2013 48th International Universities' Power Engineering Conference

(UPEC 2013)

Dublin, Ireland
2-5 September 2013

Pages 1-543

IEEE Catalog Number: **CFP13569-POD**
ISBN: **978-1-4799-3255-9**

TABLE OF CONTENTS

Inter-Area Power Oscillation Frequency Mode with Wind Turbine Generator in Irish Power System using PMU Data

Iswadi HR
Queen's University Belfast
iiswadihr01@qub.ac.uk

R.J. Best
Queen's University Belfast
r.best@qub.ac.uk

D.J. Morrow
Queen's University Belfast
dj.morrow@ee.qub.ac.uk

***Abstract*-Two case studies are presented in this paper to demonstrate the impact of different power system operation conditions on the power oscillation frequency modes in the Irish power system. A simplified 2 area equivalent of the Irish power system has been used in this paper, where area 1 represents the Republic of Ireland power system and area 2 represents the Northern Ireland power system.**

The potential power oscillation frequency modes on the interconnector during different operation conditions have been analysed in this paper. The main objective of this paper is to analyse the influence of different operation conditions involving wind turbine generator (WTG) penetration on power oscillation frequency modes using phasor measurement unit (PMU) data.

Fast Fourier transform (FFT) analysis was performed to identify the frequency oscillation mode while correlation coefficient analysis was used to determine the source of the frequency oscillation. The results show that WTG, particularly fixed speed induction generation (FSIG), gives significant contribution to inter-area power oscillation frequency modes during high WTG operation.

***Index Terms*-correlation coefficient analysis, doubly fed induction generator, Fast Fourier transform, fixed speed induction generator, inter-area oscillation frequency, phasor measurement unit, power system oscillation, power system stability, wind turbine generator**

I. INTRODUCTION

The Irish power system is comprised the Republic of Ireland and the Northern Ireland power system. This system can be considered as a 2 area power system which is connected via a double circuit 275 kV North-South interconnector and two single circuit 110 kV [1].

European legislation has mandated that European Union countries have to provide at least 20% of final energy consumption supplied by renewable energy by 2020 [2]. In the Irish power system, due to the availability of renewable resources, both of Republic of Ireland and Northern Ireland government have targeted to have 40% of renewable energy in their system by 2020. WTG will become the main renewable energy contributor in the Irish power system [1].

With the increasing penetration level of WTG in the Irish power system, it is important to analyse their influence on power system operation, particularly inter-area power oscillation frequency modes. Previous work has shown how fixed speed induction generator (FSIG) can produce power oscillation at certain characteristic frequencies [3].

Moreover, the penetration of WTG has no influence on the damping of electromechanical modes of the system. However, it can induce several oscillatory modes [4]. Authors in [5] also observed that the increasing penetration of WTG has negligible effect on frequency damping.

The purpose of this paper is to investigate the behaviour of inter-area power oscillation frequency modes during different operation conditions. The details of case studies are presented in section II of this paper.

II. THE STUDY SYSTEM

A. Description of the Study Network

Fig.1 describes the characteristics of the study network that is used in this paper. This study network is an equivalent model of Irish power system which is comprised of the Republic of Ireland (area 1) and Northern Ireland (area 2) power systems. The equivalent model is based upon the one described in [6] and whose structure has been chosen to be roughly representative of the Republic of Ireland and Northern Ireland power systems.

Although the two power systems are connected through three interconnectors, in this paper only a double circuit 275 kV interconnector was considered since only this interconnector is used for bulk power transfer between the two areas.

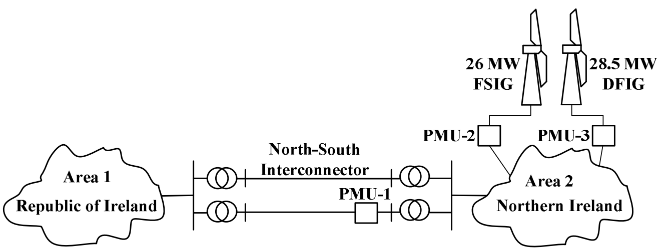

Fig. 1. Irish equivalent power system

978-1-4799-3254-2/13/$31.00 ©IEEE

Due to the limitation of data, only 10 conventional power plants and 2 WTGs are chosen in area 1 for this analysis while in area 2, there are 16 conventional power plants and 7 WTGs considered.

B. Phasor Measurement Units Data

A number of Phasor Measurement Units (PMUs) have been installed on the Irish power system. In this paper, the recorded PMU data from the three different measurement locations of PMU-1, PMU-2 and PMU-3 have been used. PMU-1 measures voltage and current (both magnitude and phase angle) and frequency at the North-South interconnector on the North side, while PMU-2 and PMU-3 have been employed for measurement at wind farms in area 2 for measurement at a 26 MW fixed speed induction generator (FSIG) wind farm and a 28.5 MW doubly fed induction generation (DFIG) wind farm respectively.

The measurements are taken at a rate 50 samples per second and time synchronized to global positioning system (GPS). Data is stored 5 minutes long comma separate value (csv) files. Recorded PMU data are available for long periods of time. The data analysed in this paper was recorded during the period of November 2011 to May 2012.

A number of generation units' (conventional and WTGs) power output data at ½ hour resolution has been used in the analysis. These data can be publically accessed from the single electricity market operator [7]. In addition, ½ hour resolution data of total wind farm generation in Republic of Ireland and power demand in Republic of Ireland and Northern Ireland can be acquired from SONI and EirGrid online publication and data centre [8], [9].

C. Case Studies

Two case studies have been analysed in this paper. Case study A is to analyse the inter-area oscillation frequency modes that occur in the interconnector during low wind and high demand operation condition. To achieve this condition, measurement data from the interconnector have been selected from the operation condition when WTG power output in the Republic of Ireland is less than 600-MW (36.5% of installed capacity) and the total Irish power demand from 4,500-MW to 6,300-MW (71.4%-100% of Peak Demand).

Conversely, case study B is to analyse the inter-area frequency oscillation mode during high wind and low demand condition when WTGs power output in the Republic of Ireland more than 800-MW (48.70% of installed capacity) while total Irish power demand is from 2500-MW to 4,500-MW (39.6%-71.4%).

Power oscillation frequency from 26-MW FSIG and 28.5-MW DFIG wind farms were analysed as well to observe whether these types of WTG give contribution to inter-area oscillation frequency by inducing its frequency to the power system.

III. METHOD

C. Fast Fourier Transform and Correlation Coefficient Analysis

A Fast Fourier transform (FFT) is performed using MATLAB by code written in m-files specifically for the task [10]. FFT amplitudes were calculated from 5 minutes length data during 6 month period. The number of FFT points from 5 minutes length of data is 2^{13} points (equal to 2.73 minutes of data) and the frequency resolution between FFT points is $50/2^{13}$=0.006103 Hz. The first 400 FFT amplitude points were analysed since this paper needs only to show the frequency amplitude spectrum from 0.2 Hz to 2.5 Hz.

Furthermore, correlation coefficient analysis is employed to identify a correlation between low resolution generator power outputs and certain frequencies in the interconnector. A positive correlation coefficient means that the increasing of generator power output would correspond to an increase in frequency spectrum amplitude while the negative coefficient means particular generator has an inverse relationship to the frequency spectrum amplitude. Furthermore, zero correlation coefficient means there is no association between generator power outputs to the oscillation frequency.

IV. RESULTS AND ANALYSIS

A. Case Study A: Inter-Area Power Oscillation Frequency during Low Wind and High Demand Operation Condition

Fig. 2 shows the power flow frequency spectrum in the North-South interconnector during low wind and high demand operation condition. From such conditions, it is possible to characterise the frequency oscillations on the interconnector when conventional thermal power plant is dominant.

It is noticeable from the fig. 2 that during case study A that several oscillation frequency modes occur on the interconnector in the range frequency from 0.2 Hz to 1.0 Hz.

The dominant oscillation frequencies are 0.268 Hz, 0.317 Hz, 0.336 Hz, 0.415 Hz, 0.446 Hz, 0.494 Hz, 0.653 Hz, 0.958 Hz and 0.995. Since during low wind and high demand operation condition some WTGs are still online so there is a possibility that these particular frequencies might be induced by excitation frequency from WTGs to the system. One of the sources of the frequency from WTG is the constant rotational turbine rotor speed, referred to as 1p (first excitation frequency). The second excitation frequency is the rotor blade passing frequency which is called as 2p and 3p excitation frequency for WTG with 2 and 3 blades respectively [11].

Some turbine manufactures have different gear ratios as describes in table I. It is shown from the table I that some of the excitation frequencies are close to the frequency on the interconnector during low wind and high demand operation condition. Frequency 0.653 Hz is probably from 2p excitation frequency while frequency 0.317 Hz and 0.336 are much closer to the 1p excitation frequency of fixed speed wind turbine with gear ratio 1:78. The peaks observed at 0.5 Hz and

1.0 Hz can be ignored as they are thought to be a function of the measurement process.

TABLE I
FIXED SPEED WIND TURBINE GEAR RATIO AND EXCITATION FREQUENCY

No	Gear ratio	Induction Generator Speed (rpm)	1p (Hz)	2p (Hz)	3p (Hz)
1	1/78	1515	0.324	0.647	0.971
2	1/91	1515	0.277	0.555	0.832
3	1/50	1515	0.505	1.010	1.515
4	1/55	1515	0.459	0.918	1.377

Furthermore, to identify which synchronous generator gives contribution to other frequency modes, correlation coefficient analysis was performed on 26 synchronous generators' power output to the oscillation frequencies in both areas.

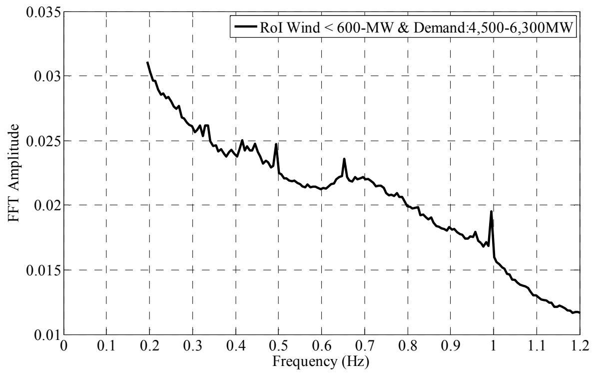

Fig. 2. Interconnector power flow frequency spectrum during high synchronous generation operation

The correlation coefficient of conventional power plants power output in area 1 and 2 to oscillation frequencies are given in fig. 3 and fig. 4 respectively. Among the 10 power plants in area 1, it has been found that 4 power plants (see fig. 3) have high positive and negative correlation coefficient to the inter-area frequency oscillations range while there are 7 power plants among 16 power plants in area 2 have been observed giving significant correlation coefficient in the inter-area oscillation frequency range.

It can be seen from the fig. 3 that these power plants give significant correlation on inter-area oscillation frequency at 0.446 Hz, 0.7-0.75 Hz and 0.958 Hz respectively. Power plant A1-3 and A1-1 give positive correlation coefficient on the frequency 0.446 Hz while power plant A1-2 and A1-4 give negative correlation coefficient. For the range of frequency 0.7-0.75 Hz, power plant A1-1 gives the highest positive correlation coefficient. Moreover, for the frequency 0.958 Hz, the highest positive correlation has given by power plant A1-3 then followed by generator A1-1 while the other two power plants have no significant correlation coefficient to the frequency 0.958 Hz.

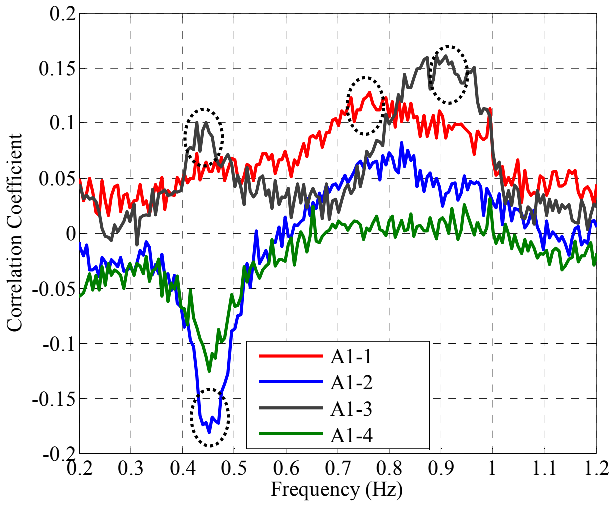

Fig. 3. Correlation of oscillation frequencies with the Republic of Ireland (area 1) synchronous generation power output during low wind and high demand operation.

Fig. 4 shows that 7 power plants in area 2 which contribute significantly to the oscillation frequency from 0.65 Hz to 1.0 Hz. Power plant A2-3, A2-7, A2-4 and A2-6 give positive correlation coefficient to the oscillation frequency 0.7-0.75 Hz while power plant A2-5 gives a small negative correlation coefficient. The highest negative correlation coefficient for the frequency 0.958 Hz is from power plant A2-2 and then followed by A2-5 while four others power plants namely: A2-7, A2-1, A2-6 and A2-4 give positive correlation coefficients.

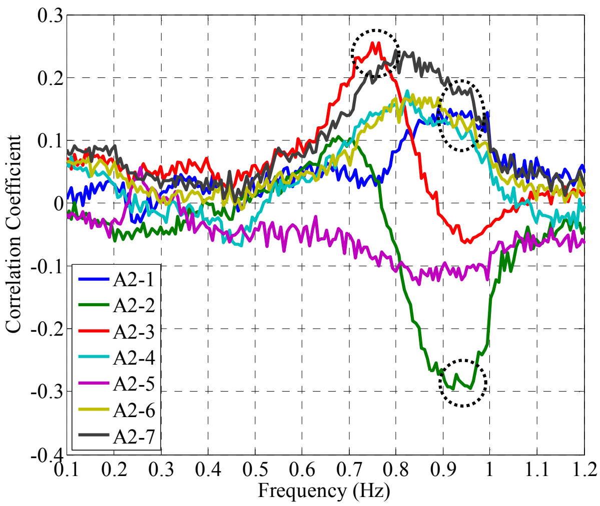

Fig. 4. Correlation of oscillation frequencies with NorthernIreland (area 2) synchronous generation power output during low wind and high demand operation.

Table II gives the summary of the correlation coefficients of different power plants from different areas on the certain oscillation frequencies during low wind and high demand condition.

TABLE II
SUMMARY OF DOMINANT CORRELATIONS OF POWER PLANTS ON CERTAIN FREQUENCIES

No	Freq (Hz)	Area 1		Area 2	
		+	-	+	-
1	0.446	A1-1 A1-3	A1-2 A1-4		
2	0.7-0.75	A1-1		A2-3 A2-4 A2-6 A2-7	A2-5
3	0.958	A1-1 A1-3		A2-1 A2-4 A2-6 A2-7	A2-2 A2-5

B. Case B: Inter-Area Power Oscillation Frequency during High Wind Low Demand Operation Condition.

Fig. 5 shows the power flow spectrum frequency in the North-South interconnector during both high wind and low demand condition (black line), and low wind and high demand condition (blue line) on the interconnection. These two operating conditions give different oscillation frequency modes on the North-South interconnector. Fig. 6 describes the significant difference of the oscillation frequency modes during these two conditions.

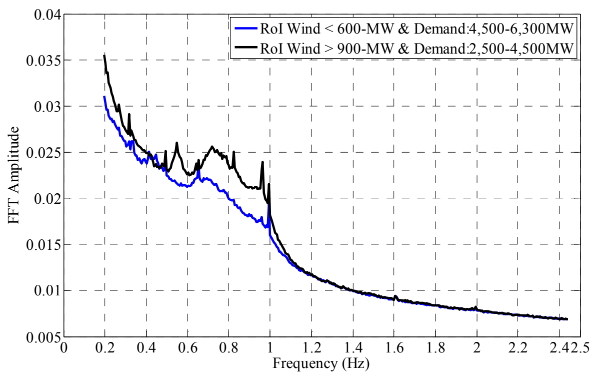

Fig. 5. Interconnector power flow frequency spectrum during high synchronous and high wind generation operation.

It can be observed from the fig. 6 that several peaks are present. Two frequencies 0.415 Hz and 0.446 Hz have negative peaks while the rest of frequencies (6 frequency modes), namely: 0.268 Hz, 0.317 Hz, 0.55 Hz, 0.64 Hz, 0.824 Hz and 0.964 Hz have a positive peak values. Negative peak values mean that these frequencies are dominant during case study A while the positive peak values mean it occurred during case study B.

Since these six frequencies are occurred during dominant wind generation in the power system, it might be useful to analyse the cause of these frequencies to look at it correlation to WTG power output.

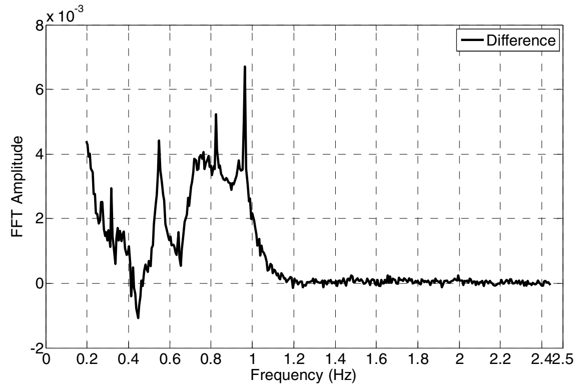

Fig. 6. Difference between Interconnector power flow frequency spectrum during high synchronous and high wind generation operation

Different types of WTGs are operated in the Irish power system, i.e. FSIG and DFIG WTGs. The recorded PMU data for these types of WTGs are available from measurement of PMU-2 and PMU-3. Using these data, the FFT analysis was performed to extract the potential power oscillation frequency from each of wind farm.

Fig. 7 shows the dominant power oscillation frequency from the 26-MW FSIG wind farm that consists of 20, 1.3 MW wind turbines. Dominant power oscillation frequency modes can be observed in the range of 0.2 Hz-1.0 Hz, namely: 0.273 Hz, 0.321 Hz, 0.55 Hz, 0.64 Hz, 0.79 Hz and 0.96 Hz. Three of these frequencies (i.e.: 0.55 Hz, 0.64 Hz and 0.96 Hz) have the same frequency as present on the interconnector. From the equality of frequency between FSIG wind farm and the frequency on the interconnector, it suggests that FSIG may contribute to certain frequencies that appear on the interconnector.

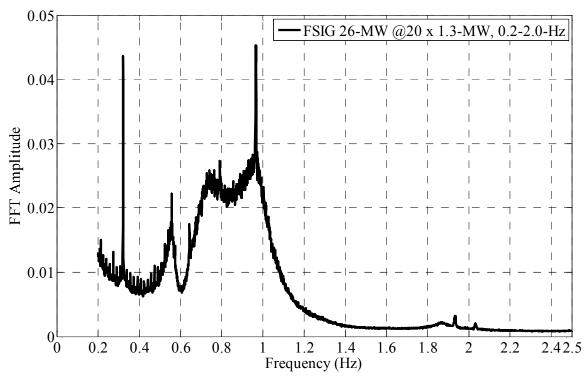

Fig. 7. Power output frequency spectrum for 26-MW FSIG wind farm of 1.3 MW turbines

Furthermore, the correlation coefficient analysis between 26-MW FSIG wind farm power outputs to oscillation frequencies on the interconnector has been performed. Fig. 8 shows the graph of correlation coefficient in the range frequency 0- 2.4 Hz. 6 frequencies can be observed from the fig. 8 that have peak values of correlation coefficients, namely: 0.268 Hz, 0.317 Hz, 0.55 Hz, 0.64 Hz, 0.824 Hz, and 0.964 Hz. These six frequency modes are also present on the North-South interconnector during high wind and low demand conditions.

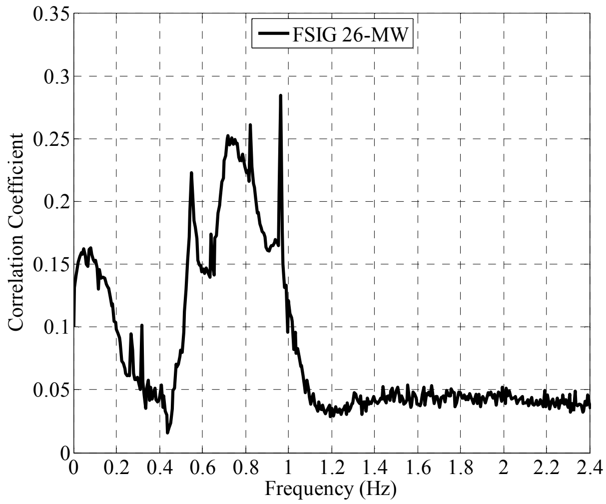

Fig. 8. Correlation of oscillation frequencies with 26-MW FSIG WTG power output

The PMU measurement data for DFIG wind farm was collected by PMU-3 and recorded data was analysed using FFT analysis as shown in Fig. 9. Dominant power oscillation frequencies from 28.5-MW DFIG in the range of 0.2-1.0 Hz can be observed as follows: 0.323 Hz, 0.64 Hz and 0.99 Hz. The frequency 0.64 Hz is also presence on the North-South interconnector during high wind and low demand condition.

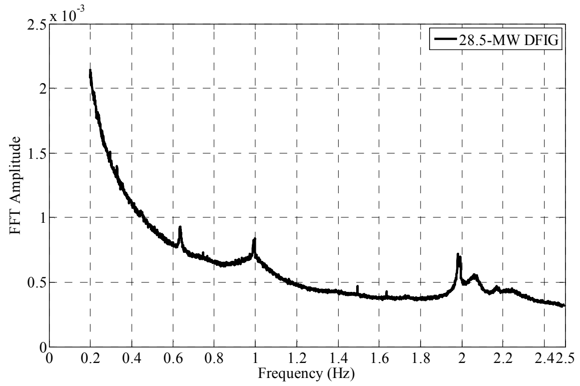

Fig. 9. Power output frequency spectrum for 28.5-MW DFIG wind farm

From the figures can be drawn a conclusion that FSIG power output give significant influence to the inter-area oscillation frequency modes that occur on the interconnector. However, further research is needed to observe whether power oscillation frequency modes from DFIG wind farm are induced to the system as inter-area oscillation frequency that exist in the interconnector.

V. CONCLUSION

In this paper, two study cases to demonstrate the influence of WTG penetration on inter-area oscillation frequency modes have been presented. FFT analysis was performed to extract dominant oscillation frequency modes in the interconnector and dominant frequency mode from both of FSIG and DFIG WTG using recorded PMU data.

Several oscillation frequency modes are observed and these oscillation frequency modes are influenced by the WTG penetration into the system.

Correlation coefficient analysis was performed for the two case studies so that the oscillation frequencies could be attributed to conventional thermal plant or WTGs. Power oscillation frequency from FSIG WTG can be observed on the interconnector as well. It suggests that frequency modes on the interconnector are influenced by FSIG WTG. Further research is needed to determine whether oscillation frequency modes from DFIG WTG are induced into the system as inter-are oscillation frequency modes on the North-South interconnector.

ACKNOWLEDGEMENTS

The authors wish to thank the Directorate General of Higher Education, Ministry of Education and Culture, The Republic of Indonesia for providing a PhD scholarship to Iswadi HR to pursue his PhD at Energy Power and Intelligent Control (EPIC) research cluster, the School of Electronic, Electrical Engineering and Computer Science, Queen's University Belfast.

REFERENCES

[1] SONI; EirGrid, "All-Island Generation Capacity Statement 2013-2022," 2012.

[2] European Parliament and The Council, "Directives 2009/28/EC," *Official Journal of the European Union,* vol. 52, pp. 16-62, 2009.

[3] S. Brownlees, B. Fox, D. Flynn and T. Littler, "Wind Farm Induced Oscillations," in *41st International Universities Power Engineering Conference, UPEC 2006*.

[4] M. H. Nguyen, T. K. Saha and M. Eghba, " Impact of high level of renewable energy penetration on inter-area oscillation," in *Universities Power Engineering Conference (AUPEC), 2011 21st Australasian*, 2011.

[5] N. Modi, T. K. Saha and N. Mithulananthan, "Effect of Wind Farms with Doubly Fed Induction Generators on Small-Signal Stability- A Case Study on Australian Equivalent System," in *IEEE PES Innovative Smart Grid Technologies, ISGT Asia 2011*, 2011.

[6] M. Kein, G. Rogers and P. Kundur, "A Fundamental Study of Inter-Area Oscillation in Power Systems," *Transaction on Power System,* vol. 6, no. 3, pp. 914-920, 1991.

[7] Single Electricity Market Operator, "semo," 2013. [Online]. Available: http://www.sem-o.com/Pages/default.aspx. [Accessed 1 January 2013].

[8] EirGrid, "EIRGRID," 2013. [Online]. Available: http://www.eirgrid.com/. [Accessed 01 January 2013].

[9] SONI, "SONI," 2013. [Online]. Available: http://www.soni.ltd.uk/. [Accessed 1 January 2013].

[10] Mathworks, "Mathworks," [Online]. Available: www.mathworks.com.

[11] J. v. d. Tempel and D.-P. Molenaar, "Wind Turbine Structural Dynamic - A Review of the Principles for Modern Power Generation, Onshore and Offshore," *Wind Engineering* , vol. 26, no. 4, pp. 211-220, 2002.