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Influence of a Wind Farm on Power System Oscillatory Stability

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Abstract*— This paper deals with the influence of wind turbine generators on oscillatory stability. Examining low-frequency oscillatory stability is important for understanding the weakest mode that leads to oscillatory problems. The performance of three types of wind generators, the doubly fed induction generator, the squirrel cage induction generator, and the permanent magnet synchronous generator, when connected to a grid was examined. Eigenvalue analysis and time-domain analysis helped to identify oscillatory instability problems in the wind farm. Moreover, the advantages of a high voltage direct current link (HVDC) for improving instability issues was studied. The simulation results show the significance of the DC link in improving the stability of the system by isolating the wind farm at the point of common couple from a fault event. The simulation software tool DIgSILENT PowerFactory was used for all modelling of wind farms, HVDC, and the IEEE 14-bus test system.

Index Terms*— Wind Turbine Generators, Oscilatory Stability, DFIG, PMSG, SCIG, HVDC, IEEE 14-bus test system, Eigenvalue analysis, DIgSILENT PowerFactory.

I. INTRODUCTION

Wind energy has become one of the most competitive forms of renewable energy industries worldwide. Increasing power generation from renewable sources, such as wind, would help to reduce carbon emissions and minimize the effect on global warming. Wind energy has attracted attention because of several advantages that lead to the extraction of maximum energy, no CO2 emissions, and the low cost of a wind turbine generator (WTG). In addition, the capacity of wind energy from a wind farm has increased by more than 20% globally [1, 2]. This increasing penetration of renewable energy has challenged the power system operators and planners who have to ensure a reliable and secure operation. As power generation increases from renewable sources of energy, such as wind, the investigation of wind power system stability becomes essential. However, the integration of wind farms could cause stability problems [3, 4]. There is a growing concern about the impact of interconnections on small signal stability. This concern on stability problems is fuelled by the many system blackouts that have been identified from power system instability of different kinds, including transient and voltage instability. Oscillations have been observed in power systems as soon as a wind power generator is interconnected to the grid [5]. The basic explanation of small signal stability deals with the capability of the system or generators to maintain synchronism when exposed to small disturbances [6]. Usually, the problem is related to the lack of sufficient damping of system oscillations. As the development of power systems has advanced, the need for small-signal studies and measures to ensure sufficient stability margin has been recognized [7]. Low-frequency stability is considered when there are small disturbances in the power system [8]. These disturbances can cause electromechanical oscillations, but most of the time the disturbances just decays within a certain period and the system is able to revert to its stable operating point [9]. However, if the system is not adequately damped, the oscillation may lead to a system blackout. This paper is organized as follows. In Section II, the methodology for analysing oscillatory stability is described. Section III presents Eigenvalue characterization. In Section IV, modelling of the HVDC link and IEEE 14-bus test system is presented. Section V presents and compares the preliminary results of low oscillatory stability in a wind farm. Lastly, conclusions are presented in Section VI.

II. METHODOLOGY

Different methods have been used to analyse small signal stability of power systems. These methods include Prony analysis and the Fourier method [4], modal analysis [10], time-domain simulations [11], and probabilistic methods [12, 13]. Small signal stability can be analysed by linearising the system about an equilibrium point represented by a steady-state operating condition. This requires understanding the dynamic characteristics of the system. System equations can be formulated by starting with nonlinear ordinary differential equations that can be linearised at the operating point [14]:

$\dot{X} = f(x, u, t)$, (1)

where x is the state variable, u is the input variable, and t is the time.

$\dot{x} = f(x, u)$ (2)

The output variables can be

$y = g(x, u)$. (3)

Linearisation

$\dot{X} = f\left(x_0, u_0\right) = 0$ (4)

$x = x_0 + \Delta x$; (5)

$u = u_0 + \Delta u$ (6)

Δ=small deviation

Substitute x and y with a small deviation

$\dot{x} = \dot{x}_0 + \Delta\dot{x}$ (7)

$= f\,[(\dot{x}_0 + \Delta\dot{x}), (\dot{u}_0 + \Delta\dot{u})]$. (8)

A nonlinear function can be expressed as a Taylor Series

$\dot{x}_{0i} + \Delta\dot{x} = f_i[(x_0 + \Delta x), (u_0 + \Delta u)]$ (9)

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$$= f_i(x_0, u_0) + \frac{\partial f_i}{\partial x_i}\Delta x_1 + \frac{\partial f_i}{\partial x_2}\Delta x_2 + \ldots + \frac{\partial f_i}{\partial x_n}\Delta x_n + \frac{\partial f_i}{\partial u_i}\Delta u_1 + \frac{\partial f_i}{\partial u_2}\Delta u_2 ++ \frac{\partial f_i}{\partial u_r}\Delta u_r\,. \qquad (10)$$

Linearisation

$$\dot{X}_{0i} = f_i(x_0, u_0)$$

$$\Delta \dot{X}_{0i} = \frac{\partial f_i}{\partial x_i}\Delta x_1 + \frac{\partial f_i}{\partial x_2}\Delta x_2 + \ldots + \frac{\partial f_i}{\partial x_n}\Delta x_n + \frac{\partial f_i}{\partial u_i}\Delta u_1 + \frac{\partial f_i}{\partial u_2}\Delta u_2 + \ldots + \frac{\partial f_i}{\partial u_r}\Delta u_r \qquad (11)$$

or

$\Delta\dot{X}$=AΔX + BΔU this from linearise $\dot{x} = f(x,u)$

$\Delta\dot{Y}$=CΔX + DΔU this from linearise $\dot{y} = g(x,u)$

A, B, C, and D are matrices with partial derivative terms, where A is the state matrix, B is the control matrix, C is the output matrix, and D is the feed forward matrix.

$$\det(SI - A) = 0 \qquad (12)$$

We can rewrite the previous equation as

$$\det(\lambda I - A) = 0 \qquad (13)$$

The eigenvalues of state matrix A are given by the values of the scalar parameter

$$\lambda = \alpha \pm j\beta\,, \qquad (14)$$

where α is the real part of the eigenvalues and β is the complex part of the eigenvalues.

Damping ratio $\zeta = \frac{-\alpha}{\sqrt{\alpha^2+\beta^2}}$ (15)

Frequency $f = \frac{\beta}{2\pi}$ (16)

The damping ratio can determine the rate of decay of the amplitude of the oscillation stability. Frequency can determine the oscillatory stability modes.

III. PROPERTIES OF EIGENVALUES

Calculation of frequency and damping ratios can give a better understanding of the system oscillation modes, the main property of eigenvalues found in [8]. This includes:

(1) If all the eigenvalues of the system have negative real parts after linearising, the system is asymptotically stable.

(2) If the system has at least one of the eigenvalues with positive real parts, the system is unstable.

(3) If all the eigenvalues of the system have negative real parts, except one complex pair having purely imaginary values, the system exhibits oscillatory motion.

IV. WIND TURBINE AND TEST SYSTEM MODELS

A. The Aerodynamics Model

The maximum mechanical power output of a wind turbine is produced by the following equation:

$$P_m = \frac{1}{2}\rho . A . C_p(\lambda,\beta) . V_w^3, \qquad (17)$$

where P_m is the mechanical power [W] , ρ is the air density ($\rho = 1.225\,[kg/m^3]$, A represents the areas swept by bald of the wind turbine, which can be calculated from ($A = \pi R^2\ (m^2)$), $C_p(\lambda,\beta)$ is the power coefficient of the particular wind turbine, v_w is the wind speed $[m/s]$, β is the pitch, λ is the tip speed ratio, and v_t/v_w is the ratio between the blade tip speed v_t and the wind speed.

The tip speed ratio (λ) is related to the power coefficient defined as

$$\lambda = \frac{R.W_r}{V_w}, \qquad (18)$$

where R is the rotor radius in meters and W_r is the rotor speed in pu.

The power coefficient can be calculated by using

$$C_p(\lambda,\beta) = 0.73\left(\frac{151}{\lambda} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{\left(\frac{-18.4}{\lambda}\right)} \qquad (19)$$

$$\lambda = \left(\frac{1}{\frac{1}{\lambda+0.02\beta} - \frac{0.003}{(\beta^3+1)}}\right). \qquad (20)$$

B. Pitch Angle Controller

The pitch angle controller is used for adjusting the wind turbine blade pitch angle during high wind speeds. The pitch angel degree at low wind speeds must remain constant and is equal to zero. Figure 1 illustrates the power coefficient (C_p) virus tip-speed ratio (λ). The figure shows that for a higher power coefficient (Cp) corresponding to a lower pitch angle value (β=0), maximum mechanical power is achieved for a lower wind speed.

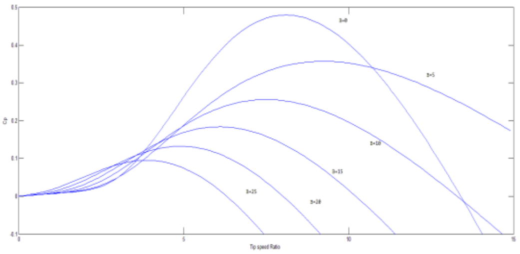

Fig. 1 Power Coefficient Curves with Different Pitch Angles

C. Type of Wind Turbine Generators

Three common WTGs are commonly used in wind energy industry.

- *Fixed speed wind turbine*

Typically, turbines are built-in with squirrel cage induction generators (SCIG) that connect to a rotor that converts the wind to kinetic energy and then connects to a grid through a step-up transformer. Figure 2, shows the main components of squirrel cage induction generators. Capacitors are connected to a stator that provides reactive power compensation that connects to the grid [15, 16].

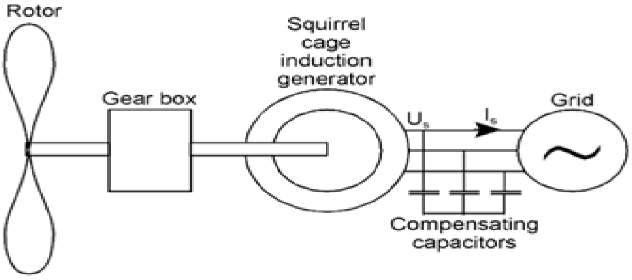

Fig. 2 Components of a Fixed Speed Wind Turbine [11]

There are some advantages to a wind turbine with an induction generator, including a simple structure, low cost of construction, and no requirement for a synchronization device [17, 18].

However, there are some drawbacks, such as limited speed, the need for a constant speed for high starting current, low efficiency, and the demand for reactive power [15].

- *Doubly fed induction generator system (DFIG)*

Most of the new advanced wind farms use a DFIG, as illustrated in Figure 3. This system uses an induction machine with a wound rotor, which is connected to the grid via a back-to-back voltage source converter, while the stator is directly connected to the grid. [12].

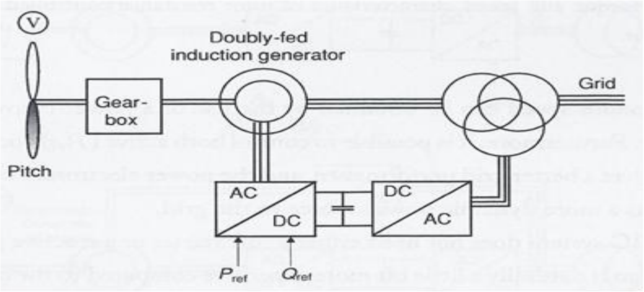

Fig. 3 Wind Turbine Circuit Model DFIG [16]

The DFIG performs well when 30% partial full converter is adjusted, usually using voltage source converter. The pitch controller controlled the aerodynamic rotor speed that coupled via a gearbox to the generator. As the frequency converter only transmits the rotor power, it can be designed for typically 25%−30% of the total turbine power [18].

- *Permanent magnet synchronous generator (PMSG)*

A synchronous generator can be used to model a PMSG. This type of generator needs to couple with a full back-to-back converter, such as a full-scale PMW voltage source converter [19]. For a multiple PMSG to run at a very low speed, a high number of poles is required in the PMSG wind turbines. This generator is self-exciting because of the permanent magnets in place of the rotor [12].

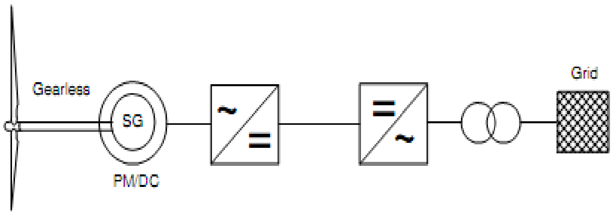

Fig. 4 Direct-Drive Synchronous Generator [18]

D. High Voltage DC Link (HVDC)

A monopolar HVDC link is the basic type of HVDC or DC link. This model can be considered as a DC link because it uses the distribution system [7]. The model contains two converters that connect to the AC system or generator side and convert the voltage from AC to DC. Two inverters with the same voltage rate are linked to convert DC to AC, connecting to the grid as can be seen in the model. Some loads are placed between the model to check whether the model works perfectly. Two three-winding transformers are connected to the converter and inverter, which are connected to the generator and grid, respectively.

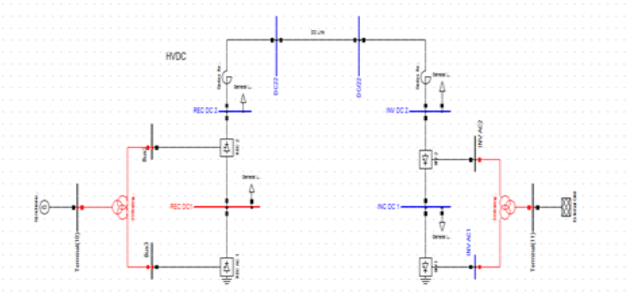

Fig. 5 High Voltage Direct Current (HVDC) Link

The HVDC link is currently of interest for connecting two or more systems. Many offshore wind farms use an HVDC link for the following reasons [5, 7]:

- To keep the rated power of the converter as high as possible for a given current and voltage ratings.
- To minimize voltage drops at the AC terminals as loading increases.
- To minimize the cost of the reactive power supply to the converters.

E. IEEE 14-Bus Test System

In order to study the oscillatory stability in wind farms, the IEEE 14-bus test system was modelled. More details about the system have been published [20]. In general, the rated voltage of the system is 13.8 KV at 50 Hz.

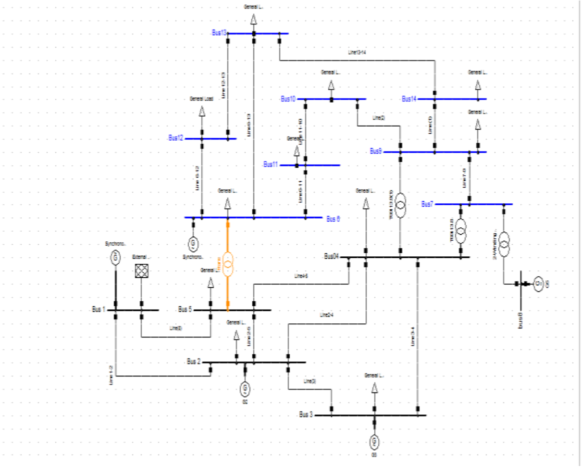

Fig. 6 Layout of a Modified IEEE 14-Bus System

V. RESULTS AND DISCUSSION

This section demonstrates the modelling of wind turbines, using the software DIgSILENT. Eigenvalue analysis and time-domain analysis are also performed using DIgSILENT. Calculations of frequency and damping ratios for each different local and inter-area mode found in the system are listed in the tables.

A. Analysis of Wind Turbine Models

Eigenvalue analysis shows the stability of the system through the location of eigenvalues. The frequency provides us with the oscillatory modes. In this analysis, focusing in local mode and inter-area mode identifies the strongest and weakest mode of the system for SCIG, DFIG, and PMSG generators.

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Very-low-frequency oscillatory stability is located in inter-area mode, which has a frequency between 0.1 to 0.3 Hz. This is called the weakest model. Tables 1, 2, and 3 show the results of the eigenvalues for SCIG, DFIG, and PMSG, respectively.

Table 1 Local Mode of Fixed-Speed Wind Generators

	Name	Eigenvalue	Frequency	Damping Ratio
	Mode	Λ	Hz	
SCIG	1	–0.6798254 ± 3.984476 i	0.634149	0.168188

This system has only one inter-area mode, which is –0.6798254 ± 3.984476 i; the frequency is 0.6 and the damping ratio is 0.168188.

Table 2 Local Mode of Fixed-Speed Wind Generators

	Name	Eigenvalue	Frequency	Damping Ratio
		Λ	Hz	
DFIG	Mode 1	–0.99593 ± 13.59297 j	2.163389	0.07307229
DFIG	Mode 1	0.003027 ± 0.01240738 j	0.00197469	–0.2369888

Table 2 shows the frequency and damping ratio of the system. This system has only one local mode in –0.99593 ± 13.59297 j and has the poorest damping ratio.

Table 3 Eigenvalues of PMSG Wind Generators

Machines	Name	Eigenvalue	Frequency	Damping Ratio
		Λ	Hz	
PMSG	Mode 1	–1.110442 ± 10.66487j	1.697367	0.1035616

Table 3 shows that the system has only one local mode in –1.110442 ± 10.66487j with a damping ratio of 0.1035616.

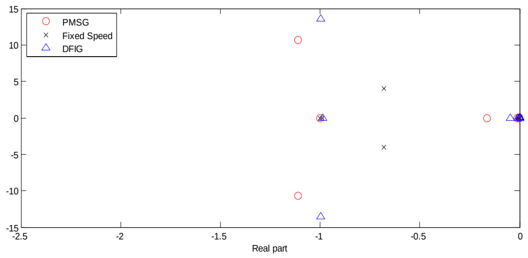

Fig. 7 Comparison of the Eigenvalues of PMSG, DFIG, and Fixed-Speed Wind Turbines

As shown in the graph of Fig. 7, both DFIG and PMSG eigenvalues are located in the left-half plane. Figure 7 shows that PMSG is better than the fixed-speed turbine because the location of a pair of complex eigenvalues of fixed-speed is near zero. Therefore, PMSG and DFIG can provide system stability by adding damping to the system. Time-domain analysis was carried out to compare the three types of wind generators. This simulation proved that PMSG is an attractive choice for a wind energy system. This simulation was applied to a three-phase fault near the grid side to see the overall result of system stability that is due to a small disturbance.

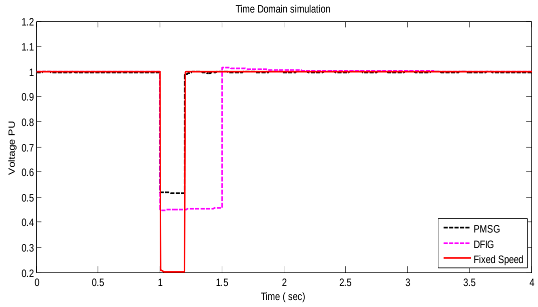

Fig. 8 Comparison of Time-Domain Simulations for PMSG, DFIG, and Fixed-Speed Wind Turbines

Figure 8 shows the voltage recovery of wind turbines when three-phase faults are applied at the end of the generation bus. The time-domain simulation shows that DFIG and PMSG have the ability to recover from the fault within a few seconds while the fixed-speed turbine continues deep when the same three-phase fault is applied.

B. Analysis of a Wind Farm Connected to an IEEE 14-Bus Test System

In this simulation, each type of wind turbine generator was connected to the IEEE 14-bus system separately. The results were combined in one graph, using MATLAB tools. The rating of each wind farm had a total capacity of 50 MW. The 25 generators of each wind turbine were rated 2 MW at 50 Hz. These wind farms have the same details as the wind turbines discussed in the previous section. The wind farms were connected to the IEEE 14-bus system via bus 12, which was chosen for the simulation.

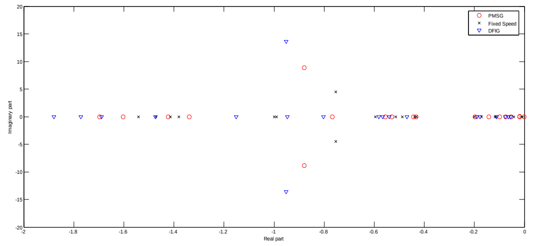

Fig. 9 Eigenvalue of 50 MW for all IEEE 14-Bus System Generators with a Scale of 0–2

Based on the eigenvalue graph above, it can be seen that all eigenvalues have negative real parts, which means that the system with the 14-bus system is stable. However, the locations of the eigenvalues of each wind farm are between –0.7 to –1, which means that oscillatory stability modes are introduced to the system when large-scale wind farms are connected to the system. PMSG eigenvalues show that the system is not damping well, while DFIG wind farms show a good damping system. This is in contrast to theory. Further simulations are needed to identify the models that can deal with low-frequency oscillatory problems.

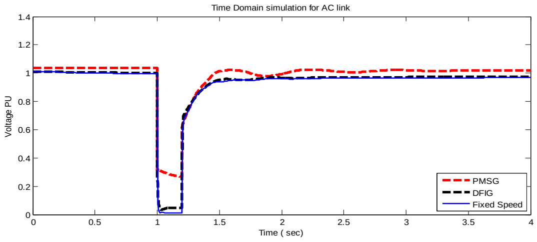

Fig. 10 Time-Domain Simulation of Wind Farms Connected to an IEEE 14-Bus System via an AC Link

Figure 10 shows all three wind farm generators that participated in the simulation models. It is interesting that PMSG has the best time voltage recovery compared to DFIG and fixed-speed wind turbines. Low-frequency oscillatory problems in the models was not determined since the methods looked at different aspects of the system, i.e., time-domain simulation looks at voltage recovery, while eigenvalue analysis looks at the oscillatory stability of the system. Consequently, more models have been built in order to perform more analyses to better understand low-frequency oscillation problems.

C. Analysis of a Wind Farm Connected to an IEEE 14-Bus Test System through an HVDC Link

In this simulation, each type of wind turbine generator was connected to the IEEE 14-bus system separately. This simulation investigated the influence of an HVDC link in damping the small signal stability of wind farms. The wind farm layout below had a total capacity of 50 MW at 50 Hz frequency. The wind generators were arranged in one strand, each connecting five wind farms with a total capacity of 50 MW. Ten generators were in each wind farm, each rated 2 MW at 50 Hz frequency. The wind farm was connected to the IEEE 14-bus test system via bus 12, which was chosen for the simulation. This system was connected via AC and DC in order to investigate low-frequency oscillatory.

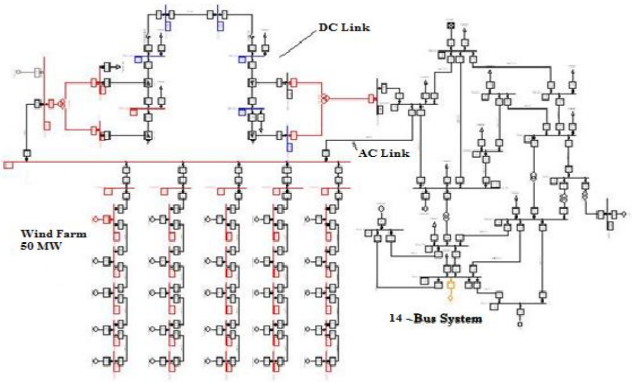

Fig. 11 Wind Farm Layout with an HVDC Link and IEEE 14-Bus System

The simulation results were obtained from connecting the wind farms first with the AC link and then plotting the eigenvalues. The DC link was then connected and the AC link disconnected, followed by the plotting of the eigenvalues of the system. Figure 11 shows the comparison of eigenvalues in both AC and DC links. The results are not clear because both eigenvalues are located at the same location. Figure 12, however, clearly shows that the AC link has good damping compared to the DC link. This is a questionable simulation result because, in theory, the HVDC link has many advantages in damping the power system oscillation problems. The configuration of the DC link may have some errors, especially in the control modes.

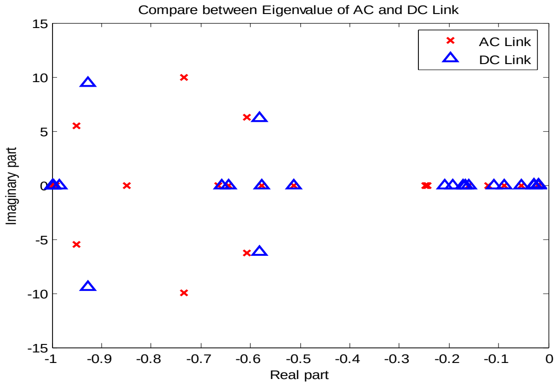

Fig. 12 Eigenvalues of AC and DC Links

A three-phase fault was applied to bus 12 in order to analyse the time-domain simulation by checking the influence of the voltage recovery of the system when connected through AC and DC links. Time-domain simulation for the AC link shows the voltage recovery of the system. This voltage at a common bus connected to the IEEE 14-bus system of the wind farm shows that the system was able to recover from the three-phase fault within a few seconds. When the IEEE 14-bus system was connected to the wind farm via the DC link and the three-phase fault was applied to bus 12, the DC link blocked the fault to reach the wind farm. This proves that the HVDC link has the ability to improve the stability of wind farms in both voltage stability and small signal stability (Fig. 13).

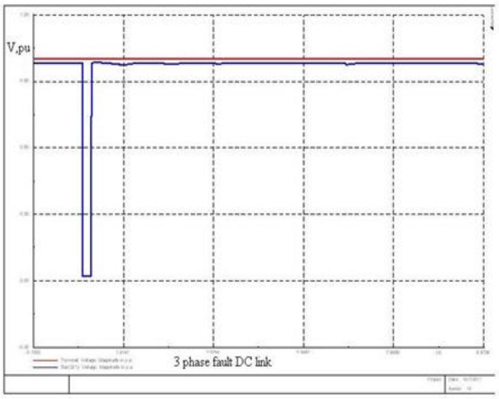

Fig. 13 Time Domain Simulation for the DC Link

VI. CONCLUSION

The purpose of this research was to analyse and understand the low-frequency oscillatory stability that occurs during the integration of wind farms with different wind farm models. Examining low-frequency oscillatory stability is important for understanding the weakest mode that leads to oscillatory problems.

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Small signal study methods, including eigenvalue analysis, are able to identify system problems and give more details about the wind farm models. Local mode and inter-area mode are the main modes that can show oscillatory problems. From the simulation results, the conclusions can be summarized as follows:

- Eigenvalue analysis showed that PMSG added more damping to the system. Furthermore, domain simulation analysis proved that the voltage recovery of the PMSG wind turbine was highest compared to DFIG and fixed-speed turbines.
- When groups of wind generators or turbines were connected together, as the wind farm to the IEEE 14-bus system, the DFIG performed better than the PMSG.
- DC links improved the stability of the system by isolating the wind farm from a fault event during time-domain analysis.

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REFERENCES

1. K. R. Steve Sawyer, "Global Wind Report," belgium 2010.
2. K. R. Steve Sawyer, "Global Wind energy Outlook 2010," belgium 2010.
3. S. Heier, Grid Integration of Wind Energy Conversion System, 1998.
4. D. Thakur and N. Mithulananthan, "Influence of Constant Speed Wind Turbine Generator on Power System Oscillation," Electric Power Components and Systems, vol. 37, pp. 478-494, 2009.
5. G. Rogers, power system Oscillations: Kluwer Academic Publishers, 2000.
6. P. W. Sauer, Power Systen Dynamics and Stability: Prentice-Hall, Inc., 1998.
7. P. Kundur, Power System Stability and Control. New York: McGraw-Hill, Inc., 1994.
8. O. A. Almasari, "Low Frequency Oscillatory Stability Study of Power System with Wind Farms," Master Degree, School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, 2011.
9. W. Chen, S. Libao, W. Liming, and N. Yixin, "Small signal stability analysis considering grid-connected wind farms of DFIG type," in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008, pp. 1-6.
10. A. F. Snyder, "Inter-Area Oscillation Damping with Power System Stabilizers and synchronized Phasor Measurements," Master thesis, Electrical Engineering, Virginia Polytechnic Institute and State University, 1997.
11. F. J. Swift and H. F. Wang, "The connection between modal analysis and electric torque analysis in studying the oscillation stability of multi-machine power systems," International Journal of Electrical Power & Energy Systems, vol. 19, pp. 321-330, Jun 1997.
12. J. G. Slootweg and W. L. Kling, "The impact of large scale wind power generation on power system oscillations," Electric Power Systems Research, vol. 67, pp. 9-20, Oct 2003.
13. R. C. Burchett and G. T. Heydt, "Probabilistic Methods For Power System Dynamic Stability Studies," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-97, pp. 695-702, 1978.
14. R. D. Fernández, R. J. Mantz, and P. E. Battaiotto, "Impact of wind farms on a power system. An eigenvalue analysis approach," Renewable Energy, vol. 32, pp. 1676-1688, 2007.
15. D. Gautam, V. Vittal, and T. Harbour, "Impact of increased penetration of DFIG based wind turbine generators on transient and small signal stability of power systems," in Power and Energy Society General Meeting, 2010 IEEE, 2010, pp. 1-1.
16. Y. Sun, L. Wang, G. Li, and J. Lin, "A review on analysis and control of small signal stability of power systems with large scale integration of wind power," in Power System Technology (POWERCON), 2010 International Conference on, 2010, pp. 1-6.
17. D. Devaraj and R. Jeevajyothi, "Impact of wind turbine systems on power system voltage stability," in Computer, Communication and Electrical Technology (ICCCET), 2011 International Conference on, 2011, pp. 411-416.
18. G. Michalke and A. D. Hansen, "Modelling and control of variable speed wind turbines for power system studies," Wind Energy, vol. 13, pp. 307-322, May 2010.
19. I. D. Margaris and N. D. Hatziargyriou, "Direct drive synchronous generator wind turbine models for power system studies," in Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2010), 7th Mediterranean Conference and Exhibition on, 2010, pp. 1-7.
20. Kodsi S. K. M, Canizares C. “Modeling and Simulation of IEEE 14 Bus System with FACTS controllers”, Technical report 2003-3, University of Waterloo, On, Canada, 2003.