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Published in:
Proceedings of the EWEA 2012 - Europe's Premier Wind Energy Event

Publication date:
2012

Document Version
Accepted author manuscript, peer reviewed version

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Kocewiak, L. H., Hjerrild , J., & Bak, C. L. (2012). Wind Turbine Control Impact on Stability of Wind Farms Based on Real-Life Systems Analysis. In *Proceedings of the EWEA 2012 - Europe's Premier Wind Energy Event*

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Wind Turbine Control Impact on Stability of Wind Farms Based on Real-Life Systems Analysis

Łukasz Hubert Kocewiak, Jesper Hjerrild, Claus Leth Bak

ABSTRACT

This paper presents stability analysis of wind farms in frequency domain. The interaction between the wind turbine control system and the wind farm structure in wind farms is deeply investigated. Two wind farms (i.e. Horns Rev II and Karnice) are taken in to consideration in the study. It is shown that wind farm components such as long HVAC cables and park transformers can introduce significant low-frequency series resonances seen from the wind turbine terminals which can affect wind turbine control system operation and overall wind farm stability. The same wind turbine converter control strategy is evaluated in two different wind farms. It is emphasized that the grid-side converter controller should be characterized by sufficient harmonic/noise rejection and adjusted depending on wind farms to which it is connected. Various stability indices such as gain margin, vector gain margin, and phase margin are used in order to emphasize differences between the two wind farms.

Keywords: offshore wind farms, stability analysis, stability margins, wind farm aggregation, wind turbine control.

1 INTRODUCTION

WIND turbines with full-scale back-to-back converters are more and more used in large offshore wind farms. This affects the significant increase of complexity in wind farm structures [1]. The wind turbines are nowadays mainly connected through a widespread MV subsea cable network and long HV cables to the transmission system. Such configuration is still being challenging to the industry from harmonic generation, propagation and stability perspective.

Therefore it is of great importance to investigate how a certain wind turbine or a group of wind turbines can interact with various wind farm structures including MV cable network, park transformer, HVAC export cable,

This work is made as part of an Industrial Ph.D. project supported by the Danish Ministry of Science, Technology and Innovation, project numbers 08-044839.

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EWEA EWEC 2012 in Copenhagen, Denmark, 16 - 19 April 2012

shunt components (e.g. capacitor bank, shunt reactor, SVC, etc.). Nowadays wind turbines are robust devices characterized by efficient harmonic/noise rejection capability for frequencies above the power system fundamental frequency. Their robustness can be measured by respective stability margins (e.g. gain margin, vector gain margin, phase margin) however offshore wind farms tend to be bigger and bigger with more and more complex structures which can introduce unwanted resonances. Such resonances can cause stability problems in large offshore wind farms.

1.1 Research background

Many wind farm aggregation techniques are developed depending on application. Some aggregated models were presented in [2] for grid disturbances studies, or to represent a collective behavior in [3] for large power systems simulations, as well as represent the whole power system seen from wind turbine AC terminal [1]. The representation of the wind farm system used in models intended for low frequency stability analysis within the grid-side converter control bandwidth of wind turbines is presented in this paper. The guidelines presented are solely based on the experiences gained on earlier DONG Energy's projects and based on continuous cooperation with different wind turbine manufacturers. Some limitations affected by different aggregation techniques are emphasized based on obtained results and compared.

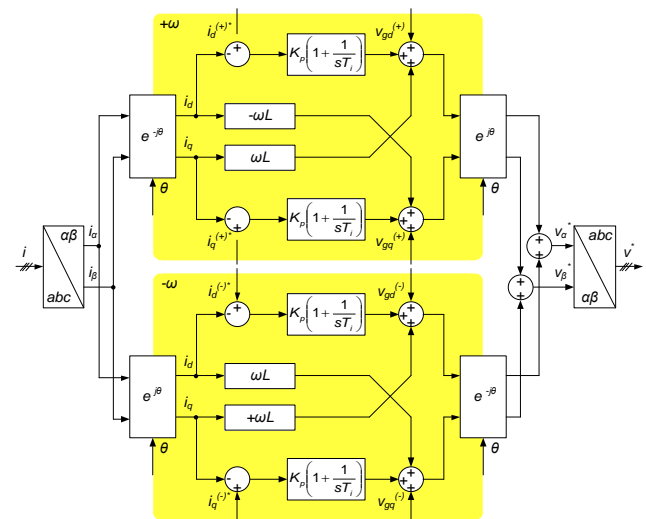


Figure 1 Control of positive and negative sequence components in the synchronous reference frame.

The model of aggregated collection grid and the external network is used for wind turbine stability assessment purposes. The analysis is carried out in frequency domain taking into consideration different wind farm internal network structures as well as external network configurations. The gain, vector gain

and phase margins are presented and evaluated in order to assess stability of wind farms with particular wind turbine converter control methods.

Different control structures are possible in nowadays wind turbine converters [4]. The implementation of the control strategy can be achieved in different reference frames such as rotating reference frame (dq), stationary ($\alpha\beta$), and natural (abc) reference frames. Each of them has its advantages and drawbacks. Based on measurements and literature studies [5], [6] it was decided to implement the model of the grid-side converter controlled by proportional-integral (PI) current controllers in rotating reference frame (dq) which is synchronized with the power system frequency (see Figure 1). However please note that the same stability analysis approach can be successfully used in case of other control structures. Grid-side converter controller frequency dependent characteristic can be normally provided by wind turbine manufacturers. In this paper an exemplary state-of-the-art controller is used to show that the controller configuration and tuning should be done taking also into consideration the wind farm structure's impact.

Different wind farms exhibit different frequency characteristics as well as different control methods can behave in various ways. Therefore there is a need to investigate more broadly stability for particular study cases. A typical control of the grid-side converter is shown in Figure 1. As it was described above different modification in the control (e.g. additional filtering, voltage feedforward, harmonic compensation) can affect changes in the frequency response of the converter and its interaction with the wind farm to which is connected [5].

2 ANALYZED WIND FARM SYSTEMS

Normally described above control method is successfully applied in the industry. Although in case of large offshore wind farms which exhibit many resonance scenarios due to widespread internal cable collector systems and other capacitances affected by capacitor banks or long HVAC export cables. This provides significant gain for higher frequencies of the plant due to possible series resonances.



Figure 2 Karnice and Horns Rev II wind farms location.

It is shown that even small changes in wind farm

internal structure due to varying number of wind turbines in operation can significantly affect possible resonance frequencies and their gains. That is why it is crucial not only to investigate stability for different wind farms but even variation in their internal structures. The study of grid-side converter control impact on overall wind farm stability is presented based on real-life systems. Two different wind farms are taken into consideration and compared. In order to present the differences between onshore and offshore solutions, two wind farms constructed by the Danish utility company DONG Energy are taken into consideration, the biggest in Denmark Horns Rev 2 Offshore Wind Farm and located in Poland Karnice Onshore Wind Farm (see Figure 2).

Horns Rev 2 is able to produce 209 MW of power. It is connected to the transmission network by the longest, 100 km HVAC cable in Denmark. The system with large shunt capacitance and reactor inductance may result in problems not normally observed in onshore wind farms. Karnice Wind Farm has a total capacity of 30 MW. Cable length between the last wind turbine and the point of common coupling is 2.5 km. Both analysed wind farms are equipped with SWT-2.3-93 which is a variable speed with a full-scale converter wind turbines.

3 SYSTEM DESCRIPTION FOR STABILITY STUDIES

In order to investigate stability in continuous frequency domain (i.e. s -domain) there is a necessity to precisely represent both the converter current control as well as electrical system in frequency domain. An illustrative draft of wind turbine grid-side converter connected to the grid is presented in Figure 5.

3.1 Wind farm representation

Wind farm aggregation is done based on single line diagram and the aggregated impedance is seen from the grid-side converter AC terminals towards the grid. The aggregation can be successfully used for stability analysis and assessment purposes. Basically such study investigates the wind turbine current controller interaction with the external network. Due to this fact there is a need to represent the wind farm as a single line diagram. The system description is obtained by means of the network frequency characteristic based on the wind farm single phase equivalent circuit. The stability analysis is carried out in frequency domain. Therefore frequency response of all components either based on measurements or theoretical assumptions is needed. Please note that the system simplification to single line diagram used to analyze interaction between the wind turbine converter and the plant (i.e. wind turbine main power circuit, wind farm internal network, and external network.) can be assumed only if there is no coupling in the grid-side converter control structure. This assumption will be described later in more details.

All partial impedances have been scaled to wind turbine transformer LV side voltage level. The wind turbine transformer impedance, the converter output

filter impedance and the main reactor impedance are scaled taking into consideration how many turbines are in operation. Please note that it is considered that the wind turbines are connected in parallel in the aggregation process. Therefore components from the wind turbine main power circuit (i.e. main reactor, shunt filter, wind turbine transformer) are scaled depending on number of wind turbines in operation.

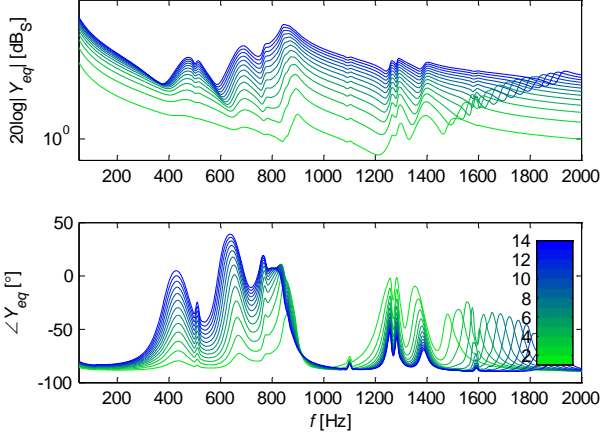


Figure 3 Karnice admittance seen from converter terminals and dependent on number of wind turbines in operation.

Based on results presented in Figure 3 and Figure 4 one can see how the system admittance can change depending on number of wind turbines in operation. It should be emphasized that this effect can be more significant in case of large offshore wind farms such as Horns Rev 2 where much more wind turbines are installed. Therefore this creates also a need to introduce more subtle stability analysis in case of large offshore wind farms equipped with many wind turbines, widespread internal cable network, and connected by long HVAC cables.

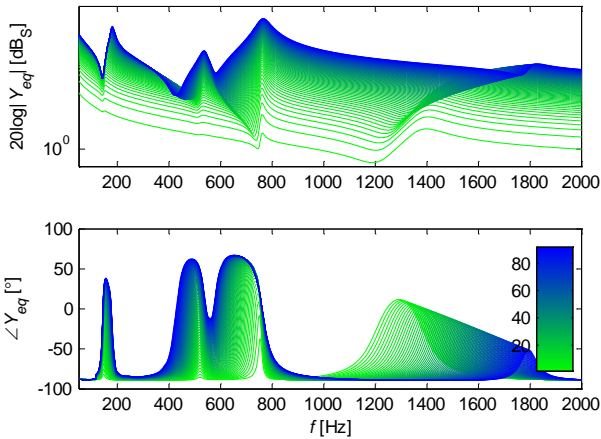


Figure 4 Horns Rev 2 admittance seen from converter terminals and dependent on number of wind turbines in operation.

Aggregated models of Karnice Wind Farm as well as Horns Rev 2 were obtained in the same way. Wind turbines used in both wind farms are identical, i.e. contain the same power converters (including reactors and shunt PWM filters) and wind turbine transformers. This creates an ideal opportunity to compare both wind

farms. The external networks are different, as previously described, but they can be treated as representative networks to which offshore and onshore wind farms can be connected. This issue even emphasizes the differences in impact and interaction between wind farms and external network. As it was observed earlier, the analysis shows that the system admittance seen from the converter terminals significantly changes when the number of turbines in operation varies. This is presented in case of Karnice Wind Farm in Figure 3 and for Horns Rev 2 in Figure 4.

Another aspect to take into consideration is the variation of resonant points. Changes in the overall system impedance cause changes to resonant peaks. This becomes a crucial thing in harmonic studies 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 [1].

Both wind farms evaluation exhibits small differences when only few wind turbines are in operation. Typical series resonance points around 800 Hz and strongly damped close to 500 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 in Horns Rev 2 around 200 Hz seen in Figure 4 is due to the wind farm 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.

3.2 Converter control representation

Many nowadays grid-side converter regulators use dq reference frame transformations to convert three-phase electrical network AC quantities into DC quantities. The dq transformation essentially performs frequency shifts of the system signals. [7], [8]. This frequency shift can provide misleading interpretation of the controller in the rotating reference frame and its interaction with the external system harmonic impedance. That is why it is better to express the regulator either in natural reference frame or stationary reference frame.

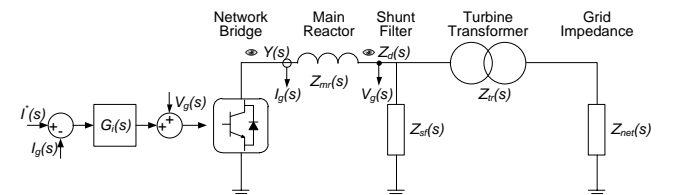


Figure 5 Single line diagram showing the admittance seen from AC terminals and the impedance seen from voltage measurement point as well as simplification of the control method.

The PI controller in synchronous reference frame

presented in Figure 1 can be expressed in stationary reference frame for stability evaluation in the following way

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

The controller transfer function is calculated according to the following equation derived in [7]

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

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. 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 [9]. This solution can cause some stability issues which will be shown later.

A typical notch filter can be represented in the following way

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

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 $2\omega_o$. It is worth to emphasize that the notch filter affects the direct chain in the control loop which can affect stability constraints.

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

$$G_N^{a\beta}(s) = Q_d \begin{bmatrix} s^4 Q_n Q_d + s^3 (Q_n + Q_d) \omega_N \\ + s^2 (2 Q_n Q_d \omega_o^2 + 2 Q_n Q_d \omega_N^2 + \omega_N^2) \\ + s ((Q_n + Q_d) \omega_o^2 \omega_N + (Q_n + Q_d) \omega_N^3) \\ + (Q_n Q_d \omega_o^4 + Q_n Q_d \omega_N^4 + \omega_o^2 \omega_N^2 - 2 Q_n Q_d \omega_o^2 \omega_N^2) \end{bmatrix}^{-1} \times Q_n \begin{bmatrix} s^4 Q_d^2 + s^3 2 Q_d \omega_N \\ + s^2 (2 Q_d^2 \omega_o^2 + 2 Q_d^2 \omega_N^2 + \omega_N^2) \\ + s (2 Q_d \omega_o^2 \omega_N + 2 Q_d \omega_N^3) \\ + (Q_d^2 \omega_o^4 + Q_d^2 \omega_N^4 + \omega_o^2 \omega_N^2 - 2 Q_d^2 \omega_o^2 \omega_N^2) \end{bmatrix} \quad 3.4$$

Additionally it is worth emphasizing that in real-life applications a non-ideal integrator can be used, as presented in [10]. The transfer function of such non-ideal integral controller used in rotating reference frame with angular frequency ω is as follows [11]

$$G_I^{dq}(s) = \frac{K_i}{1 + \frac{s}{\omega_c}} \quad 3.5$$

where K_i is the controller gain and $\omega_c \ll \omega$ is the controller cut-off frequency. Based on Eq. 3.2 the controller can be expressed in stationary reference frame

$$G_I^{a\beta}(s) = K_i \frac{s \omega_s + \omega_c^2}{s^2 + 2 \omega_c s + \omega_c^2 + \omega} \quad 3.6$$

The A/D converter can be approximated by the simplest Padé first-order approximation (i.e. first-order transfer function) [12]. It is worth emphasizing that the delay associated with the hold has a major impact in the digital implementation. In general a delay in any feedback system degrades the stability and damping of the system. The same approach is taken in case of pulse-width modulation delay of the voltage source converter. Additionally, considering non-ideal switches, the dead-time of the converter can be included. Please note that sample-and-hold as well as converter delays are already represented in stationary (also natural) reference frame. Please note that possible harmonic compensation can also cause unstable operation of the grid-side converter. Therefore it is of great importance to investigate the converter stability taking into consideration the whole wind farm structure to which it is connected.

3.3 Stability evaluation

The Nyquist plot shows the number of encirclements and thus the stability of the closed-loop system. Gain and phase margins are defined to provide a two-point measure of how close the Nyquist plot is to encircling the -1 point. The gain margin (GM) is the factor by which the gain can be increased before causing the system ($D(s)G(s)$) to be unstable, and is the inverse of the magnitude when its phase is 180° . The phase margin (PM) is the difference between -180° and the phase of the open-loop system when its amplitude is equal to 1. The PM is a measure of how much additional phase lag or time delay can be tolerated

in the loop before instability results [12], [13], [14].

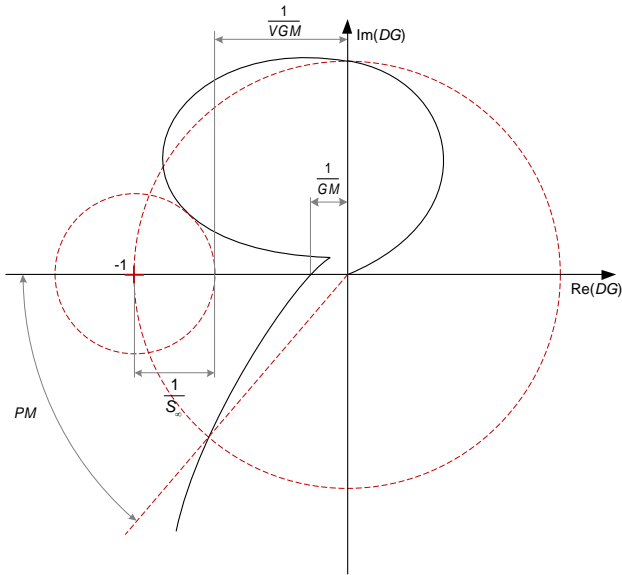


Figure 6 Nyquist plot showing various stability margins.

The gain and phase margins give useful information about the relative stability of nominal systems but can be misleading as a guide to the design of realistic control problems [12]. A more accurate vector gain margin (VGM) can be given in terms of the sensitivity function. It can be also seen that the maximum value of the sensitivity function can be associated with different frequency than indicated by either gain margin or phase margin (see Figure 6). This becomes a crucial issue in tuning the control of grid-side converter as well as in the analysis of possible resonances in the external network. Knowing that the frequency response of the plant can also be strongly affected by the wind farm internal cable network and export cable, this analysis approach can be also used at the wind farm design stage. The VGM is defined to provide a one-point measure of how close the Nyquist plot is to encircling the -1 (i.e. the system is on stability boundary) point and is a very good supplement for stability analysis based on PM and GM.

4 WIND FARM STABILITY

As it was presented, grid-side converter controller tuning is not straightforward task and even if all design criteria (e.g. overshoot, settling time) are met, it is still not sure that this particular control can be successfully applied in every system [15].

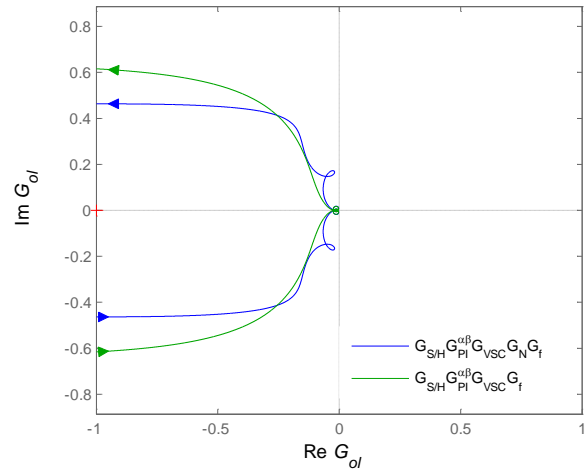


Figure 7 Nyquist plot of open loop system with and without notch filter in the main control chain.

Figure 7 presents how the notch filter affects the overall stability of the system in the Nyquist plot. Please note that the notch filter used in both positive and negative sequence synchronous reference frame is tuned for low frequencies. Thus only low frequency part of the Nyquist plot is changed. The controller frequency response from Figure 7 includes: the converter sample-and-hold delay ($G_{S/H}$), PI controller expressed in the stationary reference frame ($G_{PI}^{\alpha\beta}$), voltage source converter delay (G_{VSC}), notch filter expressed in the stationary reference frame (G_N), and the wind turbine main power circuit comprising of the main reactor, the shunt filter and the wind turbine transformer (G_I).

It is also of common practice to use different types of notch filters in the main control chain [5], [15] in order to improve noise (harmonic) rejection of the control system for higher frequencies. One of the good examples is to attenuate the effect of converter filter resonance [15]. The resonance poles of the filter can be compensated by application of appropriately tuned notch filter. Another practice of using notch filters is the compensation of resonant poles of the plant caused by significant capacitance in the system (e.g. capacitor banks, long HVAC cables) [5].

The effect of notch filter in the main control chain as well as low-frequency resonances in the plant will be investigated based on real-life existing systems. Once again Karnice onshore wind farm and Horns Rev II offshore wind farm are taken closely into consideration. Earlier it was presented how modeling (i.e. passive components models, aggregation techniques) can affect the frequency domain representation of the system. Now it will be shown how control techniques can interact with real-life systems.

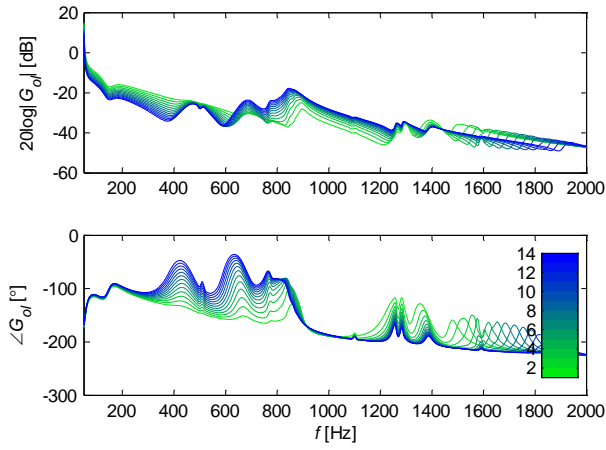


Figure 8 Open loop system frequency response where Karnice is the plant.

It was presented how the frequency response of the current controller can change depending of different factors (e.g. filters, harmonic compensation). It was also presented how to represent the controller in stationary reference frame (equal to natural reference frame [7]). Based on the results it is now possible to analyst how both the grid-side converter (i.e. compensator) and the wind farm (i.e. plant) can interact. In order to investigate the system within the wide range of frequency Bode and Nyquist plots are used.

Figure 8 represents Bode plot of the open loop system for frequencies higher than the fundamental and lower than around Nyquist frequency of the command signal. In this particular system the plant is the Karnice wind farm. The plot shows how the frequency response can change depending on number of wind turbines connected in the wind farm. Please note that Karnice contains 13 wind turbines connected together by relatively small MV network and relatively short cable to the distribution system

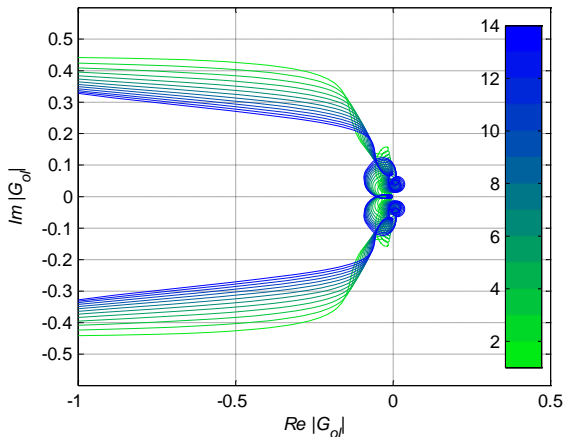


Figure 9 Nyquist plot of the open loop system where Karnice is the plant.

The Nyquist plot of open loop system comprising designed control and aggregated Karnice wind farm is shown in Figure 9. As it can be seen from the figure, the system is stable for all analyzed cases. Calculated stability margins (i.e. gain margin, phase margin, and vector gain margin) dependent on number of wind

turbines in operation are presented in Figure 10. It can be seen that all margins indicate the system robustness. It is interesting to emphasize that actually the gain margin and the vector gain margin significantly differs between each other. The vector gain margin is much smaller. Please note that gain margin and vector gain margin are supplementary, i.e. when the system is on the stability boundary both margins are equal to 0 dB.

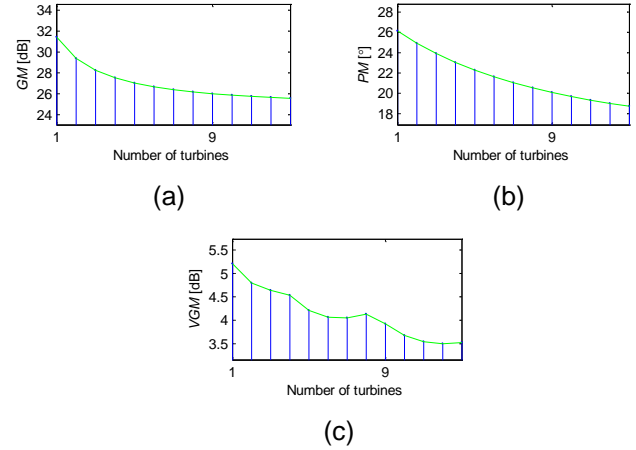


Figure 10 Gain margin, phase margin, and vector gain margin calculated for different number of wind turbines in operation of Karnice wind farm.

The vector gain margin presented in Figure 10(c) is much smaller from the gain margin in Figure 10(a) because of the notch filter tuned for $2\omega_0$ in synchronous reference frame. The notch filter affects the Nyquist characteristic when it is closer to the -1 point but does not affect any crossover points and therefore this change in the open loop characteristic cannot be observed by the gain margin.

In order to compare different wind farm systems also Horns Rev II offshore wind farm was considered. The Bode plot of open loop system is presented in Figure 11. Please note that the same current controller is used in case of both wind farms (i.e. Karnice and Horns Rev II). It is assumed that both wind farms are equipped with the same wind turbines with the same control strategy. Even if in real-life they are the same wind turbines it is not difficult to adjust the control strategy for particular systems of interest. It was presented that for different wind farms, especially large offshore wind farms with complex structure, the frequency dependent characteristic of the plant can significantly change. Therefore robustness assumption stated by different wind turbine manufacturers can be violated. It might not be unusual that wind turbines control should be changed depending on application (i.e. internal wind farm structure and the grid to which the wind farm is connected).

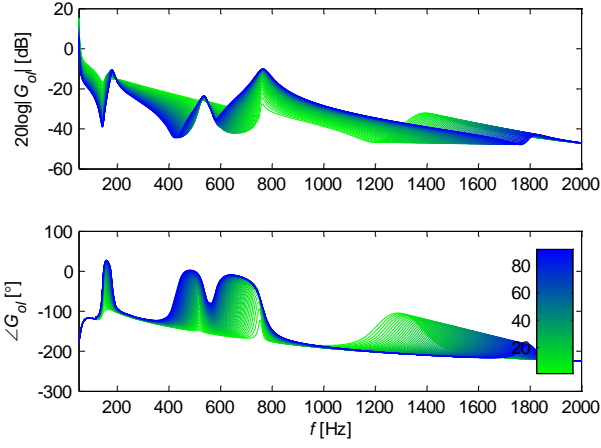


Figure 11 Open loop system frequency response where Horns Rev 2 is the plant.

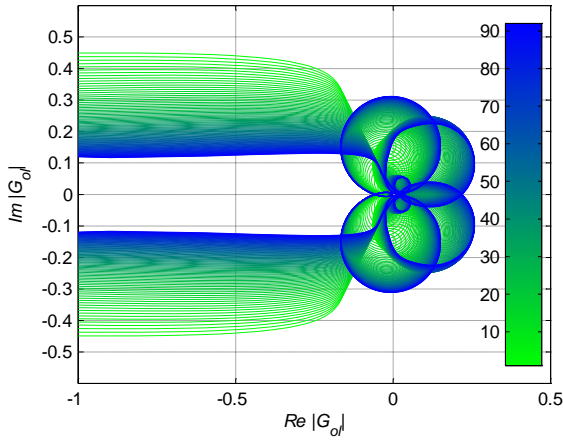


Figure 12 Nyquist plot of the open loop system where Horns Rev 2 is the plant.

Figure 11 and Figure 12 show how the open loop system can vary depending on number of wind turbines in operation. In case of Horns Rev II the changes are even more significant because the wind farm comprises of 91 wind turbines connected together by a widespread MV cable network. In Figure 11 one can see quite significant resonance peak around 200 Hz. This is caused by a series resonance between the park transformer inductance and the long HVAC cable capacitance. Such phenomenon cannot be seen in case of Karnice as shown in Figure 8 because there are no such long cables. This indicates that the overall system stability may be of concern, especially in large offshore wind farms.

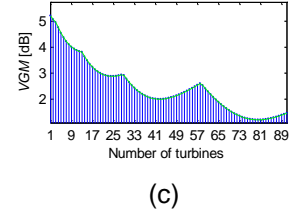
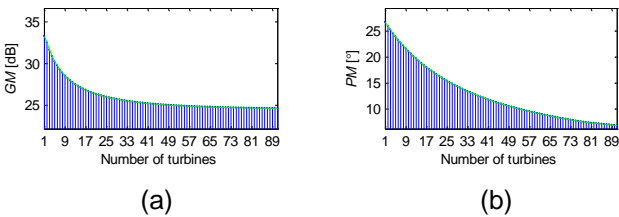


Figure 13 Gain margin, phase margin, and vector gain margin calculated for different number of wind turbines in operation of Horns Rev II wind farm.

Also based on stability margins from Figure 13 it can be seen that the vector gain margin is significantly lower when almost all wind turbines are connected. It was observed that the notch filter can significantly affect the vector gain margin in Karnice while the gain margin was high (around 26 dB). In case of Horns Rev II also the series resonance easily seen in the Bode plot additionally affects the system overall stability. Comparing Figure 11 and Figure 13(c) one can see that the vector gain margin is more affected by the notch filter for lower number of wind turbines in operation whereas more affected by the series resonance for higher number of wind turbines in operation.

5 CONCLUSIONS AND DISCUSSION

Analysis of impact of different wind turbine grid-side converter control scenarios on wind farms based on real-life systems (Karnice, Horns Rev II) is presented in this paper. The wind farm stability in frequency domain is presented based on Nyquist stability criteria. Additionally possible stability margins (i.e. gain, vector gain and phase margins) are calculated for different control structures and wind farm structures.

It is shown that more careful wind turbine grid-side converter control design is needed in case of large offshore wind farms, especially with significant shunt capacitances in the form of capacitor banks or long HVAC cable (e.g. Horns Rev II export cable). Differences between different control scenarios from stability perspective are pointed out and explained.

It was observed that large offshore wind farms can introduce additional unwanted resonances within the low frequency range. This can significantly affect the overall system stability. Therefore, analysis and design optimization of large offshore wind farms are more complex than smaller onshore wind farms. In the case of the Horns Rev 2 analysis, it was observed that the capacitance of long HVAC export cable and series inductance of the wind farm transformer creates unwanted and significant series resonance. Such situation is of concern in most of the erected large offshore wind farms.

Various control strategies were taken into consideration, and their impact on possible harmonic emission and overall system stability. The analysis was performed mainly in the frequency domain. One analyzed how particular components (e.g. filters, controllers, etc.) can affect the control and its harmonic rejection capability. The influence of control strategies on overall wind farm stability was deeply investigated.

The vector gain margin was suggested as a supplementary index to evaluate overall system stability in the frequency domain.

6 ACKNOWLEDGMENT

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

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