Nowadays, where power electronic converter application in OWFs is significant, the extension of harmonic analysis becomes needed.

When the waveform is non-sinusoidal but periodic with a period of one cycle of the power system frequency, current and voltage waveforms can be decomposed into a sum of harmonic components. For the voltage this can be mathematically expressed as

$$v(t) = V_0 + \sum_{h=1}^H V_h \sqrt{2} \cos(h\omega t - \gamma_h)$$

With $\omega = 2\pi f_0$ and f_0 the fundamental frequency or power system frequency: $f_0 = 1/T$ with T the (fundamental) period of the signal. In the same way, the current waveform can be expressed. The phase angle of the fundamental component of the voltage γ_1 can be set to zero without loss of generality [5].

A. Analysed System Configuration

In this paper the Burbo Bank Offshore Wind Farm (BBOWF) [26] 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 in the shallow waters (2 to 8m) off the Burbo Flats in Liverpool Bay at the entrance to the River Mersey, approximately 6.4km (4.0 miles) from the Sefton coastline and 7.2km (4.5 miles) from North Wirral, covering an area of 10km². It comprises 25 wind turbines accounting for a total installed capacity of 90MW.

The 25 wind turbines in BBOWF are Siemens SWT-3.6-107 turbines with a rated power of 3.6MW, 107m rotor diameter and 83.5m hub height. It cuts-in at 3-5ms⁻¹ increasing power output linearly until rated wind speed at 13-14ms⁻¹ where the power is kept constant until cut-out at 25ms⁻¹. The power curve of SWT-3.6-107WT is presented in Fig. 2 [26]. It is a variable speed pitch controlled wind turbine, equipped with an asynchronous generator (WRIG) and full scale converter. The full scale converter performs reactive power compensation providing a smoother connection to the grid.

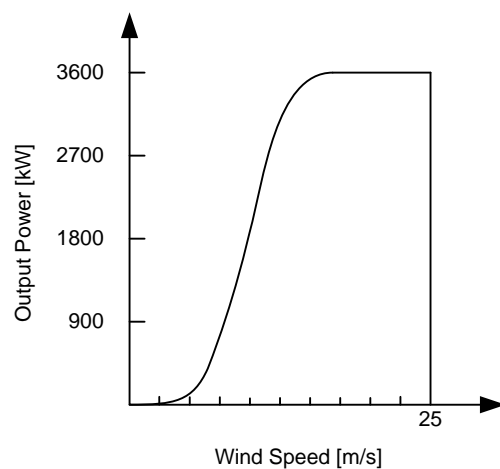


Fig. 2 Siemens Wind Power SWT-3.6-107 wind turbine calculated power curve.

The SWT-3.6-107 wind turbine is the latest model in the product range [6]. It is suitable for offshore applications and for onshore WFs. The rotor of the SWT-3.6-107 turbine is a three blade cantilevered construction, mounted upwind of the tower. The SWT-3.6-107 turbine is fitted with power electronic system that is compliant with even very demanding grid codes. The system has low voltage fault ride-through (LVRT) capability for all normal faults. It allows generator operation at variable speed, frequency and voltage while supplying power at constant frequency and voltage to the MV transformer.

The collection 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) [9].

Offshore submarine power cables, unlike land cables, have complicated structures, having many concentric layers of different materials. This has a significant impact on the overall cable impedance, which consequently affects the level of voltage and current waveform distortion and amplification due to possible resonances. This feature increases the complexity of the analysis and modelling process of OWFs [7, 8].

The BBOWF is connected to SP Manweb's Network which is designed to operate substations in interconnected groups with standard transformer and cable sizes. The 132kV and 33kV networks comprise sections of underground cable or overhead lines or combinations of each. The BBOWF is connected to the 132kV Wallasey Circuit 1. The cables and overhead lines in the network can create harmonic resonances dependent on the system configuration characterised by the system impedance. To predict this behaviour the whole external network at the 132kV level has been modelled.

It is difficult to identify the external network configuration and load basis of measurement data. The network model configuration for simulation purposes has been chosen based on load profiles from Scottish Power Long Term Development Statement [9]. Few cases have been studied.

B. Measurement System and Accuracy

The measurement campaign in BBOWF took place from the end of November to the beginning of December 2007.

The measurements were carried out with a PC equipped with National Instruments data acquisition card, running by a programme developed in LabVIEW programming environment. Voltage and currents were sampled at 44.1kHz, using NI PCI-4472 8-Channel Dynamic Acquisition (DAQ) Board. Wind speed and digital signals were sampled at 5Hz with NI PCI-6052E DAQ card.

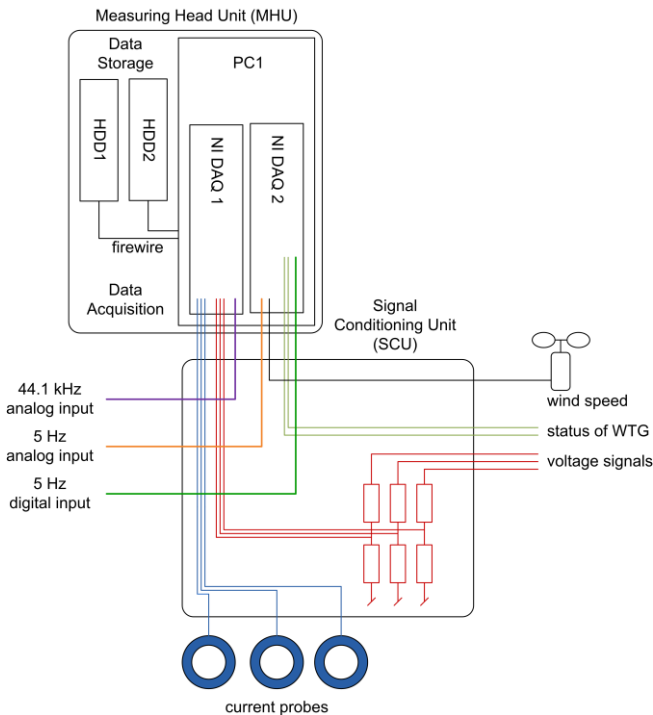


Fig. 3 DELTA powerLAB measuring system used in measurement campaign in Burbo Bank Offshore Wind Farm.

The dynamic signal acquisition board has an analog filter to remove any signal components beyond the range of the analog to digital converters (ADCs). To prevent high-frequency components, above half programmed sampling rate, from affecting the measured spectrum, an anti-aliasing filter is used. The anti-aliasing filter is an analog low-pass filter that is placed before the analog-digital (A/D)

conversion. The described measurement setup is shown in Fig. 3 [27].

Analysing the sampled voltage or current waveforms offers quantitative descriptions of power quality, such as the dominant harmonic components and their associated magnitudes. If the measurement data (or block of the data) are stationary, frequency-domain decomposition of the data is often desirable. A standard and commonly preferred method is the discrete Fourier transforms (DFT) or its fast algorithm, the fast Fourier transform (FFT) [4].

The harmonic voltages of OWFs normally result from the combination of emitted harmonic currents produced by non-linear power converter devices and non-linear passive components of the WF. Power converters are generally not fluctuating with significant correlation. Furthermore, quasi-stationary loads are also connected to the power system. Therefore, fast fluctuating harmonic voltage levels with a high fluctuation magnitude are an exception and seldom occur in the OWF [25].

However, strictly stationary signals do not exist in real-life WFs and power systems. Both small and large statistical changes occur in the electrical signal parameters. The presence of small and relatively slow statistical changes is addressed through so-called block-based methods [22, 23]. The signal is assumed stationary over a short duration of time (or window), a so-called block of data. The signal features are estimated over this window. The size of the window is not arbitrarily defined and should be adjusted based on experience and measurement data analysis [13, 21].

Note that in some cases it can be difficult to judge whether a signal is stationary or non-stationary. To mathematically prove the stationarity requires the knowledge of the probability density function (PDF) of the signal and is therefore not a straightforward task.

C. Simulation Model

For simulation purposes, two power converter models have been used. Harmonic current and voltage sources with harmonic levels defined as look-up tables have been applied during analysis process.

The current source model has its limitations in that the load current in reality is not independent of the voltage. There is a possibility to linearise the voltage dependence around an operational point by representing the load by its Norton equivalent (current source in parallel with source impedance). But the way to determine the impedance is not straightforward. This neglects a lot of dependencies between power converter internal control working in closed loop and the whole system and may not give any better results than the pure current source model [2].

The traditional way of representing a nonlinear load in a harmonic penetration study is as a harmonic current source. The underlying assumption is that the harmonic current spectrum is not too much affected by the system voltage (or by its fundamental or by its distortion). For the traditional sources of waveform distortion such as HVDC links this is a very acceptable model.

Let us consider the basic model of the grid converter as a part of the back-to-back converter. Normally, such kind of devices have a broad application in modern WTs. The grid-side converter with a large capacitor can be recognised as a

DC voltage source seen from the AC side of the converter. This model is shown in Fig. 4. There are two switches for each phase. Each switch connects the DC voltage source to the AC network. The resulting current is due to the difference between the voltage of AC side (typically distorted) and the DC voltage. Depending on which of the switches is closed, the two DC voltage sources of the same magnitude but opposite polarity can be recognised (appropriate for two level voltage source converter).

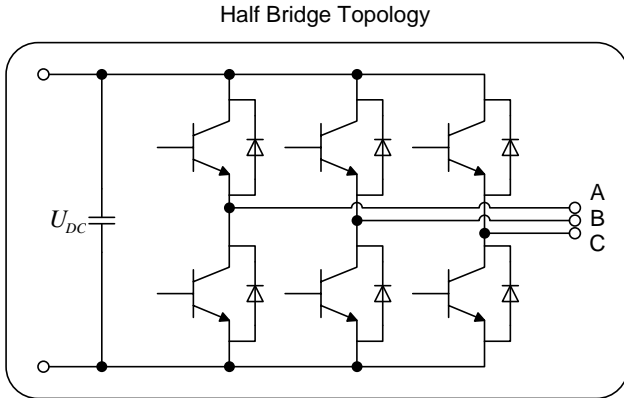


Fig. 4 Simplified diagram of two level and three phase voltage source converter.

During the conduction period the VSC can be represented as a voltage source. However, this does not yet justify the use of harmonic voltage sources for harmonic penetration studies. A serious argument against it is that the voltage outside the conduction period is not defined by the source. Outside the conduction period the current is zero, so that a current source model (with zero current) would be more appropriate. In the time domain, modelling a voltage source model would be possible, but not in frequency domain studies. As the voltage is not defined during the whole cycle, it is not possible to determine the spectrum of the voltage waveform, and thus it is not possible to determine the harmonic voltage sources needed for the penetration studies [20].

The widespread MV submarine cable network connects 25 SWT-3.6-107 wind turbines to each other and to the HV submarine and land cables, which connect the WF to the onshore substation in Wallasey (34/132kV). All land and submarine cables have been modelled as long-lines with skin effect approximated as a square-root function against harmonic order.

Other OWF components are simulated based on already implemented models in the simulation software without including any frequency dependent characteristics [10].

D. Resonance phenomena

The current source model for distorting devices in WFs can also be used to explain a phenomenon called harmonic resonance. Due to a combination of the source reactance and shunt capacitance at a certain location, the impedance seen by the current source becomes very large. The effect of this is a large voltage distortion, even for moderate current distortion.

Parallel resonance occurs when the capacitive and inductive reactance cancel each other. The frequency at

which this phenomenon occurs is called the parallel resonant frequency. Neglecting the resistance, and with assumption $\omega = 2\pi f$, it can be expressed as follows

$$f_p = \frac{1}{2\pi} \sqrt{\frac{1}{LC}}$$

Where C can be the capacitance of capacitor bank or the shunt capacitance of long cables, and L can be the inductance of transformers or series reactors.

The ideal current source will lead to an infinite harmonic voltage at the connection bus and an infinite harmonic current through the capacitor and the inductor. The harmonic distortion will in practice be limited by two effects:

- The resistance present in the system will determine the impedance at the resonance frequency.
- The current source model is no longer valid for HV distortion.

The resonance phenomenon is especially common with MV capacitor banks. Also long AC cables can lead to a resonance but normally at higher frequencies where the amount of current distortion is less and the amount of damping is higher. Both WF components are present in the analysed system and model as well.

There are certain instances when a shunt capacitor and the inductance of a transformer or long cables may appear as a series LC circuit to a source of harmonic currents. If the resonant frequency corresponds to a characteristic harmonic frequency of the analysed system, the LC circuit will attract a large portion of the harmonic current that is generated in the wind power plant.

III. SIMULATION RESULTS AND VALIDATION

A. Harmonic Emission

The harmonic power flow study has been conducted to determine fundamental and harmonic line currents and bus voltages for different models of the WT power converter.

Odd-harmonic distortion is typically dominant in power networks and WFs. Even-harmonic distortion of voltage or current is normally rather small as it can be seen in Fig. 5, 6. Even harmonics are generated by some large converters, but modern rules on harmonic distortion state that equipment should not generate any even harmonics [20]. In fact, a measurement of the supply voltage shows that the amount of even harmonics is indeed very small (see Fig. 5, 6). Even harmonics may also be generated by transformer energizing what should not be taken into consideration for steady state WF operation.

Generally, it can also be observed that basis of measurement data study odd-harmonics multiple of 3 exist in the real system. It might be due to an unbalanced situation in the BBOWF during measurement time. During simulations, an unbalanced situation has not been taken into consideration. The main assumption has been to show obvious differences in results dependent on power electronic devices modelling. This has also been observable if balanced network representation has been studied.

Firstly a certain period of measurement data has been processed using the above described analysis methods

applicable for stationary and quasi-stationary signals. The blocks of the data have been carefully chosen to represent the BBOWF harmonic emission. Different time windows have been analysed and it was observed that harmonic measurements in the PCC are dependent on production and day time.

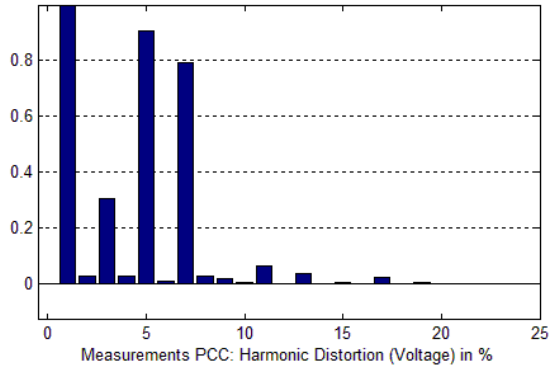


Fig. 5 Harmonic decomposition of measured voltage waveform. Voltage absolute value in % of the main harmonic is presented versus harmonic order.

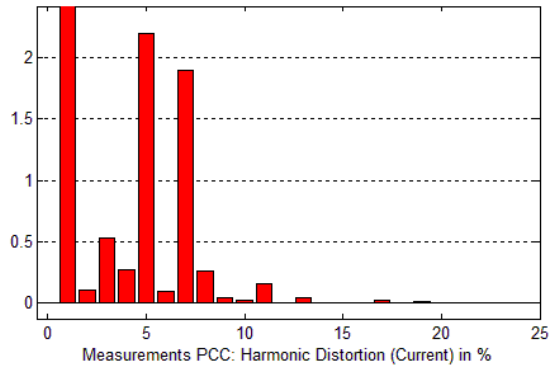


Fig. 6 Harmonic decomposition of measured current signal. Current absolute value in % of the main harmonic is presented versus harmonic order.

The spectrum analysis of the measurement data from the BBOWF shows that in both voltage waveform and current waveform the 5th harmonic dominates. This observation is not so obvious based on the simulation results. In case of the harmonic voltage source (in Fig. VSC) the 5th dominates only in the voltage harmonic plot, and when the harmonic current source (in Fig. CSC) is applied, the 7th harmonic dominates all the time.

From the harmonic emission analysis in the PCC it can be observed that both models are not able to give satisfactory results. Harmonic levels from the BBOWF measurements are somewhere in between and both obtained from calculations. The harmonic voltage source gives higher harmonic levels while the harmonic voltage source is much lower than expected. From the measurement data analysis of different periods during day and night it has been observed that harmonic levels, especially in case of 5th and 7th, had never been so high as observed in simulation with the harmonic current source and as low as it has been calculated from simulations with the harmonic voltage source.

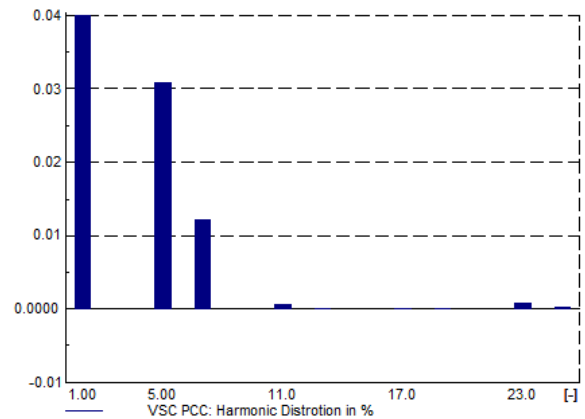
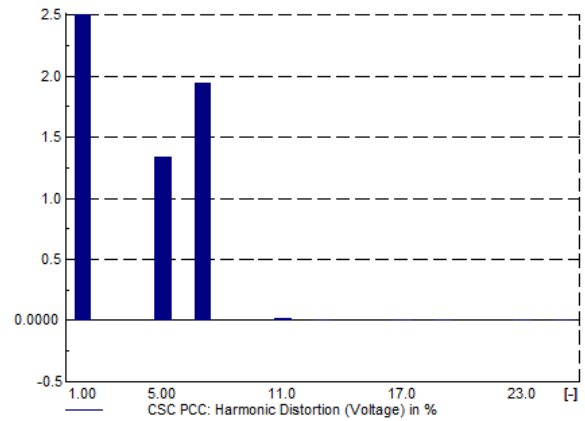


Fig. 7 Voltage harmonic emission of Burbo Bank offshore wind farm. Voltage absolute value in % is presented versus harmonic order.

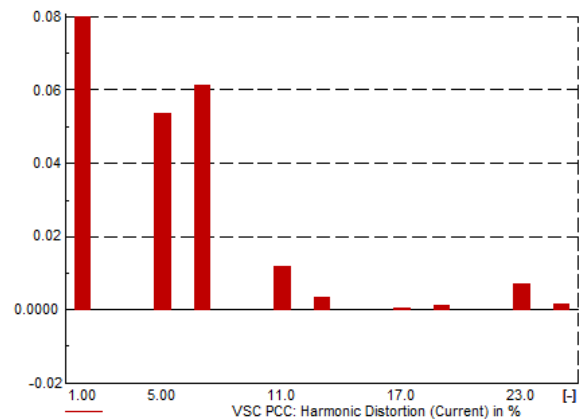
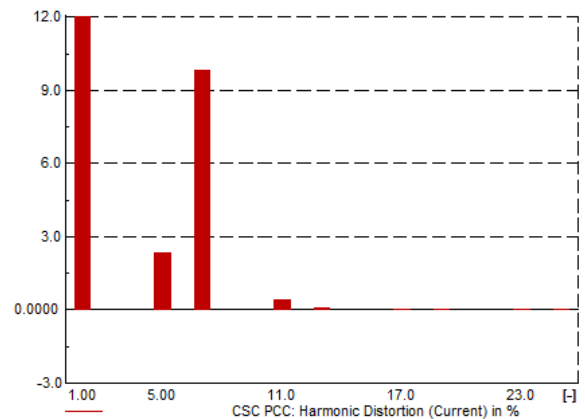


Fig. 8 Current harmonic emission of Burbo Bank Offshore Wind Farm. Current absolute value in % is presented versus harmonic order.

B. Impedance Sweep

Harmonic studies are conducted to inspect the impact of non-linear devices and to analyse certain harmonic situations. They are aimed at detecting resonance and calculating distortion factors. An impedance scan, also known as a frequency scan, is a plot of the magnitude of driving point impedance at the bus of interests versus harmonic order or frequency and is useful in identifying resonance conditions. A dip occurring in the impedance value implies series resonance. Parallel resonance, on the other hand, is identified a sharp rise in the impedance value.

In the analysed in this paper study case, the system configuration has been constant. Only power converter as a harmonic source modelling method has been changed to show its influence on the whole system impedance in the PCC.

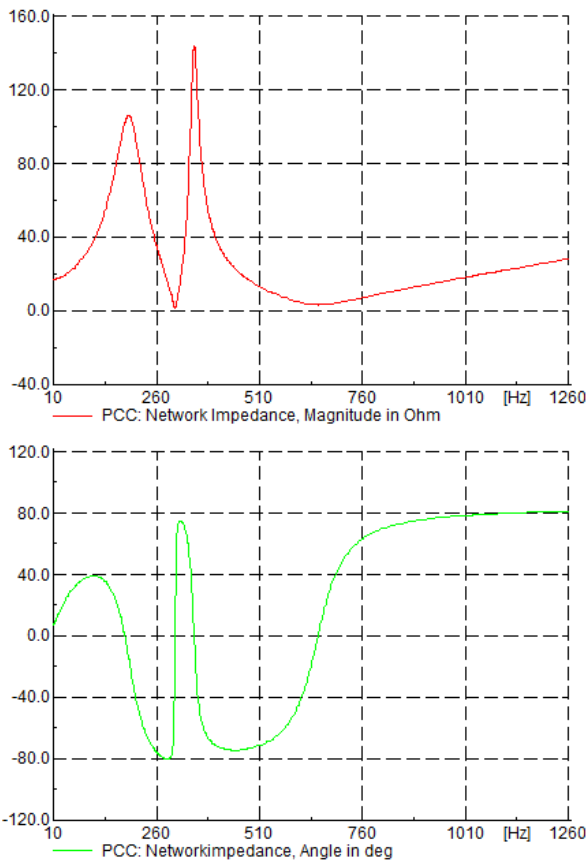


Fig. 9 Impedance plot in the point of common coupling from model with harmonic current source.

Different power converter models for harmonic load flow analysis have also shown that a different modelling approach has an influence on harmonic impedance in the PCC. This affects harmonic level changes, and in consequence the WF harmonic emission assessment. It has been shown that appropriate power converter modelling can play a crucial role in analysis process and power quality assessment, especially before a certain WF would be established and measured in a real life.

Fig. 9 and 10 show the different values and frequencies of resonance points in the frequency response at the PCC. This slight difference can have significant influence on harmonic

assessment, especially if there will be a harmonic source in the system corresponding resonance points.

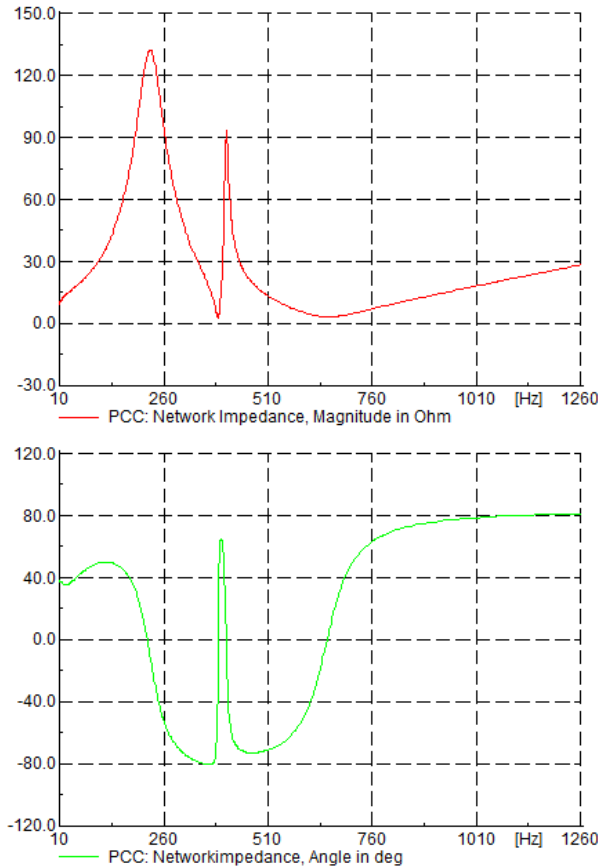


Fig. 10 Impedance plot in the point of common coupling from model with harmonic voltage source.

IV. Conclusion

It has been shown that classical harmonic analysis in frequency domain, which is normally used for assessment of disturbances to the public grid, could be insufficient. Lack of reliable models for power converters in relevant frequency range, manufacturer data are normally provided according to applicable standards [19], also contributes to obtain insufficient results. This shows that there is a need to define in standards appropriate WF components modelling.

Due to this fact every WF system configuration should be investigated separately in cooperation with manufacturers which increases the modelling complexity and causes difficulties. This problem is not only with reference to harmonic analysis, it exists in all branches of modelling. It shows the necessity to extend data and models provided by manufacturers and to better describe modelling methods in standards.

Modelling strategies for harmonic sources for power system harmonic analysis are sometimes insufficient. Simulation techniques in the frequency, time and harmonic domains and modelling of the wind turbines as harmonic sources should be extended. The way to find a very good agreement between theory and experiment is necessary.

Power electronic converters for harmonic analysis can simply be represented by a harmonic current source

suggested in standards or voltage source taking into consideration the nature of back-to-back as voltage source inverters but unfortunately both cases give inappropriate results as it has been shown in the paper.

This paper shows the necessity to produce new knowledge of power converters, as a harmonic source, modelling. At present, applied methods of full scale converter modelling are insufficient in reference to standards and measurements. In this paper differences between already developed models prepared for harmonic studies are shown. Not so good agreement between simulations and measurements as a premise for future work is shown. Both IEEE [16] and IEC [18] standards consider harmonics in a general sense, without regard to characteristic harmonics generated by certain types of equipment or special operation modes. The paper presents the need to extend harmonic sources description in standards.

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VI. BIOGRAPHIES

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