Active Filtering Application in Large Offshore Wind Power Plants

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Abstract— **The application of active filtering in large offshore wind power plants are presented in this paper. The harmonic problems such as sources of harmonic emission and resonances are identified. Also modern remedial harmonic mitigation methods in terms of active filtering are described. It is shown that wind power plant components such as widespread MV cable system and park transformers can introduce significant low-frequency resonances which can cause a significant harmonic distortion at the point of common coupling. It is underlined that there is a potential in terms of active filtering in modern grid-side converters used in wind turbine generators simultaneously keeping sufficient harmonic/noise rejection.**

Keywords-active filtering; harmonic emission; harmonic stability; wind turbine generator; offshore wind power plant

I. INTRODUCTION

Wind power plants (WPPs) equipped with advanced power electronic solutions are becoming more and more popular in power systems [1]. Power electronic equipment in modern power systems is obviously a source of additional harmonic components not seen previously. Appropriately used power electronics can definitely improve the quality of power.

Wind turbine generators (WTGs) with full-scale back-to-back converters are more and more used in large offshore WPPs. This affects the significant increase of complexity in WPP structures [2]. The WTGs are nowadays mainly connected through a widespread MV subsea cable network and long HV cables to the HVAC or HVDC transmission system [1] Such configuration is still being challenging to the industry from harmonic generation, propagation and stability perspective [3].

Therefore it is of great importance to investigate how a certain WTG or a group of WTGs can interact with various WPP structures including MV cable network, park transformers, HVAC export cable, shunt components (e.g. capacitor bank, shunt reactor, SVC, STATCOM, etc.) [4].

A. Harmonic Mitigation

Harmonics have always been of special concern in power system studies. In the past the power system comprised mainly of passive components with relatively linear operating range as well as synchronous generators. Harmonic analysis of such power systems is state-of-the art right now [5].

Renewable energy sources (e.g. WTGs, etc.) are becoming more and more popular. On one hand, the power electronic equipment for the grid connection of the WTGs in modern power systems is a source of additional harmonics components not seen previously. On the other hand, the application of advanced and fast control in grid-connected power converters introduces a possibility of affecting or even controlling some of the higher frequency components [6]. Appropriate use of power electronics by means of active filtering which is shown in this paper can help to improve the power quality [7], [8].

The application of active filtering on a system level in WPPs has so far not been documented and perhaps not seen before. However a strong potential seen in this technology drove an extensive research which is described. The major pros of active filtering application in WPPs are the following:

- Already existing technologies such as WTGs can be utilised for the active filtering at the PCC,
- Active tuning might be permissible during commissioning and even during operation,
- Significant control potential (e.g. selective harmonic compensation, wide band high-pass active filtering, etc.),
- Network impedance changes during operation could be addressed,
- Control methods can be tuned for different WPPs independently taking into consideration grid code issues as well as structure,
- Reduce risk due to uncertainties related with lack of information from manufacturers (e.g. models) and TSO (e.g. harmonic background, models, etc.).

II. ANALYSED WIND POWER PLANT SYSTEM

It was decided to optimise the Anholt Offshore WPP harmonic performance by application of active filtering on the WTG converter level. Anholt Offshore WPP is located in Denmark approximately 58 km of the eastern coast of Jutland. The installed capacity of the WPP is 400MW, with 111 SWT-3.6-120 WTGs [9], [10] which together with the array cables are installed by DONG Energy Wind Power. The 111 WTGs are equipped with a full-load converter. The export AC system, including the offshore substation, is designed and constructed by the Danish TSO, Energinet.dk. There are three 140 MVA main transformers on the offshore substation, each connected to a group of 37 WTGs. The point of common coupling (PCC) is defined on the LV-side of each of the main offshore transformers (i.e. MV level) as illustrated in Figure 1. The 220 kV export system consists of one 24.5-km aluminium 3x1600 mm^2 submarine and one 58-km aluminium 3x1x2000 mm^2 underground cable with compensation placed in-between of 120 MVAr and it is connected to the 400 kV external grid at the onshore substation via two 450 MVA autotransformers. The shunt compensation 4x60 MVAr is also installed at onshore substation as presented in Figure 1.

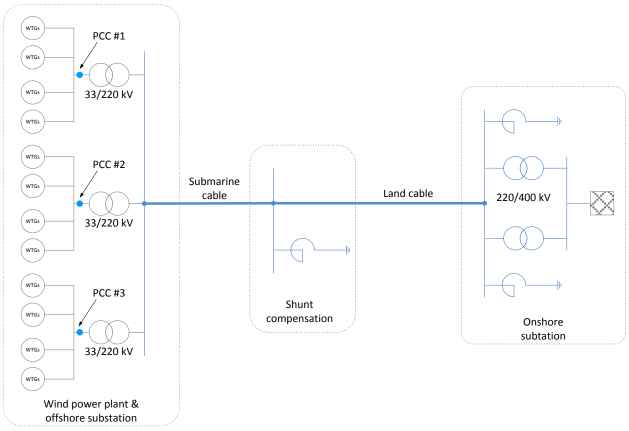


Figure 1 Single line diagram of Anholt Offshore Wind Power Plant and export system.

150 mm^2, 240 mm^2 and 500 mm^2 copper cables are used in the MV subsystem to connect the WTGs to the offshore substation. The layout of the wind farm is non-uniform leading to a big difference in the total length of array cables connected to each PCC as stated in Table 1.

Table 1 MV array cable network

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

A. Modelling

All studies are based on simulations performed in the power system analyses tool PowerFactory. The entire WPP detailed model and export system are built in PowerFactory. All component data are supplied from different manufacturers and suppliers, when possible they are based on test reports. Frequency characteristics for the different components have been applied when available (e.g. WTG transformer). For the harmonic studies the external grid is represented by different impedance characteristics supplied by the TSO, which are based on different configurations of the transmission system in Denmark.

Each of the 111 WTGs is modelled with a Thévenin equivalent connected to the LV-side of the WTG transformer [11]. Thévenin harmonic source and equivalent impedance are developed by the manufacturer based on measurements. The equivalent converter impedance is dependent on the grid-side converter control strategy. This modelling approach can represent the converter from a harmonic perspective independent on network connection [12].

Structure of the converter harmonic model:

- The harmonic emissions from the converter is represented as a number of Thévenin equivalent circuits each representing the harmonic emissions and the interaction in terms of its controller to background harmonics at a particular harmonic frequency.
- Typically the equivalent converter impedances (Z_c) in the harmonic model represent both the converter reactor and the converter control frequency response which represents converter interaction to background harmonic disturbances.
- The equivalent voltage sources (V_h) in the model represent the disturbances which are caused by the PWM switching, dead time of IGBT switching, the non-ideal properties of the converter hardware (e.g. network bridge, etc.) and selection of control strategies.

The Thévenin equivalent circuit is presented in Figure 2.

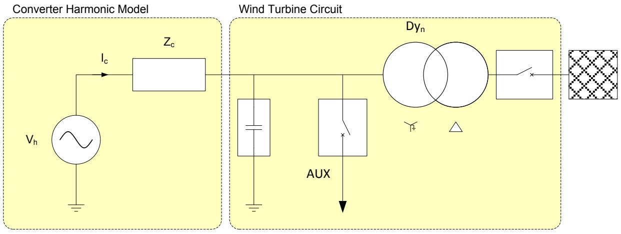
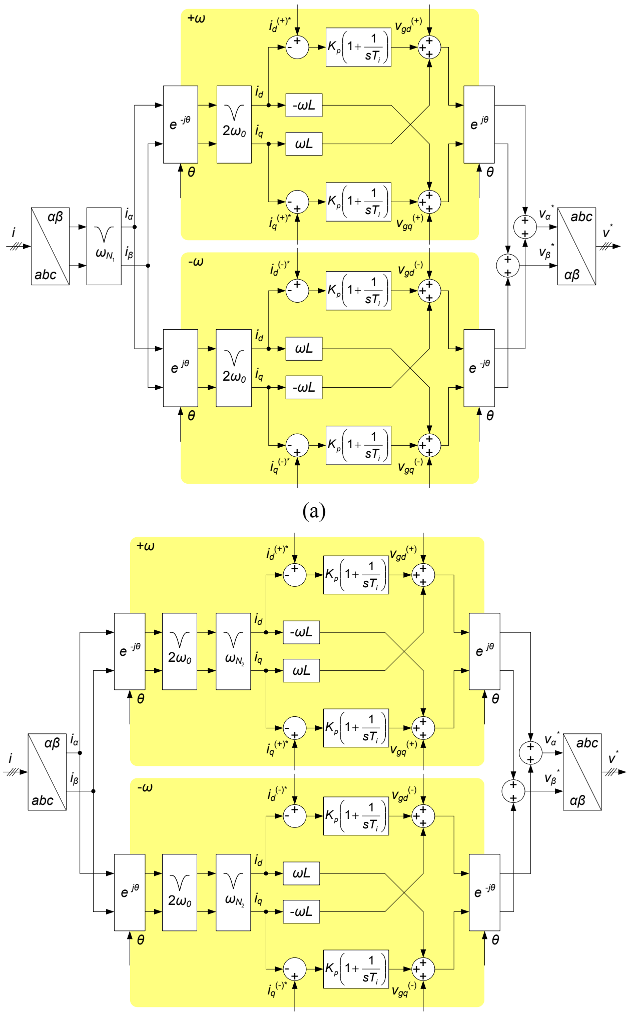


Figure 2 Wind turbine generator harmonic model represented as Thévenin equivalent circuit.

B. Converter system

In order to perform harmonic studies of WPPs, there is a necessity to precisely represent both the WTG network bridge control as well as electrical system in frequency domain. Typically the control of the network bridge current is achieved by using double synchronous reference frame (SRF) [3], [6], [13]. An example of a schematic diagram of WTG grid-side converter current controller is presented in Figure 3. Within such a controller, which would typically be implemented digitally in a microprocessor or digital signal processor (DSP), the positive sequence component is controlled within the positive sequence SRF ($+\omega$) and the negative sequence component within the negative sequence SRF ($-\omega$). In rotating frames in steady state operation the signals are basically DC quantities controlled by respective proportional-integral (PI) controllers [14]. Typically such a control arrangement also includes a voltage feed-forward component, typically of the WTG LV busbar voltage, which also affects the total PWM output voltage as it is also presented in Figure 3.



(a)

(b)

Figure 3 Control of positive and negative sequence components in the synchronous reference frame, (a) with extra notch filter in the stationary reference frame, (b) with extra notch filter in the synchronous reference frame.

Many grid-side converter regulators use synchronous reference frame (*dq*) transformations to convert three-phase electrical network AC quantities into DC quantities. The transformation essentially performs frequency shifts of the system signals [15], [16]. This frequency shift can provide misleading interpretation of the controller in the synchronous reference frame and its interaction with the external system harmonic impedance. That is why it is better to express the regulator either in a natural reference frame (*abc*) or stationary reference frame (*αβ*). Please note that the regulator frequency response is equal in natural and stationary reference frame if there is not coupling between in *d* and *q* quadrature signals in the current controller [15].

The PI controller in synchronous reference frame with radial frequency ω_o presented in Figure 3 can be expressed in stationary reference frame for stability evaluation in the following way

$$G_{PI}^{\alpha\beta}(s)=G_{PI}^{\alpha\beta(+)}+G_{PI}^{\alpha\beta(-)}=2\begin{bmatrix} K_p+\frac{K_i s}{s^2+\omega_o^2} & 0 \\ 0 & K_p+\frac{K_i s}{s^2+\omega_o^2} \end{bmatrix} \qquad 3.1$$

The controller transfer function is calculated according to the following equation derived in [15]

$$G_{\alpha\beta}(s)= \\ =\frac{1}{2}\begin{bmatrix} G_{dq}(s+j\omega_o)+G_{dq}(s-j\omega_o) & jG_{dq}(s+j\omega_o)-jG_{dq}(s-j\omega_o) \\ -jG_{dq}(s+j\omega_o)+jG_{dq}(s-j\omega_o) & G_{dq}(s+j\omega_o)+G_{dq}(s-j\omega_o) \end{bmatrix} \qquad 3.2$$

Assuming that the controllers have no cross-coupling the diagonal components, i.e. $jG_{dq}(s+j\omega_o)-jG_{dq}(s-j\omega_o)$ and $-jG_{dq}(s+j\omega_o)+jG_{dq}(s-j\omega_o)$, are equal to 0. Therefore the converter equivalent impedance can be represented as a single phase equivalent to simplify the system for harmonic and active filtering studies. Please note that the 2^{nd} harmonic oscillations ($2\omega_o$) can be observed in both frames. Such oscillations cannot be completely attenuated by PI controllers which causes the steady-state errors. In order to improve control performance these oscillations should be cancelled to achieve full control of injected positive and negative sequence currents under unbalanced conditions. This can be obtained by application of notch filters only to attenuate the unwanted 2^{nd} harmonic component [17].

A typical notch filter can be represented in the following way

$$G_N(s)=\frac{s^2+\frac{\omega_N}{Q_n}s+\omega_N^2}{s^2+\frac{\omega_N}{Q_d}s+\omega_N^2} \qquad 3.3$$

where ω_N is the tuned angular frequency in [rad/s] and parameters Q_n, Q_d can be adjusted depending on the application. Please note that in case of the notch filters used in double synchronous reference frame the tuned frequency ω_N is equal to $2\omega_o$.

Such notch filter in stationary reference frame can be expressed by using Eq. 3.2

$$\begin{aligned} &G_N^{\alpha\beta}(s) \\ &=Q_d\begin{bmatrix} s^4Q_nQ_d+s^3(Q_n+Q_d)\omega_N \\ +s^2(2Q_nQ_d\omega_o^2+2Q_nQ_d\omega_N^2+\omega_N^2) \\ +s\left((Q_n+Q_d)\omega_o^2\omega_N+(Q_n+Q_d)\omega_N^3\right) \\ +\left(Q_nQ_d\omega_o^4+Q_nQ_d\omega_N^4+\omega_o^2\omega_N^2-2Q_nQ_d\omega_o^2\omega_N^2\right) \end{bmatrix} \\ &\times Q_n\begin{bmatrix} s^4Q_d^2+s^3 2Q_d\omega_N \\ +s^2(2Q_d^2\omega_o^2+2Q_d^2\omega_N^2+\omega_N^2) \\ +s(2Q_d\omega_o^2\omega_N+2Q_d\omega_N^3) \\ +(Q_d^2\omega_o^4+Q_d^2\omega_N^4+\omega_o^2\omega_N^2-2Q_d^2\omega_o^2\omega_N^2) \end{bmatrix}^{-1} \end{aligned} \qquad 3.4$$

Please note that the filter was tuned to the 2^{nd} harmonic ($2\omega_o$) in the rotating reference frame in order to filter 100Hz oscillations in case of unbalanced grid conditions. It can be seen that there is obvious frequency shift of ±50Hz in the stationary/natural reference frame to 50Hz and 150Hz.

The same approach should be introduced in case of extra notch filters used for active damping in SRF as presented in Figure 3b where ω_N is the tuned frequency of the notch filter possibly shifting and a little damping unwanted resonances in the system to which the WTG is connected. Therefore it is more complex task to tune the notch filter in *dq* to counteract with a resonant plant in *abc* in comparison to the notch filter in $\alpha\beta$ (see Figure 3a). Please note that improving the converters controllers rejection capability by means of the notch filter application is called active damping and is a certain type of active filtering.

C. Active filtering

Nowadays large WPP are already equipped with a number of grid connected converters either by means of WTGs or FACTS devices. The active filtering implementation would in this case only involve the converter controller turning in order to meet the controlled harmonic levels. Looking from that perspective there is no need to interfere with the WPP design but only provide additional control features. Such additional control features could be specified on a contractual level and required to be provided as an add-on together with the product. It should be kept in mind that extra control features such as active filtering need to be taken into consideration in the product design in terms of sizing, current rating, bandwidth, stability, overall WTG robustness, etc. [18].

In most cases active filtering solutions employ power electronic converters for the absorption or suppression of harmonics. In this case, the implementation of active filtering technique would only mean the retuning of the converter controller in order to meet with controlled harmonic levels.

The converter might be controlled adaptively or otherwise to suppress the selected critical harmonic components. From this perspective there is no need to interfere with the WPP basic design. In this particular case it was decided to tune the grid-side converter controller in order to shift unwanted resonances and simultaneously improve the converter harmonic rejection capability within the frequency range of interest. In the modelling it can be recognised as changes in the Thévenin equivalent impedance of the WTG harmonic model presented in Figure 2. Appropriate tuning of notch filters presented in the grid-side converter control chain as presented in Figure 3 will change the harmonic model equivalent impedance and consequently overall system resonant characteristic.

III. WIND POWER PLANT STUDIES

A. Harmonic Simulations

Various resonances were identified at PCC during the harmonic studies of Anholt Offshore WPP. The most significant parallel resonance was caused by the capacitance of the MV array cables and the inductance of the offshore main transformers and the resonance peak was placed around the 16th harmonic. Due to the characteristics of the resonance it could be difficult to precisely predict the harmonics level within the resonance range based on simulations not knowing exactly the overall system damping affected by copper losses, skin effect, proximity effect in three phase submarine cables, etc. It has especially impact on resonant frequencies where the impedance value can significantly vary depending level. It is mainly caused by cable, transformer, converter, etc. model uncertainties caused by e.g. cable capacitance tolerance, transformer build, converter harmonic stochastic behaviour, etc. and low damping of the resonance due to e.g. low park transformer losses. Typically the harmonic emission within the low frequency range from the WTG converters is very low, however it can contribute to significant voltage distortions at PCC when it is combined with resonance characteristics for offshore WPPs. Therefore when the WPP was commissioned the level of the 17th harmonic voltage measured was slightly higher than expected.

The level was not critical, however, in order to be compliant with grid code requirements harmonic remedial mitigation was needed. Active filtering as an alternative solution to a physical filter which was considered. This section describes how active filtering was introduced by tuning the WTG converter control system, thus affecting the system impedance seen from PCC and thereby lowering the harmonic level at the PCC.

The layout of the WPP is not uniform; this leads to a different total length of the array cables of each of the WTG groups (Table 1). Since the resonance at PCC is mainly caused by the array cables and the offshore main transformers, the difference in length of the array cables also has an impact. The highest level of the 17th harmonic was identified at the PCC to which the central group is connected (PCC #2 in Figure 1). Based on simulations it was observed that even a small change in the system impedance seen from PCC could solve the problem, as the high level of the 17th harmonic (voltage) at PCC only exist because of a resonance. Therefore it was decided to tune the converter controller. By tuning the converter control system of each WTG it was possible to damp and move the resonance to a lower frequency. The effect of controller tuning is seen in the impedance plot from PCC #2 and #3 (#1 is somewhere in between) presented in Figure 4 and Figure 5. The reduction, seen from PCC, of the impedance at 17th harmonic order, caused by the tuning of the converter control system is stated in Table 2. The results presented in Figure 4 and Figure 5 are obtained for one specific external grid frequency-dependent characteristic with WPP normal operation.

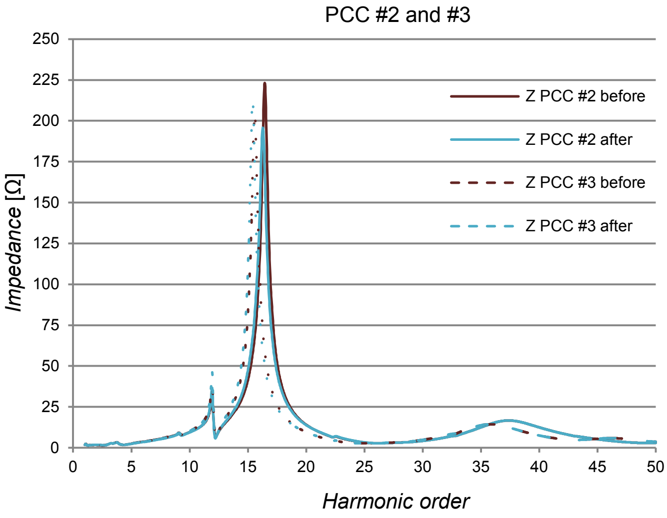


Figure 4 Impedance plots from PCC #2 and #3, (1st – 50th harmonic order).

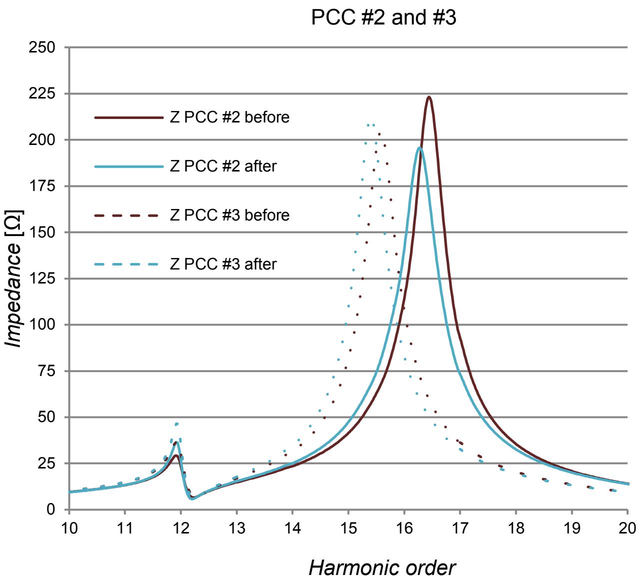


Figure 5 Impedance plots from PCC #2 and #3, (10th – 20th harmonic order).

Table 2 Reduction of the impedance at 17th harmonic order seen from PCC.

	PCC #1	PCC #2	PCC #3
Impedance reduction at 17th harmonic order	14%	21%	10%

B. *Real-Life Implementation and Validation*

The Elspec G4k power quality measurement system was installed at PCC to continuously monitor and log harmonics. The scatter plots in Figure 6 and Figure 7 are based on measurements for one month before and one month after the converter control system tuning. Only results from PCC #2 and #3 are depicted as #1 is somewhere in between. It is specified in the TSO requirements that the harmonic distortion level for each individual harmonic component cannot exceed 1% and the overall total harmonic distortion limit is 1.5%.

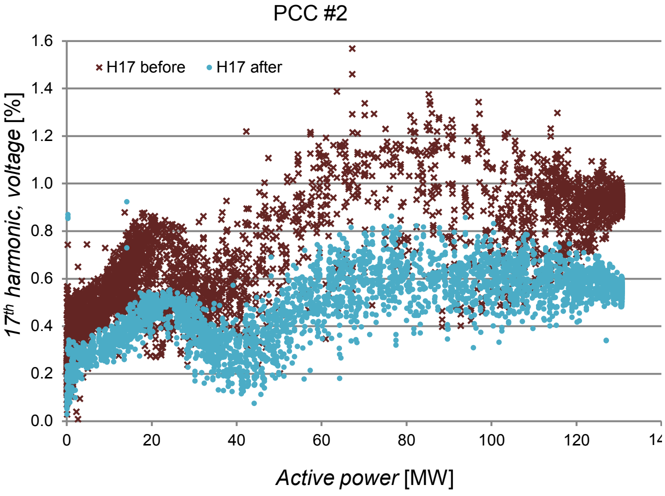


Figure 6 Level of 17th voltage harmonic measured at PCC #2 before and after the tuning of the converter control system.

After the tuning of the converter control system, the level of the 17th harmonic at PCC is not only reduced but it is also more stable throughout the different levels of power production, as can be seen in Figure 6 and Figure 7. Before the tuning the 17th harmonic level was above 1% at PCC #2 as can be seen in Figure 6. By moving the resonance peak further away from the 17th harmonic order, the system has become less sensitive towards external grid variation or/and background harmonic distortion level which is a strongly desired property. It can be seen that the 17th harmonic variation for different levels of power production after the converter controller tuning is less significant due to linear dependency of the harmonic level and impedance change.

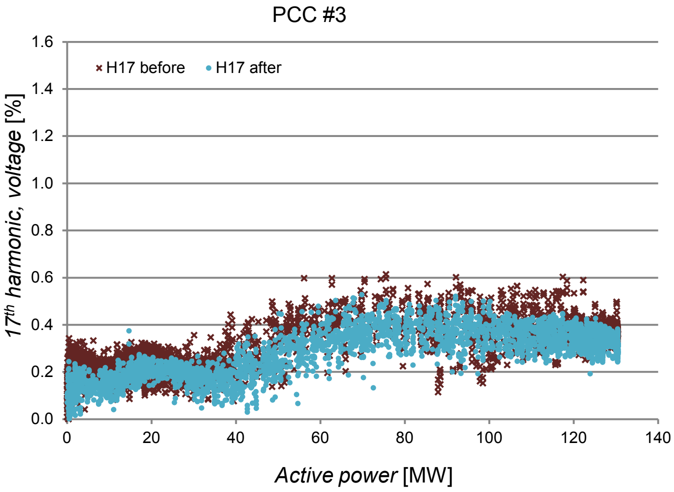


Figure 7 Level of 17th voltage harmonic measured at PCC #3 before and after the tuning of the converter control system.

The changes seen at PCC #3 are less significant than for PCC #2, this is due to the non-uniform layout of the WPP causing the resonance peak at PCC #3 to be at a lower frequency than the resonance peak at PCC #2. (Figure 4 and Figure 5). Please note that the impedance variation caused by the WTG converter control system tuning presented in Table 2 are only for one specific frequency sweep study obtained from simulations. However the measurements presented in Figure 6 and Figure 7 cover changes in the external grid during two months of continuous harmonic distortion monitoring.

IV. SUMMARY AND CONCLUSIONS

As the size of WPPs is increasing, the harmonic problems are becoming more and more significant. Therefore, there is a need to identify the harmonic resonance issues and devise appropriate strategy's to avoid them by design or through the use of active and passive filters.

Potentially, optimised solutions can be achieved by the application of active filtering in various grid-connected converters (e.g. WTGs, etc.) connected together with passive filtering. A hybrid filtering solution introduces significant potential in reducing the cost of energy not only by de-risking the grid code issues with regards to harmonic stability and compliance; but also by improving the operational efficiency of the WPP.

Successfully applied active filtering solution on the system level (i.e. Anholt Offshore WPP) contributed successfully to the improvement of power quality at the PCC. It was shown that active filtering by means of controller harmonic rejection improvement for the frequencies of interest can be introduced in order to reduce voltage harmonic distortion at PCC and consequently meet the grid code requirements. This controller adjustment process was done exclusively for the Anholt Offshore WPP structure characterised by specific resonances such as parallel resonance around the 16th harmonic.

It should be emphasized that there is a significant potential in application of active filtering in future offshore WPP projects which reduces the risk due to uncertainties related with lack of information from manufacturers (e.g. models) and TSOs (e.g. harmonic background, models, etc.), model uncertainties as well as possible network impedance changes. As a next step in the development an adaptive active filtering could be introduced as this would be less sensitive to possible grid impedance changes.

An application of active filters in grid connected converters (e.g. WTGs, STATCOMs, etc.) by means of additional harmonic controllers/compensators or filters in the main control chain (e.g. band rejection filters, band stop filters, notch filters, etc.) can reduce harmonic emission at the point of interest (e.g. PCC) and improve overall stability in offshore and onshore WPPs. This can be achieved by reducing the harmonic content generated by converters as well as changing existing resonances (i.e. improving damping or shifting resonance/natural frequencies).

V. BIBLIOGRAPHY

[1] T. Ackerman, *Wind Power in Power Systems*. Wiley and Sons, 2005.

[2] Ł. H. Kocewiak, J. Hjerrild, and C. Leth Bak, "Wind Farm Structures' Impact on Harmonic Emission and Grid Interaction," in *European Wind Energy Conference*, Warsaw, 2010, pp. 1-8.

[3] Ł. H. Kocewiak, J. Hjerrild, and C. L. Bak, "Wind Turbine Converter Control Interaction with Complex Wind Farm Systems," *IET Renewable Power Generation*, pp. 1-10, 2013.

[4] R. Jones, R. V. Fulcher, and E. A. Lewis, "Control Methods for Pulse Width Modulation (PWM)," Patent US 2008/00622728 A1, Mar. 13, 2008.

[5] G. J. Wakileh, *Power Systems Harmonics: Fundamentals, Analysis, and Filter Design*. Springer, 2001.

[6] M. Lieserre, R. Teodorescu, and F. Blaabjerg, "Multiple Harmonics Control for Three-Phase Grid Converter Systems with the Use of PI-RES Current Controller in a Rotating Frame," *IEEE Transactions on Power Electronics*, vol. 21, no. 3, pp. 836-841, May 2006.

[7] Ł. H. Kocewiak, J. Hjerrild, and C. Leth Bak, "The Impact of Harmonics Calculation Methods on Power Quality Assessment in Wind Farms," in *International Conference on Harmonics and Quality of Power*, Bergamo, 2010, pp. 1-9.

[8] Ł. H. Kocewiak, "Harmonics in Large Offshore Wind Farms," PhD Thesis, Aalborg University, Aalborg, 2012.

[9] DONG Energy Wind Power. (2013) ANHOLT Offshore Wind Farm. [Online]. http://www.dongenergy.com/anholt

[10] V. Akhmatov, J. Nygaard Nielsen, J. Thisted, E. Grøndahl, P. Egedal, M. Nørtoft Frydensbjerg, and K. Høj Jensen, "Siemens Wind Power 3.6 MW Wind Turbines for Large Offshore Wind Farms," in *Proc. 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms*, 26-27 May 2008, pp. 494-497.

[11] P. Brogan and N. Goldenbaum, "Harmonic Model of the Network Bridge Power Converter for Wind Turbine Harmonic Studies," in *The 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, Lisbon, 2012, pp. 538-544.

[12] B. Andresen, P. B. Brogan, and N. M. Goldenbaum, "Decomposition and mitigation of a disturbance being present at an electric connection between an electric power generating system and a power grid," Europe Patent EP2630510 A1, Apr. 26, 2012.

[13] P. Brogan, "The stability of multiple, high power, active front end voltage sourced converters when connected to wind farm collector systems," in *EPE Wind Energy Chapter Seminar*, Stafford, 2010, pp. 1-6.

[14] A. Timbus, M. Liserre, R. Teodorescu, P. Rodriguez, and F. Blaabjerg, "Evaluation of Current Controllers for Distributed Power Generation Systems," *IEEE Transactions on Power Electronics*, vol. 24, no. 3, pp. 654-664, Mar. 2009.

[15] D. N. Zmood, D. G. Holmes, and G. Bode, "Frequency-Domain Analysis of Three-Phase Linear Current Regulators," *Transactions on Industry Applications*, vol. 37, no. 2, pp. 601-610, Mar. 2001.

[16] A. Kulka, T. Undeland, S. Vazquez, and L. G. Franquelo, "Stationary Frame Voltage Harmonic Controller for Standalone Power Generation," in *European Conference on Power Electronics and Applications*, Aalborg, 2007, pp. 1-10.

[17] H.-S. Song and K. Nam, "Dual current control scheme for PWM converter under unbalanced input voltage conditions," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 953-959, Oct. 1999.

[18] Ł. H. Kocewiak, S. K. Chaudhary, and B. Hesselbæk, "Harmonic Mitigation Methods in Large Offshore Wind Power Plants," in *The 12th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms*, London, 2013, pp. 443-448.