Impact of Wide-Area Oscillation Damping Control using Measurement-Driven Approach on System Separation - Saudi Grid Case Study

Ibrahim Altarjami, Lin Zhu, Dongbin Lu, Xianda Deng
Department of Electrical Engineering and Computer Science
The University of Tennessee
Knoxville, TN USA
ialtarja@vols.utk.edu, lzhu12@utk.edu, hustludb@126.com, xdeng6@vols.utk.edu

Yilu Liu
1. *Department of Electrical Engineering and Computer Science*
The University of Tennessee
Knoxville, TN USA
2. *Oak Ridge National Laboratory*
Oak Ridge, TN USA
liu@utk.edu

Evangelos Farantatos, Deepak Ramasubramanian, Mahendra Patel
Electric Power Research Institute
Palo Alto, CA USA
efarantatos@epri.com, dramasubramanian@epri.com
mpatel@epri.com

Muhammad Ijaz, Ahmed H. Al-Mubarak
Salem O. Bashraheel
Saudi Electricity Company
Saudi Arabia
MIALI3@se.com.sa, AHMubarak@se.com.sa
SOBashraheel@se.com.sa

Abstract— In any interconnected power grid, low-frequency oscillations is a major problem that limit the power transfer capability and deteriorate power system security due to potential low-damped or even undamped oscillations. Synchronized measurements provided by PMUs enable the design and development of wide-area oscillation damping controllers (WADC) based on measurement-driven model to overcome the limitations of traditional controllers. This work focuses on the impact of a WADC based on a measurement-driven approach on system separation for the Saudi Electricity Company (SEC) grid. A grid model is provided by SEC for this study. Modal analysis is performed to identify the oscillation mode of interest for which the controller is designed. Damping the dominant oscillation mode help slightly to improve transient stability of the system. Considering bus frequency at different locations in SEC's system as the candidate observation signals, the optimal observation signal is chosen for the WADC by using the FFT method. The system transfer function model is constructed by utilizing probing measurements. Then, the WADC parameters are calculated based on the identified model. The performance of the designed WADC is tested under different contingencies.

Keywords— Low frequency oscillation, System identification, Transfer function model, Wide-area damping controller (WADC), System Separation, Transient stability.

I. INTRODUCTION

Low-frequency oscillations is considered as a major issue in the power system that could restrain the power transfer capability and deteriorate the power system security [1]-[3]. Many controllers in power system can be used to suppress the low-frequency oscillation such as Power System Stabilizer (PSS) devices in which the generator excitation system can provide supplementary control actions [4], Flexible Alternating-Current Transmission Systems (FACTS) devices [5], [6], High-Voltage Direct Current (HVDC) links [7], [8] and wind generation [9], [10].

However, the design of these controllers are based on the system circuit model around a specific operating point. This process is known as circuit model-based approach, which demands detailed dynamic models and system component parameters, such as the generators, loads, and transmission lines [11]–[13]. According to power grid operating paradigm, dynamic models are typically updated several times a year. However, with changing grid conditions regularly render one snapshot model not very useful.

With exploiting the benefits of increasing deployment of Phasor Measurement Units (PMUs), deriving a measurement-based transfer function model is possible to describe the oscillatory behavior of the power system, which can defeat the issues related to the circuit model-based approach [14]–[16]. The measurement-driven model can be updated in real-time where the changes of power system operating conditions can be tracked. Therefore, no needs for the circuit model and the system components parameters and the accuracy of the measurement-driven approach can be higher than the system circuit approach [17]. In this paper, the system separation is investigated when wide-area damping control (WADC) designed based on a measurement-derived approach. The system identification process that are used in the measurement-driven approach is through using probing measurements to imitate the oscillatory behavior of the system [18]. The identified model is used to tune the WADC based on the system operating condition. The primary purpose of the WADC is to improve small-signal stability; also, the impact can be noticed slightly on transient stability problems.

This paper is organized as follows: Section II is a brief introduction about Saudi Electricity Company (SEC) system. Section III presents methodology of the optimal observation selection for the case study (SEC system). Section IV presents methodology of the selection of actuation signal. Section V demonstrates the performance of the designed WADC on the studied case to prevent system from separation. Finally, Section VI conclude this paper.

This work was primarily supported by Saudi Electricity Company (SEC) and Electric Power Research Institute (EPRI), and partly supported by National Science Foundation under the Award Number 1509624 and 1839684. This work also made use of Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

II. SAUDI GRID

Saudi system frequency is 60 Hz and the peak electricity demand approximately reached to 62 GW in 2017 [19]. There are five main operation areas in SEC system, which are Central, East, West, North, and South, as shown in Fig. 1 [19]. The dominant oscillation mode in the system is around 0.30 Hz between West and Central. There is one tie-line (double circuits) in which these areas are connected. The power flow of the tie-line is from Central area to West area. The power flow of the tie-line is from Central area to West area. The major SEC grid separate into two group when the tie-line tripped. This transient issue is considered as one of main concern of SEC grid when generation trip occurred in the west.

Two single-phase PMUs, so called Frequency Disturbance Recorders (FDRs), are deployed in Saudi distribution grid. One is in western area, and the other is in central area. FDRs can measure gird frequency, voltage, and angle at an outlet on the wall to detect system disturbances. From May to July in 2018, 18 oscillation events were detected by FDRs. Fig. 2 shows an oscillation event detected on June 21, 2018, which has confirmed the dominant 0.3Hz oscillation mode between the western and central area.

Fig. 1. SEC System grid.

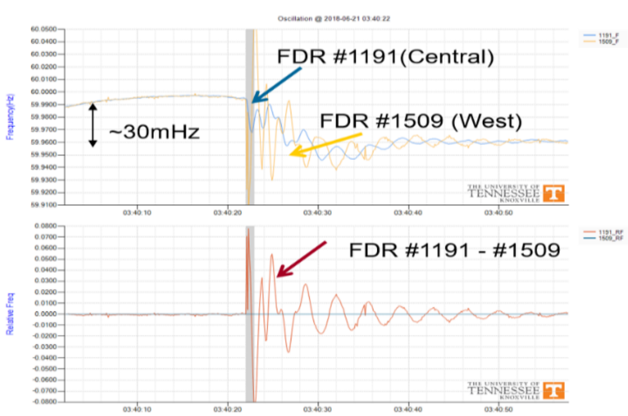


Fig. 2 One sample oscillation event detected by FDRs. June-21-18 03:40:22 - 03:40:57 (UTC time)

III. OPTIMAL OBSERVATION SIGNAL

With the increasing installations of PMUs, a large power system includes a great number of candidate observation signals for oscillation mode analysis. However, since only some of them have good observability of the dominant mode, a comprehensive method is needed to select the optimal observation signal for the critical mode among all the candidate observation signals. The conventional method is to conduct observability analysis based on a linearized system model with high order. In this paper, Fast Fourier Transform (FFT) is adopted to select the optimal observation signals of the damping control loop by extracting the measurement signals to the frequency domain. The time window is 20 seconds and the sampling rate is 100 per second.

Since the target mode is the oscillation between western and central area, the frequency at high voltage buses in western and area/zone are pre-selected as candidate observation signals. These candidate signals are listed in TABLE I and TABLE II respectively.

TABLE I. CANDIDATE OBSERVATION SIGNAL IN CENTRAL AREA

No.	Bus Number	Mean Amp. (Hz)
1	Area_C1	0.0040
2	Area_C2	0.0040
3	Area_C3	0.0040
4	Area_C4	0.0035
5	**Area_C5**	**0.0043**
6	Area_C6	0.0012
7	Area_C7	0.0017
8	Area_C8	0.0041
9	Area_C9	0.0014

TABLE II. CANDIDATE OBSERVATION SIGNAL IN WESTERN AREA

No.	Bus Number	Mean Amp.(Hz)
1	Area_W1	0.0133
2	Area_W2	0.0130
3	Area_W3	0.0096
4	Area_W4	0.0120
5	Area_W5	0.0098
6	**Area_W6**	**0.0134**
7	Area_W7	0.0133
8	Area_W10	0.0117
9	Area_W11	0.0098

Approximately 30 temporary line fault disturbances are used to excite the mode of interest. Under each disturbance, the bus frequency signals are ranked from high to low according to the magnitudes at the frequency of the dominant mode. Finally, according to all the ranks for different cases, the final rank is derived and the highest ranking signal is selected as the optimal observation signal to suppress this dominant mode, as shown in TABLE I and TABLE II. In central area, the frequency at Bus Area_C5 has the highest mean amplitude. Similarly, the frequency at Bus Area_W6 has the highest magnitude in western area. Note that the bus frequency in western area always have higher amplitude than those in central area. Therefore, the frequency at Bus Area_W6 is selected as the optimal observation signal. Also, since the target oscillation mode is between western and central area, the bus frequency difference between Area_W6 and Area_C6 is also a good observation signal.

IV. ACTUATION SIGNAL SELECTION

This section introduces the methods and procedure to select the optimal actuation signal, which is also the input and feedback signal of the designed WADCs. The WADCs could provide supplementary control via SVCs, generator exciters and generator governors. Three SVCs are assigned by SEC as the actuators, while the optimal generator exciters and governors to executes WADC control commands could be selected by the following two methods.

One method is to inject a down step signal into the voltage set point of each generator exciter. Then, the frequency responses of Bus Area_W6 (based on the optimal observation signal analysis) are compared. The bus frequency response with higher magnitude means higher controllability of the corresponding generator exciter. Fig. 3 illustrates the frequency response at Bus Area_W6 when each generator exciter is subjected to a 0.05 down step signal. TABLE III lists top 10 generator exciter actuators based on their magnitudes.

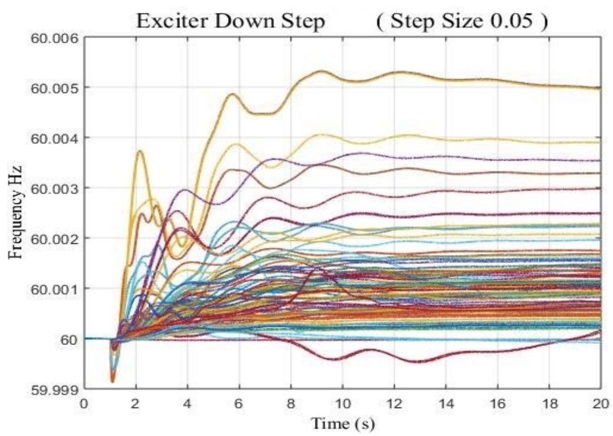
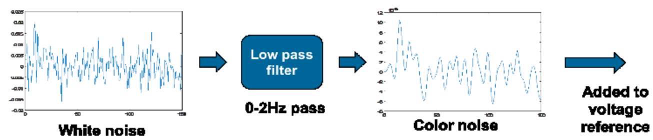


Fig. 3 Bus frequency responses to 0.05 down step at exciter set point

TABLE III. TOP 10 GENERATOR EXCITER ACTUATORS BASED ON RESPONSE MAGNITUDE

No.	Area	Bus NO.
1	South	S_57
2	West	J_17
3	East	E_81
4	West	R_55
5	East	E_88
6	East	E_37
7	West	R_94
8	West	R_80
9	West	W_69
10	East	E_81

The other method is to inject color noise to the exciter voltage set point and then compare the calculated residue magnitudes from the identified transfer function models. Color noise is white noise after a low pass filter (0-2Hz), as shown in Fig. 4 (a). This probing signal is injected to the voltage set point of the each generator exciter. Based on the probing signal and the collected frequency at Bus Area_W6, a single-input single-output transfer function model can be identified, as shown in Fig. 4 (b). After the transfer function models are identified, the residue magnitudes of the models are compared. Note that residue magnitude is a joint measure of controllability and observability. Given that the same bus frequency signal is selected as the observation signal, the controllability can be compared in an indirect way by comparing residue magnitude. TABLE IV lists top 10 generator exciter actuators based on the calculated residue magnitude.



a) Color noise as probing signal

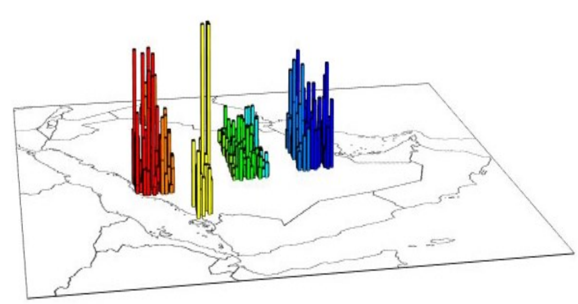
b) Identified model structure

Fig. 4 Transfer function model identification using probing signal

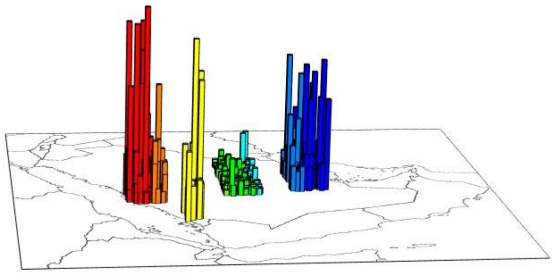
TABLE IV. TOP 10 GENERATOR EXCITERS ACTUATOR BASED ON RESIDUE MAGNITUDE

No.	Area	Bus NO.	Residue Magnitude (Normalized)
1	South	S_57	1.0000
2	West	J_17	0.9368
3	West	R_55	0.8250
4	East	E_88	0.8015
5	East	E_37	0.7609
6	West	R_94	0.6390
7	West	R_80	0.6302
8	South	S_11	0.4705
9	East	E_44	0.4600
10	South	S_07	0.4512

The selected top 10 generator exciter actuators from the both methods are quite similar to each other. Moreover, the comparison between the two methods is given in Fig. . Fig. 5 (a) shows the results from response magnitude comparison method, while Fig. (b) shows the results from residue magnitude comparison method. Both indicate that generators in eastern, western and southern area have higher controllability of the target oscillation mode than those in central area. Similarly, refining the governors of the system units to possible actuators can be done using the same two methods that had used with the exciter.



(a) Controllability comparison (frequency magnitude comparison)



(b) Controllability comparison (residue magnitude comparison)

Fig. 5 Comparison of generator exciters' controllability

V. THE IMPACT OF WADC ON SYSTEM SEPARATION

WADC is designed based on measurement-driven approach [17]. WADC mainly used to improve the small-signal stability. However, it could help to improve transient stability as well. The system separation could happen in SEC grid if tripping three generators (2040 MW) in the western area simultaneously, like in 14-11-2017 Jeddah South incident. In this section, the impact of the designed WADCs on system separation is studied through emulating the real events. Specifically, under how large generation trip the system separation can still be prevented when adding multiple WADCs is investigated.

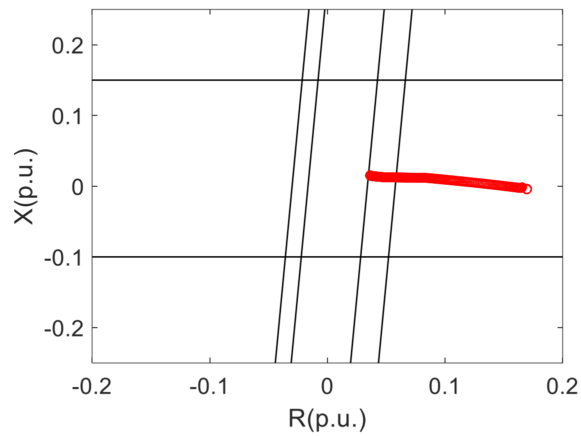
TABLE V. TRANSIENT STABILITY IMPROVEMENT WITH WADCS

No.	WADC location	Marginal amount of generation trip in the west (MW)
0	No WADC	1,860
1	Three SVCs	1,872
2	Three Exciters	1,938
3	Three Governors	>=2,040
4	Three Governors + Three SVCs	>=2,040
5	Three Governors + Three Exciters	>=2,040

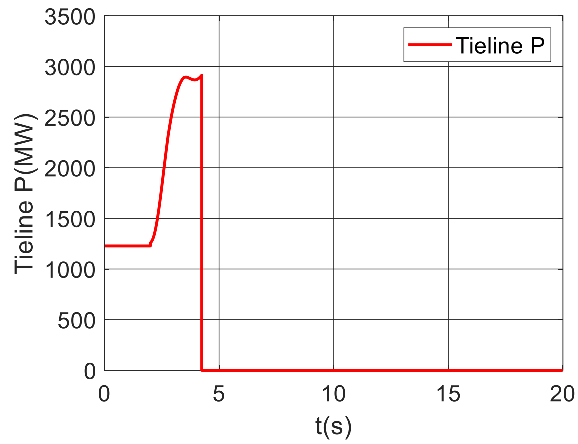
TABLE V shows the marginal amount of generation trip for different WADC configurations. For instance, when there is no WADC, the system will be separated by the out-of-step relay if the generation trip amount is larger than 1,860 MW. When three WADCs via SVCs are activated, the system will be still connected even if the total amount of generation trip is 1,872 MW. When governors have enough headroom, the maximum generation trip amount could be larger than 2,040 MW.

Next, three main power plants in western and southern area are chosen as the locations of WADCs, which would be a more realistic application scenario which are West_J17, West_R55 , and South_S57.

As demonstrated in TABLE V, WADCs are equipped with one unit at each selected plant to prevent the system from separation under large generation trip. Therefore, multiple WADCs via both generator governors and exciters are investigated to prevent the system from separation. In case of 2,040 MW generation trip in West, the system separation can be prevented if three WADCs via both governors. Fig. 7 and Fig. 8 show that the designed WADCs can prevent system separation.

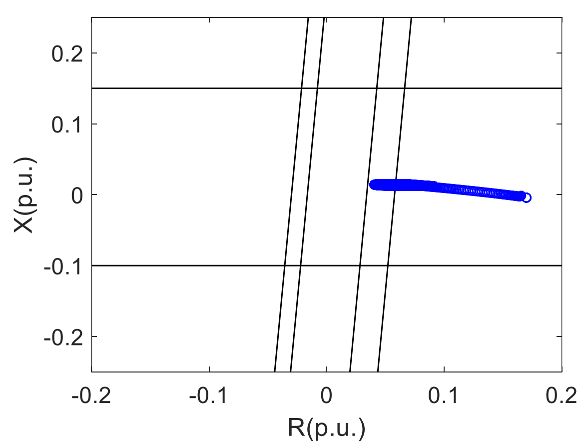


(a) Out-of-step Relay

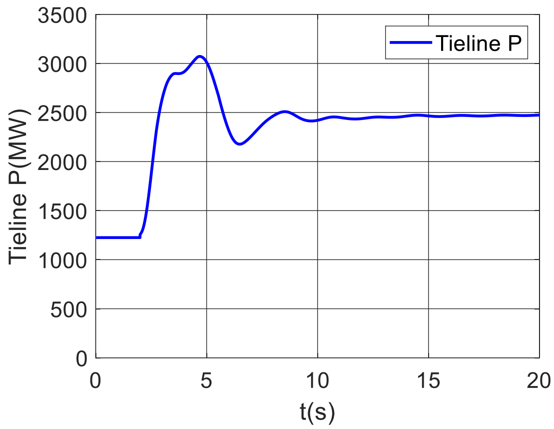


(b) Tie-line Active Power

Fig. 6 Case 0 : No WADC (1,872 MW generation trip)

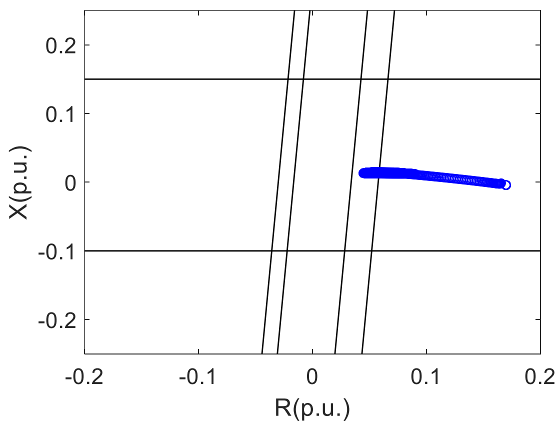


(a) Out-of-step Relay

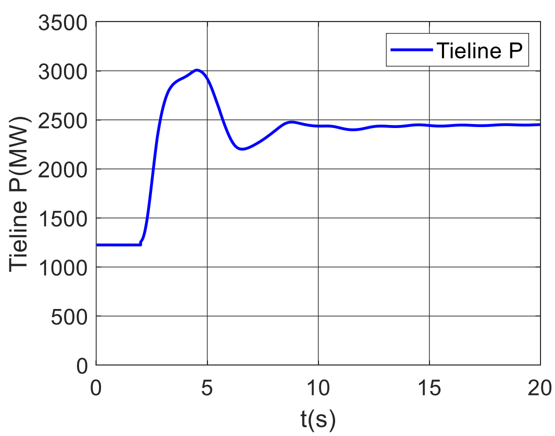


(b) Tie-line Active Power

Fig. 7 Case 3: WADCs on Three Governors (2,040 MW generation trip)



(a) Out-of-step Relay



(b) Tie-line Active Power

Fig. 8 Case 5: WADCs on Three Governors & Three Exciters (2,040 MW generation trip)

VI. Conclusions

The WADC using a measurement-driven transfer function model is designed and validated to improve SEC's small-signal stability by computer simulations. The frequency at Bus Area_W6 is selected as the optimal observation signal for the target oscillation mode. Also, the frequency difference between Bus Area_W6 and Bus Area_C5 is an alternative. The measurement-driven approach was used to design the WADC. WADCs via both SVCs, selected generator exciters and governors can further improve the damping ratio of the target oscillation mode. The simulation results validated the effectiveness of the measurement-driven WADC design approach. Meanwhile, multiple WADCs can prevent system from separation under large generation trip events.

References

[1] Graham Rogers, Power System Oscillations. Boston, London, 2000.

[2] B. and B. C. Pal, Robust Control in Power Systems. 2005.

[3] M. Begovic, "Inter-Area Oscillations in Power Systems: A Nonlinear and Nonstationary Perspective (Messina, A.R.) [Book Reviews]," Power Energy Mag. IEEE, 2011.

[4] M. E. Aboul-Ela, A. A. Sallam, J. D. McCalley, and A. A. Fouad, "Damping controller design for power system oscillations using global signals," IEEE Trans. Power Syst., 1996.

[5] I. Kamwa, R. Grondin, and Y. Hébert, "Wide-area measurement based stabilizing control of large power systems - A decentralized/hierarchical approach," IEEE Trans. Power Syst., 2001.

[6] H. Nguyen-Duc, L. A. Dessaint, A. F. Okou, and I. Kamwa, "A power oscillation damping control scheme based on bang-bang modulation of FACTS signals," IEEE Trans. Power Syst., 2010.

[7] W. Yao, L. Jiang, J. Wen, Q. H. Wu, and S. Cheng, "Wide-area damping controller of Facts devices for inter-area oscillations considering communication time delays," IEEE Trans. Power Syst., 2014.

[8] S. Pirooz Azad, R. Iravani, and J. E. Tate, "Damping inter-area oscillations based on a model predictive control (MPC) HVDC supplementary controller," IEEE Trans. Power Syst., 2013.

[9] J. Morato, T. Knuppel, and J. Ostergaard, "Residue-based evaluation of the use of wind power plants with full converter wind turbines for power oscillation damping control," IEEE Trans. Sustain. Energy, 2014.

[10] Y. Liu, J. R. Gracia, T. J. King, and Y. Liu, "Frequency Regulation and Oscillation Damping Contributions of Variable-Speed Wind Generators in the U.S. Eastern Interconnection (EI)," IEEE Trans. Sustain. Energy, 2015.

[11] W. Yao, L. Jiang, Q. H. Wu, J. Y. Wen, and S. J. Cheng, "Delay-dependent stability analysis of the power system with a wide-area damping controller embedded," IEEE Trans. Power Syst., 2011.

[12] W. Yao, L. Jiang, J. Y. Wen, Q. H. Wu, and S. J. Cheng, "Wide-Area Damping Controller for Power System Interarea Oscillations: A Networked Predictive Control Approach," Ieee Trans. Control Syst. Technol., 2015.

[13] Y. Zhang and A. Bose, "Design of wide-area damping controllers for interarea oscillations," IEEE Trans. Power Syst., 2008.

[14] R. Eriksson and L. Soder, "Wide-area measurement system-based subspace identification for obtaining linear models to centrally coordinate controllable devices," IEEE Trans. Power Deliv., 2011.

[15] Y. Liu, K. Sun, and Y. Liu, "A measurement-based power system model for dynamic response estimation and instability warning," Electr. Power Syst. Res., 2015.

[16] J. Zhang, C. Y. Chung, C. Lu, K. Men, and L. Tu, "A Novel Adaptive Wide Area PSS Based on Output-Only Modal Analysis," IEEE Trans. Power Syst., 2015.

[17] Lin Zhu, Hesen Liu, Yiwei Ma, Yilu Liu, Evangelos Farantatos, Mahendra Patel, and Sean McGuinness, "Adaptive and coordinated oscillation damping control using measurement-driven approach," in 19th Power Systems Computation Conference, PSCC 2016, 2016.

[18] Hesen Liu, Lin Zhu, Feifei Bai, Yong Liu, Yilu Liu, Mahendra Patel, Evangelos Farantatos, and Navin Bhatt, "ARMAX-based transfer function model identification using wide-area measurement for adaptive and coordinated damping control," IEEE Trans. Smart Grid, 2017.

[19] "Annual Report 2017." [Online]. Available : https://www.se.com.sa/enus/Lists/NGReports/Attachments/3/NG_2017_AR.pdf.

[20] "System Identification Toolbox User's Guide - MathWorks." [Online]. Available: http://www.mathworks.com/help/pdf_doc/ident/ident.pdf.