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Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Kocewiak, L. H., Hjerrild, J., & Bak, C. L. (2010). Wind Farm Structures' Impact on Harmonic Emission and Grid Interaction. Paper presented at The European Wind Energy Conference & Exhibition, EWEC 2010, Warszawa, Poland.

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Wind Farm Structures' Impact on Harmonic Emission and Grid Interaction

Łukasz Hubert Kocewiak, Jesper Hjerrild, Claus Leth Bak

ABSTRACT

THE impact of a wind farm's internal structures on harmonic emission at the point of common coupling and on the whole system frequency characteristic is investigated in this paper. The largest wind farms in the world, Horns Rev 2 Offshore Wind Farm and Polish Karnice Onshore Wind Farm, are thoroughly analyzed. Different wind farm configurations are taken into consideration in order to entirely describe phenomena associated with harmonics. Some aspects of wind farm modelling for harmonic studies are also presented in this paper. The simulation results are compared with measurement data in order to validate modelling accuracy.

I. INTRODUCTION

Nowadays, the number of wind turbines (WTs) with full-scale converters used in large offshore wind farms (OWFs) is increasing. They are mainly connected through a widespread MV submarine cable network and long HV cables to the transmission system [1]. This represents new challenges to the industry in relation to understanding the nature, propagation and effects of harmonics [2].

In order to present the differences between onshore and offshore solutions, two wind farms (WFs) constructed by the Danish utility company DONG Energy have been taken into consideration, the largest in the world Horns Rev 2 Offshore Wind Farm and located in Poland Karnice Onshore Wind Farm.

Horns Rev 2 is able to produce 209 MW of power and is thereby the largest WF in the world. It is connected to the transmission network by the longest, 100 km HVAC

cable in Denmark (Figure 2). The system with large shunt capacitance and reactor inductance may result in problems not normally observed in onshore WFs. Karnice Wind Farm has a total capacity of 30 MW. Cable length between the last WT and the point of common coupling (PCC) is 2.5 km. Both analyzed WFs are equipped with SWT-2.3-93, which is a variable speed with a full-scale converter WT.

Nowadays, variable-speed WTs are grid friendly machines in most power quality respects. The power electronic devices with advanced semiconductor technology and advanced control methods that are used in WTs for transferring power from the generator to the grid can meet the most demanding grid requirements seen today [3]. However, there are issues with regard to the power quality, voltage stability, transmission losses, and reliability that need to be addressed and improved in order to exploit the potential and advantages that large OWFs have as important elements in the efforts to reach renewable energy targets while maintaining a stable and robust power system [4].



Figure 1 Large offshore wind farm with widespread MV submarine cable network.

The WF's internal impedance changes when the number of turbines in operation varies, and resonant points vary as well. This becomes an important issue when a large OWF is taken into consideration. In large OWFs the internal impedance can vary significantly. Mainly, this is affected by different number of WTs in operation and power factor correction capacitor banks switching operation. It shows the need to take into account the harmonic emission of WFs, especially offshore WFs where the number of WTs in service can vary from few to even hundreds, for different configurations [5]. The paper presents the impact of both WFs configurations on harmonic emission [6].

In order to investigate different structures on WFs, an

The Industrial Ph.D. project "Harmonics in Large Offshore Wind Farms" supported by the Danish Ministry of Science, Technology and Innovation, project number 08-044839, and DONG Energy Power, Electrical Power Systems and Analysis.

Ł. H. K. is with DONG Energy Power A/S, Kraftværksvej 53, Skærbæk, 7000 Fredericia, Denmark

(e-mail: lukko@dongenergy.dk, phone no. +45 9955 7851).

C. L. B. is with Institute of Energy Technology, Aalborg University, Pontoppidanstræde 101, 9220 Aalborg, Denmark

(e-mail: clb@iet.aau.dk, phone no. +45 9940 9281).

J. H. is with DONG Energy Power A/S, Skærbæk, Kraftværksvej 53, 7000 Fredericia, Denmark

(e-mail: jeshj@dongenergy.dk, phone no. +45 9955 2989).

Paper submitted to the European Wind Energy Conference 2010 in Warsaw, Poland, April 20th-23rd, 2010

impedance scan, also known as a frequency scan, can be used with success. It 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 as a sharp rise in the impedance value [7].

II. SYSTEM DESCRIPTION

Both WFs are equipped with 2.3 MW, pitch-controlled, variable speed WTs with full-rating power electronic converters and induction generators from Siemens Wind Power (SWP). The WT technology of both WFs will utilize the full-rating converters providing the excitation and voltage control of the wind turbine generators.



Figure 2 Horns Rev 2 and Karnice Wind Farm location.

The WFs characterise completely different internal structures. The most significant difference is the number of installed WTs. The change of harmonic impedance due to the number of WTs variation has been thoroughly investigated within this paper. It must be emphasized that the internal MV cable structure is extended in Horns Rev 2. Nowadays, OWFs are mainly connected through a widespread MV submarine cable network and long HV power cables which can be clearly seen in Horns Rev 2. A completely different scenario is observable in Karnice Wind Farm where the internal MV cable structure is much smaller and no HVAC underground cable is used to connect to the external distribution network [8].

A. Horns Rev 2 Offshore Wind Farm

Horns Rev 2 contains 91 SWP WTs. The grid connection of Horns Rev 2 Offshore Wind Farm is arranged through a 100 km HVAC cable connecting the offshore transformer substation with a 165/400 kV transformer in the 400 kV substation at Endrup in the transmission system.

Horns Rev 2 is constructed and operated by DONG Energy. The wind farm is situated off the west coast of Denmark, 30 km from the coast line near Esbjerg. The WF is situated in a shallow water area with water depths

of 9-17 m and average wind speed is less than 10 m/s. The connection to land consists of three main parts: a transformer platform, a subsea cable and a land cable. The total length of the cable is above 100 km. A 42 km long 165 kV 3x630 mm² submarine cable is jointed with a 2.3 km land cable at station Blåbjerg. The cable is produced by Nexans. The submarine cable is a three phase cable where the three conductors are placed in a common metallic sheath. The insulating consists of an 18 mm layer of cross-linked non-polar thermoplastic polyethylene (XLPE). The 2.3 km land cable is jointed with another 55.4 km land cable to reach the Endrup 400/150 kV substation. Both land cables are of the same type – three single-phase conductor aluminum cables are produced by ABB. The voltage rating is 165 kV, and the cross section of the conductor is 1200 mm². The dielectric used in the cable is XLPE, and the thickness of this layer is 17 mm.

Three 170 kV shunt reactors are used to compensate for the reactive power produced by the cables. Two reactors are installed at station Endrup: 40 MVar and 80 MVar. Between the 2.3 km and 55.4 km land cable at station Blåbjerg an additional 80 MVar reactor is installed.

B. Karnice Onshore Wind Farm

The Karnice Wind Farm comprises of 13 SWP SWT2.3-93 WTs with a capacity of 2.3 MW each. The farm is connected to the 110 kV Trzebiatów – Niechorze line through an 11/20 kV transformer with a capacity of 31.5 MVA located in the wind farm area. Therefore, the farm's point of connection to the National Power System (NPS) is the 110 kV bus system. The turbines are connected to 20 kV Main Supply Point (MSP) Skrobotowo switching station with three cable lines. The connections between particular turbines as well as the turbines and the MSP are made of XRUHAKXS 12/20 kV 120 and 240 mm² cables.

III. WIND FARM MODELLING

In many cases it could be an advantage to make a single turbine equivalent of a WF consisting of many turbines. The single turbine equivalent must be comparable to the multi turbine system of the whole WF in the relevant studies that need to be performed.

A. Cable models

Cables in WFs reveal nonlinear frequency dependent characteristics of conductors mainly due to proximity and skin effect. The ability to represent these systems accurately and efficiently for harmonic analysis constitutes an essential part of WF analysis in frequency domain [9]. For harmonic studies within 50-3000 Hz frequency range three types of cable models have been used.

For cable modelling purposes in frequency domain lumped T or Π -sections have been used. It should be emphasized that when the cable length becomes comparable with the wavelength of the interest frequency, errors become apparent [10]. In this case cascaded T-sections or Π -sections usage to represent

the cable can mitigate this problem. The more sections used, the closer the model represents the distributed nature of the cable, and the model accuracy increases. However, computation time also increases significantly due to the increasing model complexity. A good approximation of the maximum frequency range represented by the cable model is given by the following equation [11]

$$f_{max} = \frac{Nv}{8l}$$

where N is a number of Π -sections, v is the propagation speed in km/s expressed as $1/\sqrt{LC}$ where L is in H/km and C is in f/km, l is the cable length in km.

The distributed cable model operates basis of travelling wave theory. A voltage disturbance travels along a conductor at its propagation velocity until it is reflected at the end of the cable. This phenomenon is clearly observable in case of long cables as seen in OWFs. As the frequency increases, the number of T-sections or Π -sections to maintain a particular accuracy increases and the model demands longer calculation time. The computational effort can be effectively reduced and the accuracy improved with the use of an equivalent Π model derived from the solution of the second-order linear differential equations describing wave propagation along medium with damping [12].

$$Z_{\Pi} = Z_c \sinh \gamma_l$$

$$Y_{\Pi} = \frac{1}{Z_c} \frac{\cosh \gamma_l - 1}{\sinh \gamma_l} = \frac{1}{Z_c} \tanh \frac{\gamma_l}{2}$$

and $Z_c = \sqrt{Z/Y}$ is the characteristic impedance, $\gamma_l = \gamma l = \sqrt{ZY}$ where γ is the propagation constant and l is the cable length. This model seems to be the most appropriate for harmonic studies in OWFs.

For presented harmonic analysis appropriate skin effect correction factors for cables suggested by National Grid Company are used [12]. The series resistance is corrected according to following equation

$$R(0.187 + 0.532\sqrt{h}), h \geq 2.35$$

where R is the resistance at fundamental frequency and h is the harmonic order.

B. MV collector system

In order to represent the system by one single equivalent circuit, the MV collector system should be lumped together. Different cable models can be applied afterwards. The choice is dependent on many aspects such as cable length, assumed accuracy, and calculation burden. WTs, especially in OWFs, are distributed over the radial, and therefore each cable in the MV radial is not transporting the same amount of current from the wind turbines [13]. This difference should be taken into consideration in the MV radial equivalent. Because the impedance or length between the cables can vary, it is not possible to make a simple series of constants evaluation [14].

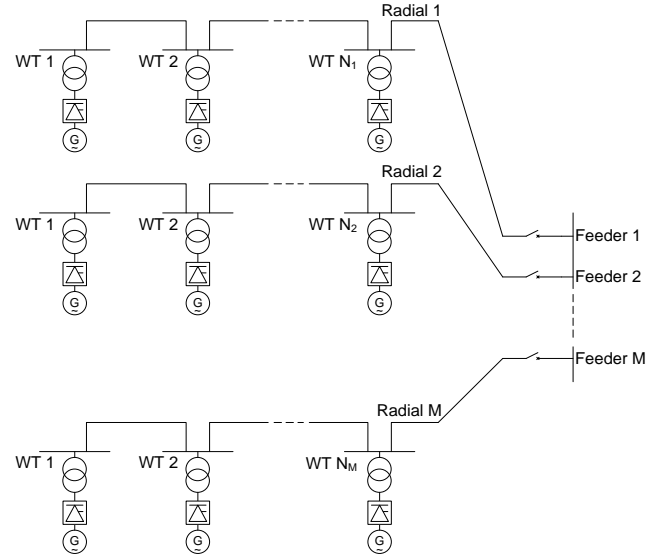


Figure 3 Typical MV cable collector system of wind farms.

Let us consider the system presented in Figure 3. The system comprises M radials with N_m wind turbines connected to every m -th radial. Under the assumption that the current injection from every single WT is the same, the current at every radial can be expressed as

$$I_m = \sum_{n_m=1}^{N_m} I_{n_m}, m = 1, 2, \dots, M$$

where m is the respective radial number and I_{n_m} is the current generated from the n -th wind turbine. The equivalent impedance Z_{eq_m} of respective radials can be obtained

$$I_m^2 Z_{eq_m} = \sum_{n_m=1}^{N_m} \left(n_m \frac{I_m}{N_m} \right)^2 Z_{n_m}$$

$$Z_{eq_m} = \sum_{n_m=1}^{N_m} \left(\frac{n_m}{N_m} \right)^2 Z_{n_m}$$

and Z_{n_m} is the cable impedance between n -th and $(n+1)$ -th wind turbine situated in the m -th radial.

The different radials can be reduced to one equivalent by parallel connection of the different radials impedances and the MV collector system equivalent impedance can be calculated

$$Z_{MV} = \left(\frac{N_1}{\sum_{m=1}^M N_m} \right)^2 Z_{eq_1} + \left(\frac{N_2}{\sum_{m=1}^M N_m} \right)^2 Z_{eq_2} + \dots$$

$$+ \left(\frac{N_M}{\sum_{m=1}^M N_m} \right)^2 Z_{eq_M}$$

The capacitance of the different MV radials is simply added together because they only vary with voltage and the voltage can be regarded as uniform in the MV collector system.

$$C_{MV} = \sum_{n_1=1}^{N_1} C_{n_1} + \sum_{n_2=1}^{N_2} C_{n_2} + \dots + \sum_{n_M=1}^{N_M} C_{n_M}$$

where C_{n_m} is the cable shunt capacitance between n -th and $(n+1)$ -th wind turbine situated in the m -th radial.

C. Other components

Other components used in WF structures that can affect system impedance changes such as series and shunt reactors, capacitor banks, filters are modelled basis of commonly applied models for harmonic studies [10], [12] and data provided by manufacturers.

WT transformers and WF transformers are modelled based on measurements and data provided by manufacturers. Additionally, field measurements have been carried out within the confines of research conducted in DONG Energy Power. In order to obtain transformer models for analysis in frequency domain, FRAX frequency sweep analyser has been used. Obtained results constitutes excellent base for harmonic studies in OWFs.

IV. EXTERNAL NETWORK

The modelling of external networks for WF harmonic studies is dependent on the network being studied. Networks vary in complexity and size and generally, it is not possible to include the detailed model of every component in the study. This is the main reason why the network consists of the most significant source of uncertainty during modelling process. A HV grid system may incorporate hundreds of generators, transmission lines and transformers. Thus, the extent to which a system should be modelled must be decided [15].

Transmission systems have higher X/R ratios and lower impedances, and the harmonics can be propagated over much longer distances. The capacitances of transformers and lines are higher, and these need to be included. The operating configuration range of a transmission system is much wider than that of a distribution system. This creates more careful investigation of transmission systems than distribution which implies a deeper analysis of large OWFs and its interaction with transmission systems.

A. Horns Rev 2 Offshore Wind Farm

The Horns Rev 2 external network harmonic model has been used on the basis of Energinet.dk's technical analyses and simulations using, among other tools, the Digsilent PowerFactory simulation software [16]. A model of the entire electrical power network has been used, with exact representation of all 400 kV, 150 kV and 132 kV power lines. The aggregated 60 kV distribution network models, main power plants, aggregated onshore wind power generation units, CHPs and loads are connected to the 60 kV. Presented in this document studies on Horns Rev 2 WF cable connection concerning harmonic network impedance have been performed using this full network model. One calculation is based on the described model harmonic impedances is shown in Figure 4.

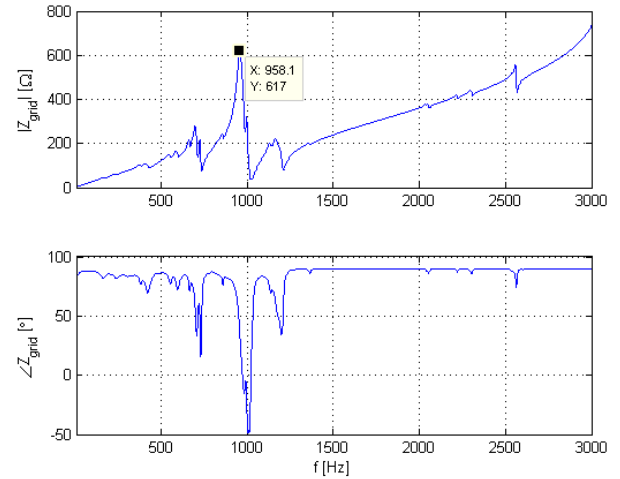


Figure 4 Short circuit impedance seen from the Horns Rev 2 connection point. For the maximum short circuit level, the normal network configuration has been used.

B. Karnice Onshore Wind Farm

The external network harmonic model has been used on the basis of detailed harmonic analysis of impedance seen from the connection point of Karnice (Skrobotowo) Wind Farm performed by Institute of Power Engineering, Gdansk [17]. The aim of the impedance calculations has been to identify resonance points at the 110 kV power busbar of Skrobotowo substation. Calculations have been carried out for different network configurations. For calculation purposes a detailed network model has been used. The model consisted of 400 kV and 220 kV grid topology of north-eastern Polish transmission system and 110 kV distribution system in the vicinity of the harmonic impedance calculation point. One of considered harmonic impedances is presented in Figure 5.

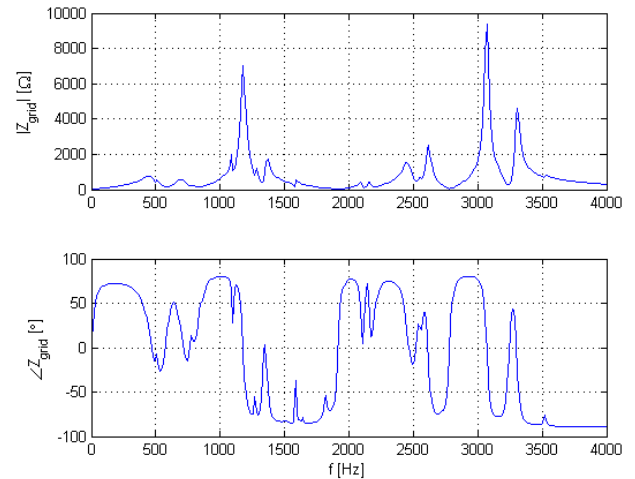


Figure 5 Harmonic impedance at the connection point of Kanice Wind Farm. Basic network configuration is taken into account.

The 400 kV and 220 kV lines have been modelled based on tower topology (distributed parameters).

Distribution lines have been modelled using line model with lumped parameters except 110 kV lines between substations Niechorze – Skrobotowo – Trzebiatów – Gryfice – Kamień Pomorski which data has been based on tower and line data received from Distribution Grid Operator ENEA Szczecin for purposes of this study.

V. ANALYSIS RESULTS

Aggregated models of Karnice Wind Farm as well as Horns Rev 2 have been obtained in the same way. WTs used in both WFs are identical, the same power converters and WT transformers. This creates an ideal opportunity to compare both WFs. The external networks are different, as previously described, but they can be threatened as representative networks to which offshore and onshore WFs can be connected. This issue even emphasizes the differences in impact and interaction between WFs and external network.

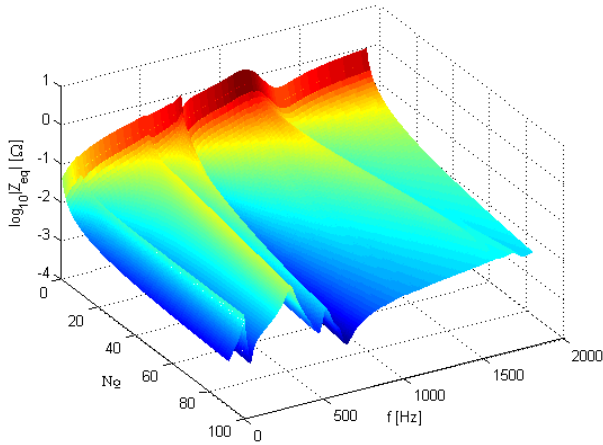


Figure 6 Horns Rev 2 equivalent impedance absolute value seen from the power converter terminals.

The analysis shows that the system impedance significantly changes when the number of turbines in operation varies as it can be observed in Figure 6 and Figure 7. The highest impedance of the whole system seen from the power converter AC terminals is in case of one WT in operation. Obviously, this situation is rare and can happen during field tests or maintenance. From Figure 6 one can conclude that the impedance rapidly decreases when the number of turbines in service increases. This occurs very important if a WF contains many power generation units what is common in case of OWFs. Horns Rev 2 is equipped with 91 units but in the nearest future much bigger wind farms are planned to be erected.

Another aspect to take into consideration is the variation of resonant points. Changes in the overall system impedance affect changes of resonant peaks. This becomes a crucial thing in harmonic analysis reliability. It indicates a necessity to take into account different system configurations, not only capacitor banks, shunt reactors or external network but even number of

turbines in operation.

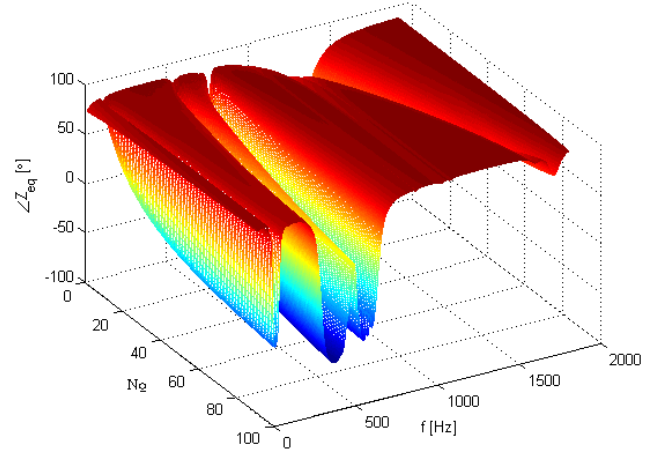


Figure 7 Horns Rev 2 equivalent impedance angle seen from the power converter terminals.

Comparing the equivalent impedance calculated in Horns Rev 2 as well as Karnice Wind Farm, we see that the values, if one WT is connected, are similar. The significant difference between impedances is clear for higher number of WTs. The analysis shows the equivalent impedance almost 10 times smaller when all WTs at Horns Rev 2 produce the power than at Karnice Wind Farm. This can be observed when comparing Figure 6 and Figure 8.

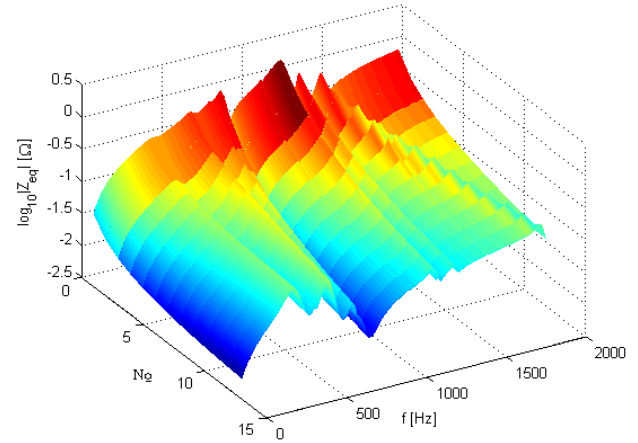


Figure 8 Karnice Wind Farm equivalent impedance absolute value seen from the power converter terminals.

Normally, large WFs are connected to the transmission network which typically characterises smaller equivalent impedance in comparison to the distribution network. This can be seen when comparing Figure 4 and Figure 5. This affects smaller voltage variations at PCC [18]. Due to the tendency to construct large wind farms, the connection will be to strong grids characterised by small short circuit impedance.

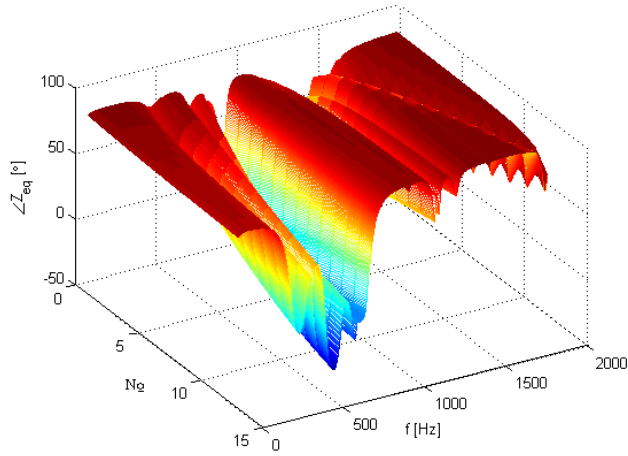


Figure 9 Karnice Wind Farm equivalent impedance angle seen from the power converter terminals.

If one thinks about a WT as a source of harmonic content injected into the power system, the question would be which is responsible for harmonic emission. The answer is the voltage source converter, which is commonly applied in nowadays wind power generation units. In order to assess harmonic currents generated by the converter, it is important to correctly specify the impedance seen from the converter AC terminals. Harmonic currents will be directly related with the impedance which is dependent on the whole system configuration. Some harmonic voltages will be dumped, but some of them will be amplified due to resonance points present in the harmonic impedance. In order to clearly present possible harmonic currents generated by the converter, the admittance of Horns Rev 2 and Karnice Wind Farm is presented in Figure 10 and Figure 11, respectively.

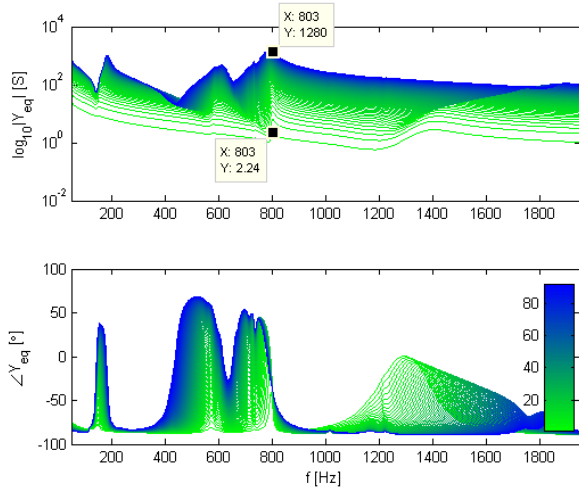


Figure 10 Horns Rev 2 equivalent admittance dependent on number of turbines in operation.

When comparing admittances from both wind farms it can be easily seen that higher currents can be generated by the same converter type in Horns Rev 2

than in Karnice Wind Farm. This emphasizes the need to conduct a more in-depth analysis of large OWFs with many number of WTs and widespread MV cable network than small, typically onshore WFs. It was observed in the industry that the harmonic analysis of large OWFs creates more frequent problems to meet the grid requirements.

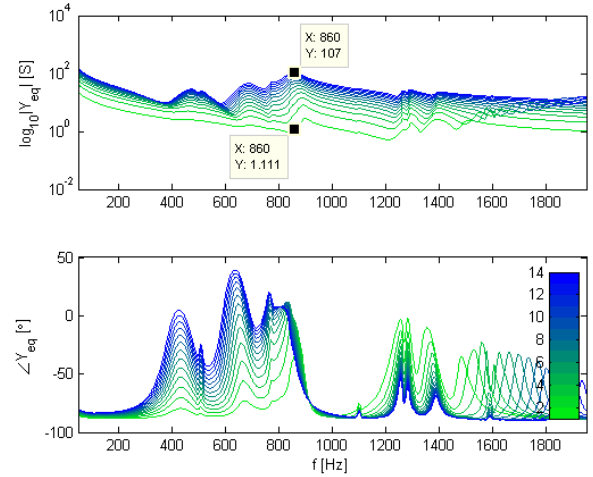


Figure 11 Karnice Wind Farm equivalent admittance dependent on number of turbines in service.

Both WF's evaluation exhibits small differences when only few WTs are in operation. Typical parallel resonance points around 800 Hz and strongly damped close to 1200 Hz are characteristic for both systems. But it can be seen that for higher number of turbines connected to the network, additional resonance points appear within low-order harmonic area. This creates significant disturbance in the system considering harmonic emission assessment. For example series resonance around 200 Hz seen in Figure 10 is due to the WF's transformer series reactance and HV cables shunt capacitance. It is obvious that the harmonic resonance seen from power converter AC terminals cannot be present in the harmonic impedance of Karnice Wind Farm which does not contain any long HVAC power cable connections.

The comparison between both systems' admittance is not a straightforward task because different resonance peaks exist in both harmonic impedances. It has been observed that the admittance of Horns Rev 2 close to common for both WFs resonance points is about 20 % higher than in Karnice Wind Farm for the same number of wind turbines in operation. This has a direct influence on possible harmonic current generation within this frequency area and is affected by bigger MV cable network in Horns Rev 2.

VI. MEASUREMENT DATA ANALYSIS

The paper shows that harmonic emission problems are more significant in large OWFs. Due to fact that system impedance changes during number of WTs in service variation as well as other WF components

operation, such as shunt reactors or capacitor banks, it is difficult to easily assess the harmonic emission at PCC.

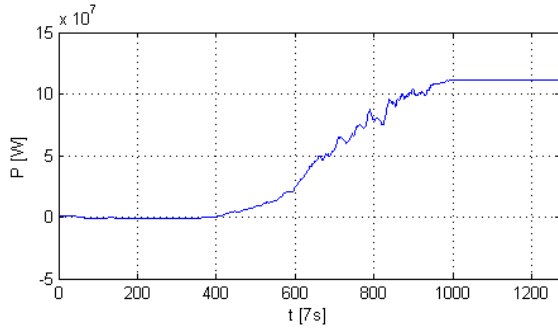


Figure 12 Active power production of Horns Rev 2.

There are also advantages of application of large WFs in modern power systems. It has been observed that the harmonic impedance hidden behind extended MV and HV cable network and other passive components commonly used in large WF structures equipped with AC power cables can contribute to power quality improvement at PCC. Based on measurement data analysis, it can be seen that when Horns Rev 2 is connected to the grid, power quality increases. From active power production presented in Figure 12, it can be observed when the WF is producing. Then harmonic voltage level decreases significantly. This exhibits that WFs cannot be threatened anymore, only as small power generation unit connected to the network, but as power system integral part that contributes to overall power quality improvement.

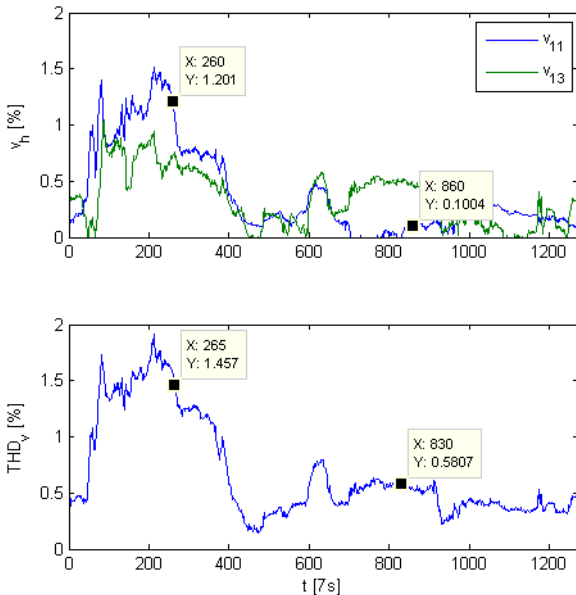


Figure 13 Voltage harmonics and total harmonic distortion at the point of common coupling in Horns Rev 2.

One has observed high harmonic voltage level if the WF is not connected. Mainly the 11th and 13th voltage harmonics become significant, but are strongly dumped when the WF is producing, as seen in Figure 13. This behaviour is due to fact that the WF changes the

impedance at PCC. Such kind of phenomena could not be seen if Horns Rev 2 was a small WF comparable to Karnice Wind Farm.

VII. CONCLUSION

This study presents a detailed harmonic analysis of impedance seen from the connection point of power converter AC terminals. Two different WFs have been taken into consideration. The aim of the calculations is to identify the variation of resonance points of harmonic impedance seen from WT converters. Calculations were carried out for different network configurations. The results for particular cases have been compared.

The design of subsea transmission scheme needs to include an assessment of waveform harmonic distortion and its interaction with the resonant frequencies of the transmission system. The large OWF connected to the transmission systems changes the frequency characteristic and therefore has an impact on the harmonic levels in the point of connection. Without appropriate models it is impossible to reliably predict system resonances and the effects of any generated harmonics.

The analysis shows that the OWF has a big influence on harmonic level at PCC and impact on the external network. The structure and number of turbines in operation do not seem to be so important for small onshore WFs.

As it was presented, the system's equivalent impedance seen from power converter terminals is lower in the OWF. It means that the harmonics can be propagated over much longer distances. The impedance difference between both wind farms becomes clearer when number of turbines in operation increases.

By using appropriate modelling techniques, large WFs can be designed in order to interact smoothly with the external network. The analysis shows that appropriate design on MV cable structure as well as HV power cable length can positively affect the power quality at PCC. Nowadays, this point of view during WFs projecting stages is not so common, but using appropriate techniques can be easily implemented and constitute an integral part of large WF's designing process.

VIII. ACKNOWLEDGMENT

The author would like to express his appreciation for Bogdan Sobczak from Institute of Power Engineering, Gdańsk for his contribution to the analysis results as well as Ole Holmstrøm from DONG Energy Power for contribution to measurement data processing.

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Łukasz Kocewiak was born in Grójec, Poland, in 1983. He received B.Sc. and M.Sc. degrees in electrical engineering from Warsaw University of Technology. Currently he is an Industrial PhD student in cooperation with DONG Energy and Aalborg University. The main direction of his research is related with harmonics and nonlinear dynamics in power electronics and power systems.

Jesper Hjerrild was born in 1971. He received the M.Sc. and Ph.D. degrees in electrical engineering from the Technical University of Denmark, Lyngby, in 1999 and 2002, respectively. 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).

Claus Leth Bak was born in Djursland, Denmark, in 1965. He received B. Sc. in Electrical Power Engineering from the engineering college in Århus in 1992, he received M.Sc. in Electrical Power Engineering in 1994. He is an Associate Professor at Aalborg University with experience on high voltage engineering, relay protection for transmission systems and substation automation and dynamic analysis (PSCAD/EMTDC) of large power systems.