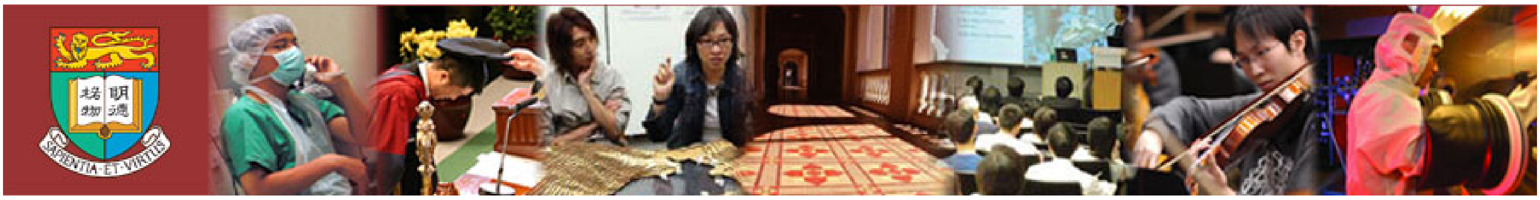
View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by HKU Scholars Hub

The HKU Scholars Hub The University of Hong Kong 香港大學學術庫



Title	**Impact of increased penetration of wind power on damping of low frequency oscillations in different network topologies**
Author(s)	**Garmroodhi, M; Hill, DJ; Ma, J; Verbic, G**
Citation	**The 2015 IEEE PowerTech Conference, Eindhoven, The Netherlands, 29 June-2 July 2015. In Conference Proceedings, 2015, p. 1-5**
Issued Date	**2015**
URL	**http://hdl.handle.net/10722/216427**
Rights	**PowerTech Conference. Copyright © IEEE.**

Impact of Increased Penetration of Wind Power on Damping of Low Frequency Oscillations in Different Network Topologies

Mehdi Garmroodi[1], *Student Member, IEEE*, David J. Hill[1,2], *Fellow, IEEE*, Jin Ma[1], *Member, IEEE*
and Gregor Verbič[1], *Senior Member, IEEE*
[1]School of Electrical and Information Engineering, The University of Sydney, Sydney, New South Wales, Australia
[2]Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong
Emails:{mehdi.garmroodi, david.hill, j.ma, gregor.verbic}@sydney.edu.au

***Abstract*—In this paper, the impact of increased penetration of wind generation on the damping of the inter-area modes in two different topologies of a three area test system is studied. Four different scenarios based on different power trading schemes between areas are defined and the role of tie-line power in the evolution of the inter-area modes is evaluated. The results magnify the importance of the tie-line power on the beneficial or adverse effect of increased wind power on the damping of the inter-area modes. It is seen the the modes are adversely affected when the wind power is increased in an area that exports power to remote areas. On the other hand, the damping of the inter-area modes improve when areas with significant wind generation import power from remote areas. Furthermore, it is seen that the inter-area modes are less affected in a more inter-connected system like ring topology compared to a string topology. PowerFactory DIgSILENT is used for the modal analysis and the penetration of wind power is increased by displacing conventional synchronous generators.**

Keywords*—*Inter-area oscillations, damping, network topology, tie-line power, wind generation.

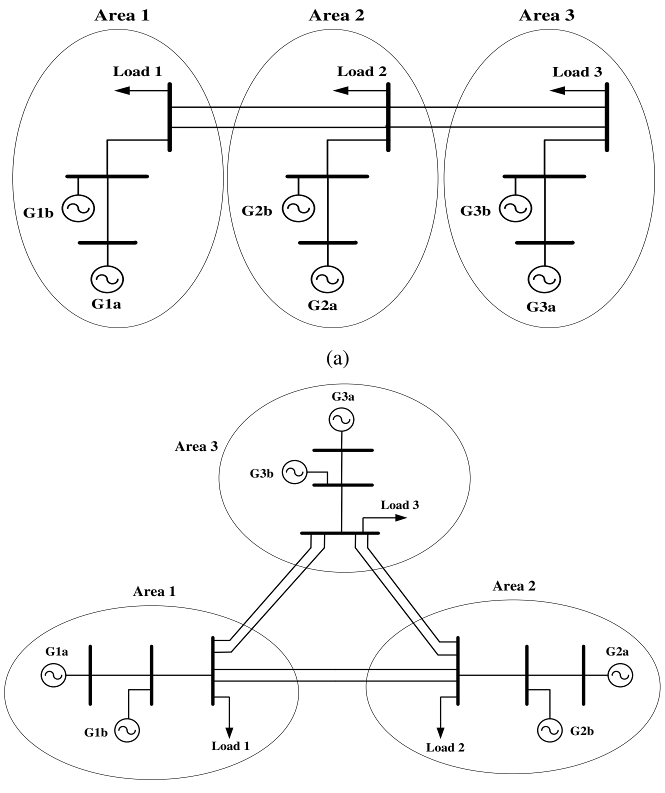
I. INTRODUCTION

With a global capacity of more than 300 GW, wind power has achieved nowadays a high level of integration in many power systems and it is the fastest growing among different types of renewable energy sources (RESs) [1]. The majority of wind turbines installed around the world are type 3 and type 4 wind turbine generators (WTGs) which are connected to the grid via a power electronic interface without introducing inertia to the system [2]. It is appreciated that the changing profile of inertia requires restudying system performance and security indices [3]. This paper studies the impact of high wind integration on the damping of low frequency oscillatory modes in different system topologies and investigates the role of tie-line power on the damping of inter-area oscillatory modes.

Low frequency oscillations (LFOs) occur in power systems as a result of a perturbation and if not well-damped, they might endanger the secure operation and lead to partial or full black-outs [4], [5]. The stability of these oscillatory modes is sometimes a limiting factor that restricts the power transfer between areas. For instance, the power transfer in the Queensland-New South Wales Interconnector (QNI) of Australian National Electricity Market (NEM) is limited to a maximum of 1078 MW due to oscillatory stability [6]. Thus, enhancing the damping of these modes could have financial benefits as well as ensuring the security of the system. In the past decade, considerable research efforts have been directed toward evaluating the implications of increased penetration of RESs on the performance and security of power systems. The impact of these resources on the oscillatory modes of the system could be direct (by reducing system inertia or changing the dynamics of the system) or indirect (through changing the power flow paths or adding congestion to the transmission corridors). The studies show that due to the various parameters involved, the impact of increased numbers of converter interfaced wind turbine generators (WTGs) on the damping of the LFO could be different depending on wind turbine technology, location, control mode and wind penetration [7]–[11]. The authors in [12] have claimed that some new electromechanical oscillatory modes might appear as a result of the interaction between existing synchronous generators and reactive power controllers in WTGs. The modes are highly dependant on controller parameters and would be manageable by proper tuning of the controller parameters.

The majority of the studies so far have been carried out on complex networks where general conclusions are very hard to derive. This paper takes the approach begun in [13] for the study of small signal stability where it is useful to consider multi-area test systems in some detail. In fact, we extend this idea as follows. The different characteristics of converter-based WTGs compared to conventional synchronous generators, the proximity of loads of different types and the different operation scenarios for a system are evaluated on simple configurations where general conclusions are not lost in the details. In general, we study the idea that not only system inertia, but also the network structure, grid strength and node type will be important. In this paper, we study the impact of increased penetration of wind generation on different configurations of a three area system. Two different topologies namely string and ring configurations for a three area network are considered, and increased penetration of wind power is accommodated by displacement of conventional synchronous generators. Damping and small signal stability of the systems are studied using modal analysis and the models are constructed in dedicated power system analysis software package PowerFactory.

The rest of this paper is organized as follows. The test systems and the assumptions for different scenarios are presented in section II. Section III and IV studies the impact of increased



(a)

(b)

Fig. 1. Test systems: (a) string configuration (b) ring configuration

TABLE I. OPERATION SCENARIOS

	Load 1 (MW)	Load 2 (MW)	Load 3 (MW)
Scenario A	1700	900	1300
Scenario B	900	1700	1300
Scenario C	1700	1300	900
Scenario D	900	1300	1700

wind generation on the string and ring topology respectively and similarities and differences are discussed. Finally section V concludes the paper.

II. SYSTEMS DESCRIPTION

Two different configurations for a three area system are considered for the purpose of this study and they are shown in Figs. 1a and 1b. The models are derived by extending the well-known two area test system proposed in [14]. Each area is comprised of two conventional synchronous generators and one load. The areas are connected with double circuit loss-less transmission lines with the length of 220 km. The synchronous generators are all equipped with standard excitation systems (IEEET1), governors (IEEEG1) and power system stabilizers (STAB1) and each provide 650 MW active power to the grid. Four different scenarios are assumed for the loading of the systems and they are summarized in Table I. Different scenarios correspond to different power trading schemes between areas. The result of modal analysis for the string configuration in scenario A is shown in Fig. 2 and it shows three local and two inter-area oscillatory modes. Local oscillatory modes correspond to the generators G1a and G1b in area 1, generators G2a and G2b in area 2 and generators G3a and G3b in area 3.

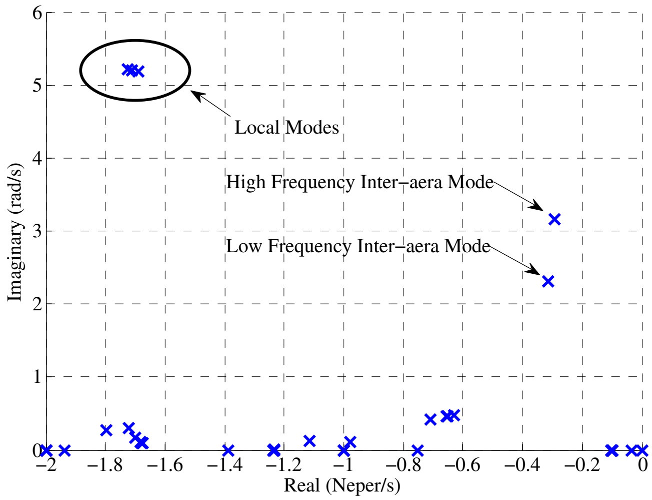


Fig. 2. Dominant modes of the system in the string network topology

Analysing the speed eigenvectors and participation factors illustrate that the high frequency inter-area mode (HFIM) is an oscillatory mode in which the generators in area 2 oscillate against the rest of the system. Similar analyses for the low frequency inter-area mode (LFIM) show that that in this mode, the generators in area 3 oscillate against generators in area 1. The oscillatory behaviour of the modes as well as their damping and frequency might change in different scenarios and different configurations. However, the number of local modes and inter-area modes remains the same.

The impacts of the increased penetration of wind power on the damping of the electromechanical modes are analysed by displacing the generators G2b and G3a with fully rated convertor wind turbine generators (FRC-WTGs). Multiple parallel units are assumed for the plants G2b and G3a and by decreasing the number of units gradually, the displaced unit is replaced with FRC-WTGs. This approach allows for discrete-step reduction of the inertia caused by increased penetration of wind power. Furthermore, in different loading scenarios, the effect of the direction of the tie-line power on the impacts that increased penetration of wind power might have on the electromechanical modes can be captured. In scenarios A and B, where the power is traded between area 1 and area 2, the generator G2b is displaced with WTGs. The generator G3a is displaced with WTGs in scenarios C and D in which the power trading is between area 1 and areas 3. The WTGs are operating at constant reactive power control mode.

III. INCREASING WIND PENETRATION IN THE STRING TOPOLOGY

A. *Replacing the Generator G2b*

Generator G2b is displaced in scenarios A and B where the power is traded between area 1 and area 2. The participation of different generators on the inter-area modes is shown in Fig. 3. In scenario A, 400 MW power is transferred from area 2 to area 1. As it is seen from Fig. 3, the generators in area 2 have significant participation on the HFIM while their participation on the LFIM is negligible. By increasing the penetration of wind power (through displacing units of G2b with WTGs),

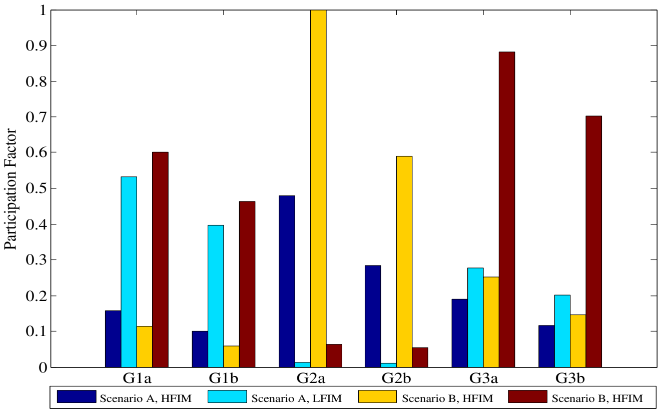


Fig. 3. Participation of the generators on the LFIM and HFIM in scenarios A and B of the string topology

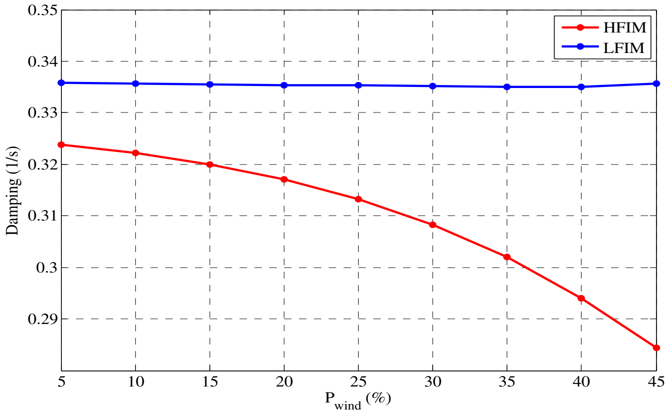


Fig. 4. Evolution in the damping of the inter-area modes in scenario A of the string topology

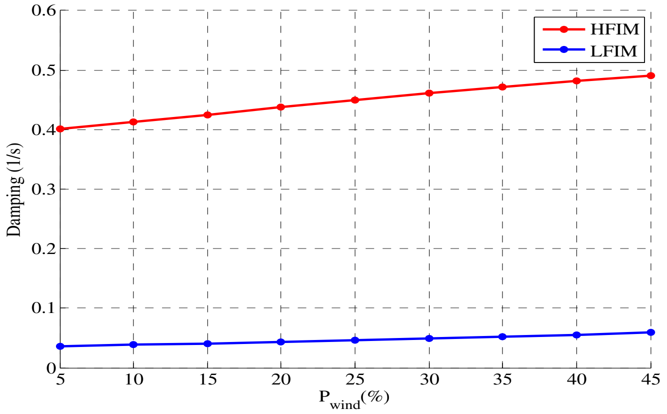


Fig. 5. Evolution in the damping of the inter-area modes in scenario B of the string topology

the eigenvalues of the system including the inter-area modes undergo some changes in terms of damping and frequency of oscillations. The damping of the modes determines the rate of decay in the oscillations after a disturbance in the system and it is the main focus of this paper. The frequency of oscillations are highly dependant on the inertia in the system and they normally increase when the inertia in the system reduces [15]. Fig. 4 shows the evolution in the damping of the inter-area modes when G2b is gradually displaced with WTGs in scenario A. In this study, the wind penetration is the percentage of wind power in total generation of an area in which the wind power is increasing and it is calculated from:

$$Pwind(\%) = \frac{P_{wind}}{P_{wind} + P_{Gia} + P_{Gib}} \tag{1}$$

where, P_{Gia} and P_{Gib} are the output power of the synchronous generators in area i. As it is seen from Fig. 4, the damping of HFIM decreases while the damping of the LFIM has not changed significantly. The negligible changes in the damping of the LFIM is expected since the participation of G2b in this mode is not significant.

In scenario B, the direction of tie-line power between area 1 and area 2 is reversed. The change in the loading pattern of the system does not change the oscillatory behavior of the inter-area modes. However, the participation of generators in area 2 on the inter-area modes is increased (see Fig. 3). Fig. 5 shows the impact of increased penetration of wind power in area 2 on the damping of the inter-area modes. In contrast to scenario A, increasing wind power in this scenario increases the damping of the HFIM. This mode is the main mode on which the generators in area 2 significantly participate, and the simulation results show that the direction of tie-line power has a key role in the variation of the damping of this mode. The generator G2b is located in area 2 which has connection to two neighboring areas. The results of scenarios C and D in the following sub-section show that the beneficial or detrimental impact of wind generation on the damping of inter-area modes could be more intense when wind power in area 3 is increased.

B. Replacing the Generator G3a

In scenarios C and D, the loading of the system is such that the power is transferred from area 3 to area 1 and vice versa. In these two scenarios, the generator G3a is displaced with WTGs to capture the effects of increasing wind power in the outer area of a string configuration. Fig. 6 shows the participation of different generators on the inter-area modes in these two scenarios. As it is seen, the generator G3a has significant participation in the both HFIM and LFIM. However, its participation in the LFIM is more than the HFIM and it is expected that this mode gets more affected if G3a is displaced in the system.

Fig. 7 and Fig. 8 show the evolution in the damping of the inter-area modes in scenarios C and D. In scenario C, the power is exported from area 3 to area 1 and Fig. 7 shows that the damping of both inter-area modes are decreased. The reduction in the damping of the LFIM is more intense and this mode loses its stability when wind power reaches penetrations above 42% and damping becomes negative. The results of the simulation for scenario D in Fig. 8 show that despite scenario C, the damping of both inter-area modes improves when G3a is displaced with WTGs. The only difference between the two scenarios is the difference in the direction of the tie line power. Comparing the simulation results for these two scenarios show that the detrimental or beneficial impact of increased wind power on the damping of the inter-area modes could be different depending on the direction of the tie-line power. When wind penetration increases in an area which

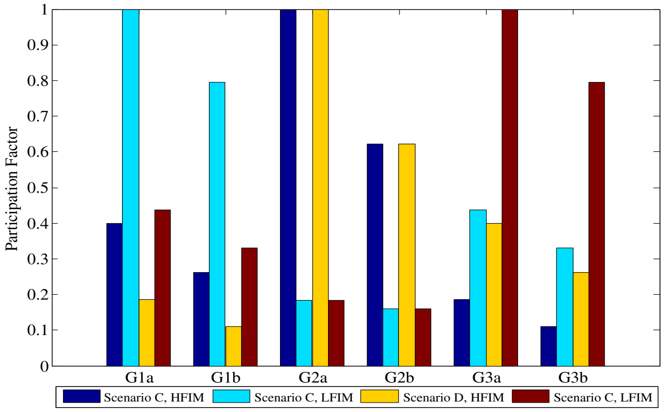


Fig. 6. Participation of the generators on the LFIM and HFIM in scenarios C and D of the string topology

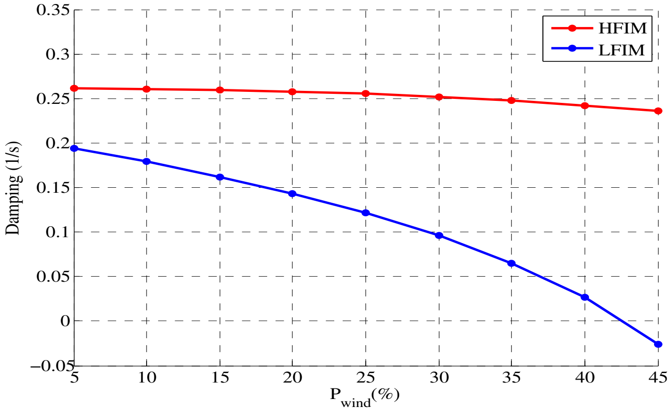


Fig. 7. Evolution in the damping of the inter-area modes in scenario C of the ring topology

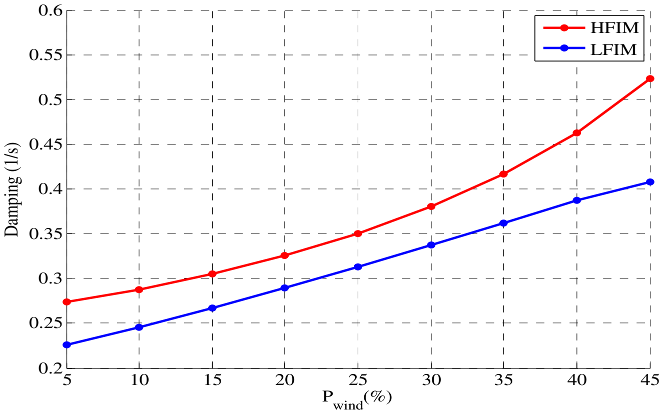


Fig. 8. Evolution in the damping of the inter-area modes in scenario D of the string topology

exports power to a remote area, the damping of the inter-area modes deteriorates and when it imports power from a remote area, the damping improves.

IV. INCREASING WIND PENETRATION IN THE RING TOPOLOGY

A. Replacing the Generator G2b

The ring topology is constructed by connecting area 1 and area 3 with a transmission line. The participation factor and speed eigenvector analyses (not shown here) have been used to determine the oscillatory behaviour of the inter-area modes. The results illustrate that in one of the inter-area modes, the generators in area 1 oscillate against the generators in area 2 and area 3. In the other one, the generators in area 2 oscillate against the rest of the system. Fig. 9 and Fig. 10 show the changes in the damping of the inter-area modes when G2b is displaced by WTGs in scenarios A and B respectively. As it is seen from Fig. 9, displacing the units of G2b causes a slight reduction in both HFIM and LFIM. However, Fig.10 shows significant improvements in the damping of the HFIM as the wind power increases in area 2. The LFIM is not affected since the G2b has negligible participation on it. Comparing the two scenarios shows that when area 2 is exporting power to area 1, the damping of the inter-area modes decrease while importing power to that area increases the damping of the inter-area modes. This is in line with the findings of the string topology where similar observations were made. This finding is useful in refining the scenarios of the future grids that have more vulnerability to instability or damping issues.

B. Replacing the Generator G3a

Due to the triangular symmetry of the ring topology, the difference of the scenarios C and D with the scenarios A and B is solely the change in the location of the generator which is displaced by wind. The variation in the damping of the inter-area modes in scenario C is shown in Fig. 11. As it is seen, similar to the other scenarios where wind power was exported from the area where wind penetration is increased, the damping of the inter-area modes reduced. The reduction in the damping is not as severe as the string topology where the small signal stability of the system was lost in some cases. This can be associated with the greater connectivity of this topology and the fact that each area is connected to two neighbouring areas. The evolution in the damping of the inter-area modes in scenario D where the tie-line power is reversed is shown in Fig. 12. The damping of the HFIM is increasing while LFIM is unaffected. The results are confirming that tie-line power can have an important role on the way the increased wind penetration affect the power system. Furthermore, the effect of the wind power on damping of the inter-area modes could be different depending on the operating condition of the system.

V. CONCLUSION

The impact of displacing conventional synchronous generators with inertia-less type-4 WTGs on the damping of inter-area modes in two different configurations of a three area test system is studied. Different power trading schemes are assumed between areas and the evolution in the damping of the inter-area modes are observed. The results show that the direction of the tie-line power has an important role in the positive or negative effect of wind power on the damping of the inter-area modes. Increasing penetration of wind power in an area which exports power to remote areas deteriorates the damping of the inter-area modes. On the other hand, if the area is importing power from remote areas, the damping of the modes improve. The level of impact depends on participation

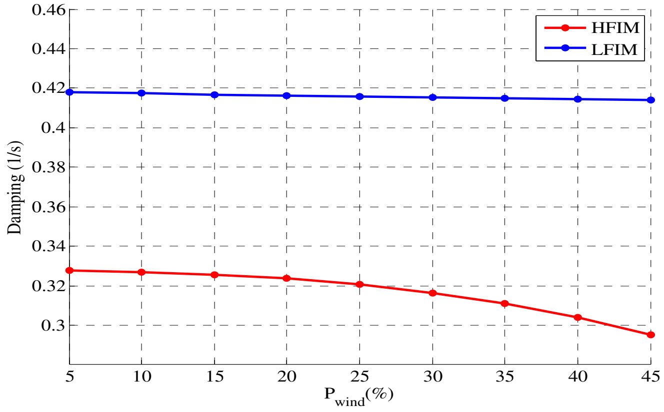


Fig. 9. Evolution in the damping of the inter-area modes in scenario A of the ring topology

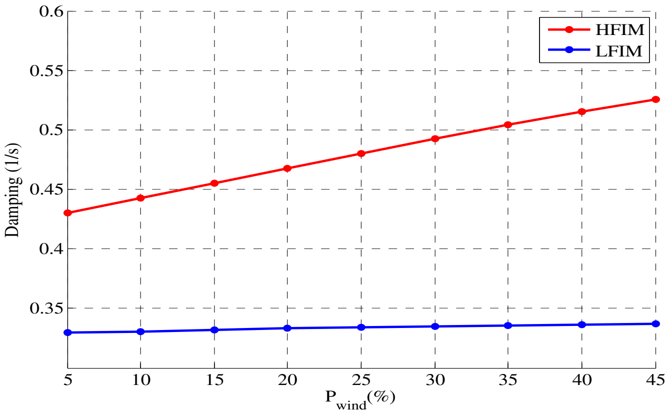


Fig. 10. Evolution in the damping of the inter-area modes in scenario B of the ring topology

of the displaced generator on a specific mode. Also the results show that damping of the inter-area modes are more adversely affected in the string topology rather than the ring topology.

REFERENCES

[1] Global Wind Energy Council, "Global cumulative installed capacity 1996-2013." [Online]. Available: http://www.gwec.net/global-figures/wind-energy-global-status/

[2] F. Blaabjerg and K. Ma, "Future on power electronics for wind turbine systems," *Emerging and Selected Topics in Power Electronics, IEEE Journal of*, vol. 1, no. 3, pp. 139–152, Sept 2013.

[3] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of Low Rotational Inertia on Power System Stability and Operation," Dec. 2013. [Online]. Available: http://arxiv.org/abs/1312.6435

[4] A. Apt, B. L. Lester, S. Talukdar, M. Morgan, and M. Ilic, "Electrical blackouts: A systemic problem," *Issues in Science and Technology*, vol. 20, pp. 55–61, 2004.

[5] N. Modi, T. Saha, and N. Mithulananthan, "Performance of power oscillation damping controllers with different static load characteristics," in *Power and Energy Society General Meeting, 2011 IEEE*, July 2011, pp. 1–7.

[6] "Integrating renewable energy - wind integration studies report," Australian Energy Market Operator (AEMO), Tech. Rep., 2013.

[7] J. L. Domnguez-Garca, O. Gomis-Bellmunt, F. D. Bianchi, and A. Sumper, "Power oscillation damping supported by wind power: A review," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 7, pp. 4994 – 5006, 2012.

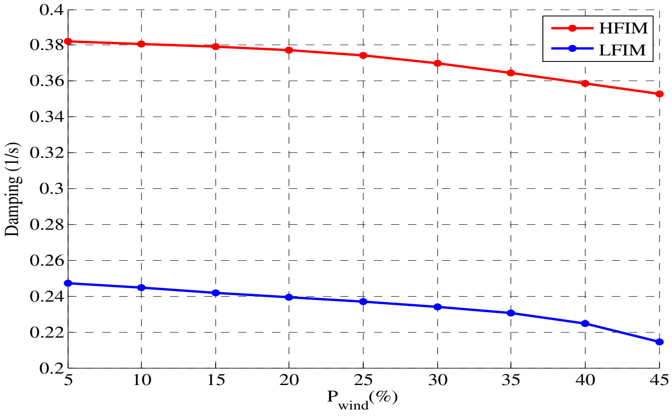


Fig. 11. Evolution in the damping of the inter-area modes in scenario C of the ring topology

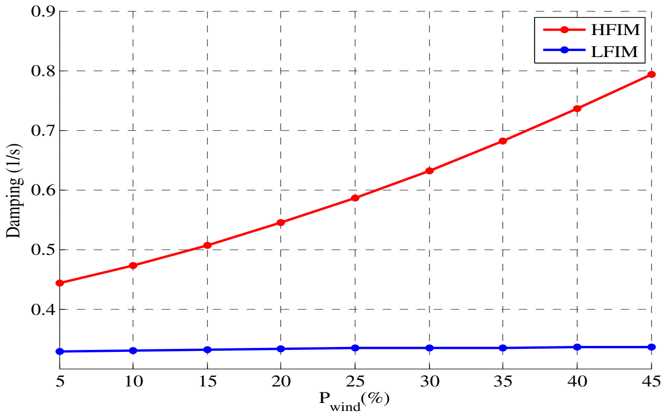


Fig. 12. Evolution in the damping of the inter-area modes in scenario D of the ring topology

[8] 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," *Power Systems, IEEE Transactions on*, vol. 24, no. 3, pp. 1426–1434, Aug 2009.

[9] N. Modi, T. K. Saha, and T. Anderson, "Damping performance of the large scale queensland transmission network with significant wind penetration," *Applied Energy*, vol. 111, no. 0, pp. 225 – 233, 2013.

[10] H. M. M. Poller, K. Theron, P. Ravalli, and R. A., "Assessment of potential security risks due to high levels of wind generation in south australia-summary of digsilent studies," National Electricity Market Management Company Limited (NEMMCO), Tech. Rep., 2005.

[11] G. Tsourakis, B. Nomikos, and C. Vournas, "Contribution of doubly fed wind generators to oscillation damping," *Energy Conversion, IEEE Transactions on*, vol. 24, no. 3, pp. 783–791, Sept 2009.

[12] J. Quintero, V. Vittal, G. Heydt, and H. Zhang, "The impact of increased penetration of converter control-based generators on power system modes of oscillation," *Power Systems, IEEE Transactions on*, vol. 29, no. 5, pp. 2248–2256, Sept 2014.

[13] M. Klein, G. Rogers, and P. Kundur, "A fundamental study of inter-area oscillations in power systems," *IEEE Transactions on Power Systems*, vol. 6, no. 3, pp. 914–921, 1991.

[14] P. Kundur, *Power System Stability and Control*. McGraw-Hill Education, 1994.

[15] C. Silva-Monroy, J. Neely, R. Byrne, R. Elliott, and D. Schoenwald, "Wind generation controls for damping of inter-area oscillations," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, July 2013, pp. 1–5.