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Online Aggregation of Coherent Generators Based on Electrical Parameters of Synchronous Generators

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Abstract

This paper proposes a novel approach for coherent generators online clustering in a large power system following a wide area disturbance. An interconnected power system may become unstable due to severe contingency when it is operated close to the stability boundaries. Hence, the bulk power system controlled islanding is the last resort to prevent catastrophic cascading outages and wide area blackout. Meanwhile, the aggregation of the coherent generators is the most important step in large power grids intentional defensive splitting to guarantee the dynamic stability of the created islands and reduce the computational burden of the huge initial search space. The proposed method of this paper determines the coherent machines based on the electrical parameters of the synchronous generators instead of the dynamical parameters such as rotor angle or speed curves, speed participation factors, etc. The stator and excitation windings flux, excitation voltage and current have been proposed as coherency indices. The proposed coherency based aggregation has been carried out on New England 39-bus test system. The time-domain simulation results demonstrate the effectiveness and capability of the proposed method to identify the coherent machines following a severe contingency.

Keywords: Coherent generators clustering; Dynamic stability; Electrical parameters of synchronous generators; Large-scale power system; Severe contingency; Wide area blackout.

1. Introduction

Nowadays, interconnected power grids are operated close to their stability margins as a result of increased demand, power industry restructuring and competition in the deregulated electricity markets. Although a large power system may be stable against small disturbances, a wide area contingency may cause the system to lose stability and even lead to the catastrophic cascading failures and system collapse. Studies show that many wide area blackouts such as 2012 India blackout may have been prevented and load-generation mismatch may have been reduced by fast, accurate, feasible controlled splitting strategies [1]-[3]. Hence, the bulk power network splitting is an emergency corrective measure to prevent the fault spreading and system blackout which separates a bulk power system into several stable islands according to the coherent groups of the generators by tripping the selected transmission lines. In a real power system with thousands of buses and branches, the islanding search space grows exponentially with the increasing of the size and the complexity of the power network. Hence, the coherency based aggregation can reduce the computational burden and the number of solutions and guarantee the dynamic stability of the created islands.

The concept of the coherency is very intuitive. Two machines are called coherent if after a severe disturbance, they present similar dynamical behaviour that is their rotor angles or speeds and frequencies keep very similar along the system trajectories. Two machines are said to be ε-coherent or coherent with precision ε if:

$$\lim_{t\to\infty} \left|\delta_i(t) - \delta_j(t)\right| < \varepsilon \qquad (1)$$

where δ_i (t) and δ_j (t) are respectively the rotor angles of machines i and j. This means the angular difference between any two generators is approximately constant over a period of time. As a limit case of the previous definition, two machines are perfectly coherent if $\varepsilon = 0$.

In the literature, many methods have been proposed to cluster the coherent generators. These procedures are divided into two general categories. The first one is the classic method that identifies the coherent machines through a time-domain simulation according to the rotor angle or speed curves. Hence, the machines with similar rotor angle (or speed) curves are assumed to be coherent. In the second category, the slow coherency theory as a two-time-scale method is used to identify the synchronized machines. This method is based on the power system oscillations. Power system oscillations can be classified into two modes; local or intra-area modes in 1–3 Hz range and inter-area modes less than 1 Hz [4]. The machines with the same inter-area mode swing together and they are called coherent in the selected inter-area modes [5]. In [6], the coherent groups have been determined through Empirical Mode Decomposition (EMD) and Stochastic Subspace Identification (SSI) method. In this method, the generator rotor speed prepared from the Wide Area Measurement System (WAMS) has only been used to cluster the coherent machines. In [7], a novel approach for grouping coherent machines based on the correlation characteristics of the generator rotor angle oscillation is presented. In proposed method, the correlation coefficients of the generators have been assessed by online measurement of rotor angle oscillations. In [8]-[11], a slow-coherency method has been used to aggregate the coherent generators of an interconnected power system. The mathematical background of the slow coherency theory and selective modal analysis can be found in [12]. In [13], the Krylov projection method has been used to cluster the coherent machines. The coherent generators have been identified by modal analysis of Electric Power Systems (EPS) in [14]. The oscillation modes have been represented by the eigenvalues obtained from the linearization of the nonlinear equations of system. The application of support vector clustering (SVC) for the direct identification of coherent synchronous generators in large interconnected multi-machine power systems has been investigated in [15]. The clustering is based on coherency measure which indicates the degree of coherency between any pair of generators. The proposed SVC algorithm processes the coherency measure matrix that is formulated using the generator rotor measurements to cluster the coherent generators. In [16], it is provided a new general approach for defining coherent generators in power systems based on the coherency in low-frequency inter-area modes. The disturbance is considered to be distributed in the network by applying random load changes which is the random walk representation of real loads instead of a single fault and coherent generators are obtained by spectrum analysis of the generators velocity variations. In order to find the coherent areas and their borders in the interconnected networks, non-generating buses are assigned to each group of coherent generator using similar coherency detection techniques. In [17], a model reduction algorithm which can divide an entire power system into a study area and an external area has been introduced. The algorithm is based on an extension of balanced truncation which evaluates the dynamic behaviour of the interconnected power system after reducing the external area. In [18], a novel approach based on the property of equal acceleration for coherent machines has been presented. This method requires only the admittance matrix of power system and the moment of inertia of generators. An expression has been developed for the coherency index between any two generators in a bulk power system. In [19], a spectrum analysis technique has been presented to identify the coherent machines. The rotor angles of generators in the early part of the transients have been predicted by the Taylor series expansion of the power system model. The obtained values have been taken as sample data for the spectrum analysis with a fast Fourier transform (FFT) algorithm. In general, Coherency analysis in stability studies of power systems is an important challenge which can supply effective information about the dynamic behavior of the power systems.

In this paper, the relationships between the rotor angular speed and its time-domain deviations, the stator and rotor windings flux, excitation voltage and current are presented to introduce a novel method for online separation of the coherent machines in a bulk power system.

The rest of the current paper is organized as follows. The mathematical background of the proposed method has been presented in section II. Section III provides the dynamic simulation results of the New England 39-bus test system and finally, conclusion appear in Section IV.

2. Proposed Approach to Cluster Coherent Generators

According to Newton's second law, the rotor speed deviations can be related to the mechanical (T_m), electrical (T_e) and damping (T_d) torques as fallows [20].

$$T_m - T_e - T_d = J \frac{d\,\omega_r}{dt} \quad (2)$$

In (2), ω_r and J are the rotor angular speed and inertia constant, respectively. The mechanical, electrical and damping torques can be calculated from (3), (4) and (5), respectively.

$$T_m = \frac{P_m}{\omega_r} \tag{3}$$

$$T_d = D\,\omega_r \tag{4}$$

$$T_e = \omega_0\varphi_d[Y_{1q}\omega_0\varphi_q + Y_{3q}\omega_0\varphi_Q] - \omega_0\varphi_q[Y_{1d}\omega_0\varphi_d + Y_{4d}\omega_0\varphi_f + Y_{5d}\omega_0\varphi_D] \tag{5}$$

where,

P_m : Mechanical input power

D : Damping constant

φ_d : Stator winding flux along d axis

φ_q : Stator winding flux along q axis

φ_D : Damper winding flux along d axis

φ_Q : Damper winding flux along q axis

φ_f : Excitation flux

More mathematical details of these equations can be found in [20]. By substituting (3), (4) and (5), equation (2) can be rewritten as follows.

$$\frac{P_m}{\omega_r} - D\omega_r - J\frac{d\omega_r}{dt} = \omega_0^2 Y_{1q}\varphi_q\varphi_d - \omega_0^2 Y_{4d}\varphi_q\varphi_f - \omega_0^2 Y_{5d}\varphi_D\varphi_q - \omega_0^2 Y_{1d}\varphi_d\varphi_q + \omega_0^2 Y_{3q}\varphi_Q\varphi_d \tag{6}$$

Therefore:

$$f(\omega_r, \Delta\omega_r) = \omega_0^2(Y_{1q} - Y_{1d})\varphi_q\varphi_d - \omega_0^2 Y_{4d}\varphi_q\varphi_f - \omega_0^2 Y_{5d}\varphi_D\varphi_q + \omega_0^2 Y_{3q}\varphi_Q\varphi_d \tag{7}$$

The resistance of damper windings is negligible. Hence, the relation between voltage and flux changes in damper windings can be rewritten as (8) and (9).

$$V_D \cong \frac{d\varphi_D}{dt} = 0 \tag{8}$$

$$V_Q \cong \frac{d\varphi_Q}{dt} = 0 \tag{9}$$

According to (8) and (9), the flux of damper windings will be constant. Hence, the equation (7) can be rewritten as following relation.

$$f(\omega_r, \Delta\omega_r) = c_1\varphi_q\varphi_d + c_2\varphi_q\varphi_f + c_3\varphi_q + c_4\varphi_d \tag{10}$$

$$c_1 = (Y_{1q} - Y_{1d})\omega_0^2 \tag{11}$$

$$c_2 = -Y_{4d}\,\omega_0^2 \tag{12}$$

$$c_3 = -\omega_0^2 Y_{5d}\,\varphi_D \tag{13}$$

$$c_4 = \omega_0^2 Y_{3q}\,\varphi_Q \tag{14}$$

Relation (10) confirms that the time-domain variations of the excitation and stator windings flux influence on the rotor angular speed and can be proposed as coherency indices for machines online aggregating following a wide area contingency. The relation between excitation voltage and flux can be written as follows.

$$V_f + r_f\, i_f = \frac{d\varphi_f}{dt} \tag{15}$$

According to the recent equation and rotor speed sensitivity to the excitation and stator windings flux, the excitation voltage and current can be used as other coherency indices. In this section it has been proved that the time-domain variations of the rotor and the stator windings flux, excitation voltage and current can be used to identify the coherent machines following a severe disturbance.

3. Simulation Results and Discussion

In order to demonstrate the effectiveness and capability of the proposed coherency indices, New England 39-bus power system has been used [21].

Based on the dynamic data of generators and the parameters of transmission system, the time-domain simulation has been carried out on the test power system in the DIGSILENT environment. In dynamic simulation, generator G39 is the reference machine.

In order to identify coherent generators following a severe disturbance, it is assumed that a solid 3-phase short circuit occurs on bus 14 at t=1.3 sec. The stator windings flux along d (φ_d) and q (φ_q) axes have been shown in Figs. 1, 2 and 3, respectively. Based on the similarity of swing curves, three coherent groups have been formed following given contingency.

- First coherent group: {G30, G37 and G38}
- Second coherent group: {G33, G34, G35 and G36}
- Third coherent group: {G31, G32 and G39}

The time-domain variations of excitation flux, voltage and current for all generators have been shown in Figs. 4, 5 and 6, respectively.

The damper windings flux along d (φ_D) and q (φ_Q) axes have been shown in Figs. 7 and 8, respectively.

According to Figs. 7 and 8, the damper windings flux is almost constant and the used assumptions in relation (10) are correct.

As shown in Figs. 1 to 6, based on the similarity of swing curves, three coherent groups and three independent islands will be formed following a solid three-phase fault on bus 14 at t=1.3 sec. Three coherent groups of islanded New England system have been shown in Fig. 9.

In order to compare the proposed approach with traditional method, the rotors' speed curves for all generators have been shown in Fig. 10.

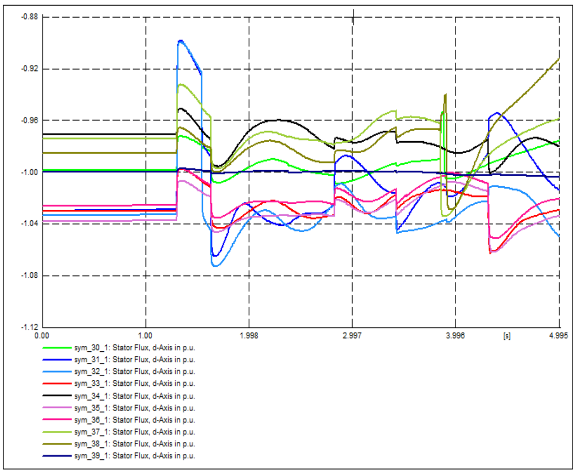

Fig. 1. Stator winding flux along d-axis for all generators

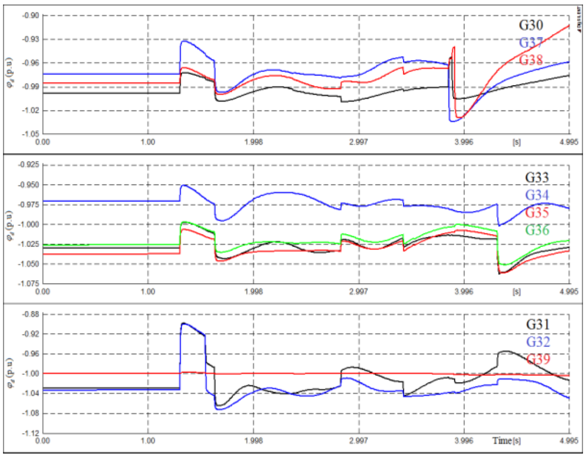

Fig. 2. Stator winding flux along d-axis

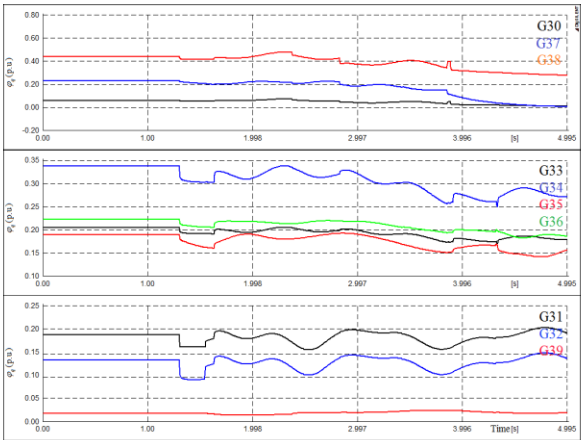

Fig. 3. Stator winding flux along q-axis

As shown in Figs. 1 to 10, the online identification of the coherent machines via the rotor speed curves is more difficult than clustering based on proposed electrical parameters. In other words, the similarity of the stator and the rotor windings flux, excitation voltage and current is more and clearer than similarity of the rotors speed curves of the coherent clusters after given contingency. In splitting studies, the similarity of the stator and the rotor windings flux, excitation voltage and current will be used to determine the coherent clusters under a sever disturbance.

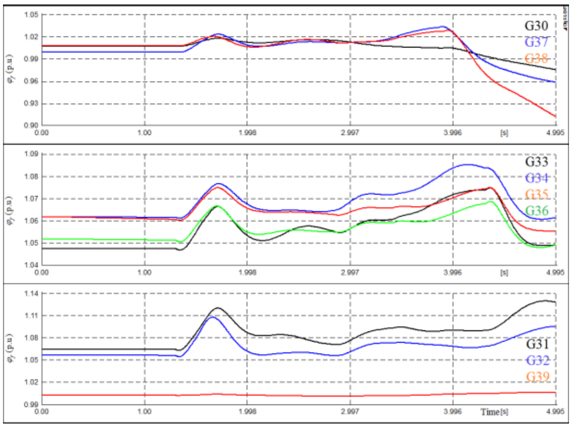

Fig. 4. Excitation flux of coherent machines

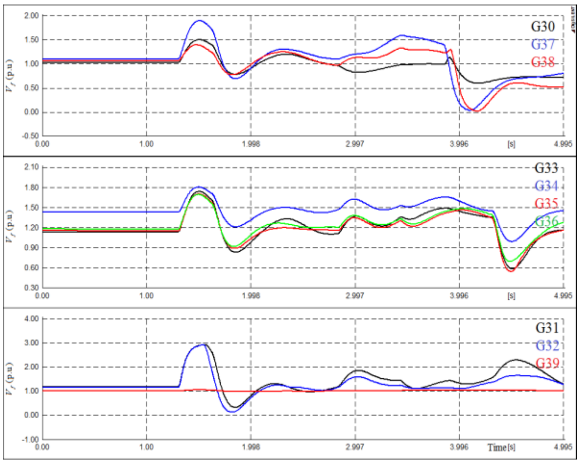

Fig. 5. Excitation voltage of coherent machines

4. Conclusion

In this paper, a mathematical framework is proposed for online aggregation of the coherent generators following a wide area contingency. It is proved that the rotor angular speed and its time domain deviations are dependent to the stator and the excitation windings flux, excitation voltage and current. Hence, the time-domain variations of the excitation and the stator windings flux, excitation voltage and current have been proposed as coherency indices to identify the synchronized machines following a large disturbance. In proposed method, the electrical parameters of the synchronous generators have been used to identify coherent clusters under given contingency. The simulation results demonstrate that the similarity of the stator and

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the rotor windings flux, excitation voltage and current is more and clearer than similarity of the rotors' speed curves of the coherent machines.

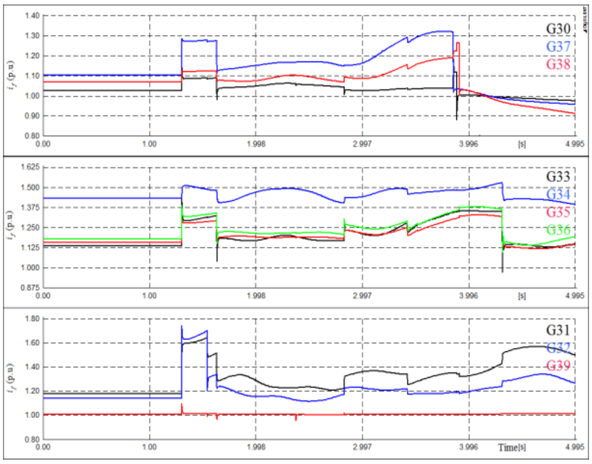

Fig. 6. Excitation current of coherent machines

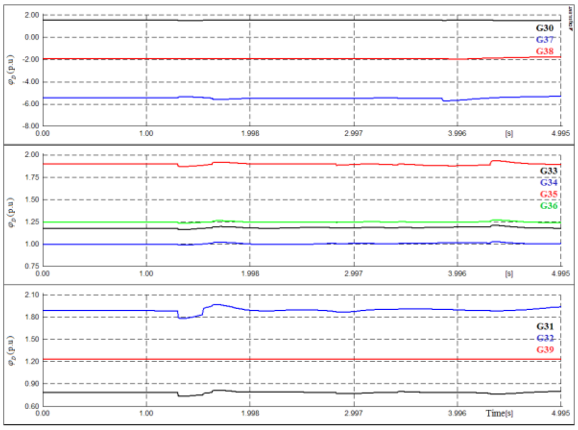

Fig. 7. Damper winding flux along d-axis

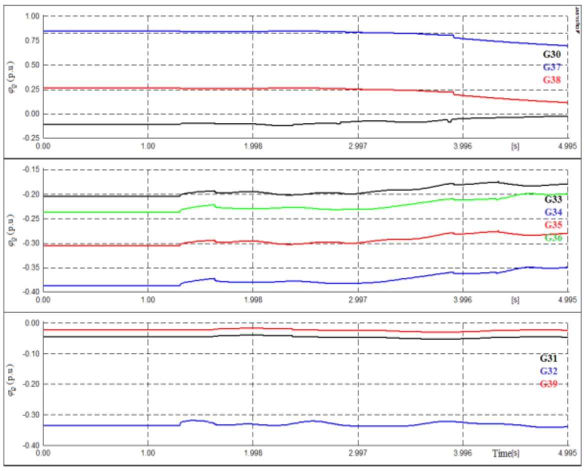

Fig. 8. Damper winding flux along q-axis

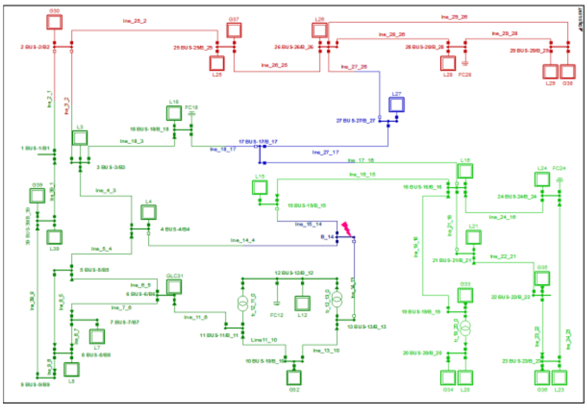

Fig. 9. Coherent generators of islanded New-England 39-bus test system

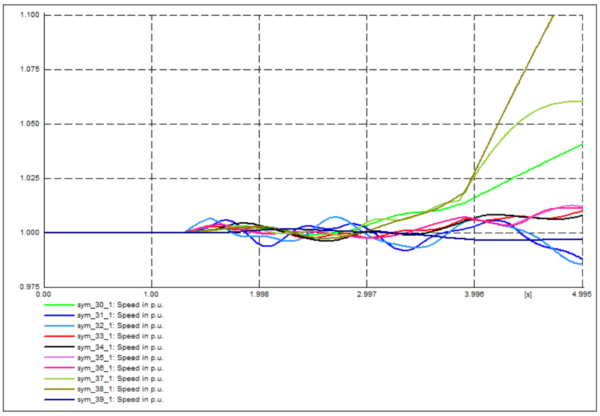

Fig. 10. Rotors speed deviations in per unit

References

[1] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, and P. Kundur, "Causes of the 2003 major grid blackouts in north America and Europe, and recommended means to improve system dynamic performance," IEEE Transactions on Power Systems, vol. 20, No. 4, pp. 1922–1928, 2005.

[2] B. Yang, V. Vittal, and G.T. Heydt, "Slow-coherency-based controlled islanding – a demonstration of the approach on the August 14, 2003 blackout scenario," IEEE Transactions on Power Systems, vol. 21, No. 4, pp. 1840–1847, 2006.

[3] X. Wang, W. Shao, V. Vittal, "Adaptive Corrective Control Strategies for Preventing Power System Blackouts," Presented at the 15th Power Systems Computation Conference, Liège, Belgium, 22-26 August 2005.

[4] Li. Liu, W. Liu, D. A. Cartes, and Il-Yop Chung, "Slow coherency and Angle Modulated Particle Swarm Optimization based islanding of large-scale power systems," Advanced Engineering Informatics, vol. 23, No. 1, pp. 45–56, 2009.

[5] X. Wang, "Slow Coherency grouping based islanding using Minimal Cutsets and generator coherency index tracing using the Continuation Method," Ph.D. dissertation, Iowa State University, pp. 1-132, 2005.

[6] G. Cai, J. Zhang, D. Yang, and K.W. Chan, "The identification of coherent generator groups via EMD and SSI," International Conference on Power System Technology, 24-28 Oct. 2010.

[7] M.R. Aghamohammadi and S. M. Tabandeh, "Online coherency identification based on correlation characteristics of generator rotor angles," IEEE International Conference on Power and Energy (PECon), 2-5 Dec. 2012.

[8] J. H. Chow, R. A. Date, H. Othman, and W. W. Price, "Slow coherency aggregation of large power system in eigen-analysis and frequency domain methods for system dynamic performance," IEEE Publications 90TH0292-3-PWR, pp. 50-60, 1990.

[9] R. A. Date and J. H. Chow, "Aggregation properties of linearized two-time-scale power networks," IEEE Transactions on Circuits and Systems, vol. 38, No. 7, pp. 720–730, 1991.

[10] J. H. Chow and R. Date, "A nodal aggregation algorithm for linearized two-time-scale power networks," IEEE International Symposium on Circuits and Systems, 1988.

[11] J. H. Chow, R. Galarza, P. Accari, W. W. Price, "Inertial and slow coherency aggregation algorithms for power system dynamic model reduction," IEEE Transactions on Power Systems, vol. 10, No. 2, pp. 680–685, 1995.

[12] S. R. Najafi, S. H. Hosseinian, and M. Abedi, "A novel strategy for stability evaluation of islanded power systems," Iranian Journal of Electrical and Computer Engineering, vol. 9, No. 1, pp. 43-51, 2010.

[13] S. Najafi, S. H. Hosseinian, and M. Abedi, "Proper splitting of interconnected power systems," IEEJ Transactions on Electrical and Electronic Engineering, vol. 5, No. 2, pp. 211–220, 2010.

[14] H. Verdejo, G. Montes and G. Olguín, "Identification of coherent machines using modal analysis for the reduction of multi-machine systems," IEEE Latin America Transactions, vol. 12, No. 3, pp. 416-422, 2014.

[15] R. Agrawal and D. Thukaram, "Support vector clustering-based direct coherency identification of generators in a multi-machine power system," IET Generation, Transmission & Distribution, vol. 7, No. 12,pp. 1357–1366, 2013.

[16] A. Vahidnia, G. Ledwich, E. Palmer, and A. Ghosh, "Generator coherency and area detection in large power systems," IET Generation, Transmission & Distribution, vol. 6, No. 9, pp. 874–883, 2012.

[17] C. Sturk, L. Vanfretti, Y. Chompoobutrgool, and H. Sandberg, "Coherency-independent structured model reduction of power systems," IEEE Transactions on Power Systems, vol. 29, No. 5, pp. 2418-2426, 2014.

[18] T. Krishnaparandhama, S. Elangovan, and A. Kuppurajulu, "Method for identifying coherent generators," International Journal of Electrical Power & Energy Systems, vol. 3, No. 2, pp. 85–90, 1981.

[19] K.L. Lo, Z.Z. Qi, and D. Xiao, "Identification of coherent generators by spectrum analysis," IEEE Proceedings - Generation, Transmission and Distribution, vol. 142, No. 4, pp. 367-371, 1995.

[20] M. Karrari, Power Systems Dynamics and Control, Amirkabir University of Technology (Tehran Polytechnic), 2004.

[21] J.H. Chow, K.W. Cheung, "A toolbox for power system dynamics and control engineering education and research," IEEE Transactions on Power Systems, vol. 7, No. 4, pp. 1559–1564, 1992.