Prevention of Cascading Outages Using Sparse Wide Area Synchrophasor Measurements

Ahad Esmaeilian, *Student Member* and Mladen Kezunovic, *Fellow, IEEE*

***Abstract*—Early prediction of cascade events outages followed by immediate and proper control actions can prevent major blackouts. This paper introduces a novel method to predict cascade event outage at early stage and mitigate it with proper control strategy. In the first step, methodology employs sparsely located phasor measurement units to detect disturbances using electromechanical oscillation propagation phenomena. The obtained information is used to update system topology and power flow. Next, a constrained spectral k-embedded clustering method is defined to determine possible cascade event scenarios, and if needed proper switching action is listed to intentionally create islands to minimize load shedding and maintain voltage profile of each island. The method was developed in MATLAB and tested with IEEE 118 bus test system. The results demonstrate effectiveness and robustness of the proposed method.**

***Index Terms*—Cascade event detection, electromechanical wave propagation, intentional islanding, phasor measurement units, synchrophasor and wide area measurements.**

I. Introduction

POWER system blackout is a fairly complicated phenomenon with very low expectation of occurrence but potentially devastating social and economic impacts. For instance, on August 14th 2003, a large blackout affected an area with around 50 million people, contributed to at least 11 deaths and estimated total costs between 4 to 10 billion dollars. Analysis of recent historical blackouts has shown that the grid catastrophic events occurred following a series of cascading events such as transmission line outages, overloads and malfunctions of protective relays [1-3].

Cascade events can be split into two stages. In the first stage, series of events are slow enough to be analyzed as steady-state condition. If no action occurs to manage the system during first stage, and meanwhile one or more major disturbances occur causing fast transient stability violation, a system collapse will take place (second stage) [4].

Different studies were devoted to prevent and mitigate cascading events, such as analyzing relay hidden failure, modeling cascade events, dynamic decision-event tree analysis, special wide area protection methods, etc.[5-8].

Another approach that has been widely used to recognize and prevent cascade event outages is based on power system contingency analysis. It is quite often impractical to list all possible contingencies for a large-scale power system. Therefore, several methods were proposed to rank possibility of contingencies and thereby reduce the computation burden of analysis. In [9], a Performance Index (PI) is introduced based on line voltage and loading condition to select reasonable contingency scenarios. A fast network screening contingency selection method is discussed in [10] which determines the location of buses with potential voltage problems, and defines a voltage-sensitive subsystem for contingency selection. A hybrid method is proposed in [11] which is a coordinated combination of PI methods, subnetwork solutions, compensation methods and sparse vector methods. Other methods include, first-order sensitivity analysis based on power flow results, neural network and pattern recognition [12-14].

In [15], a comprehensive Vulnerability Index (VI) based method is proposed which considers effects of voltage and reactive power, overload, distance relay performance, loss of generators, loads and transmission lines. Another vulnerability based analysis is proposed in [16] which determine vulnerable areas of power system based on short circuit analysis along with calculation of reserve reactive power.

Several methods have been proposed to mitigate cascade event outages by introducing optimal power system reconfiguration strategy. In [17], a three stage splitting strategy is proposed using ordered binary decision diagrams aligned with a time-based layered structure for real-time decision-making. An analytical islanding approach based on slow coherency theory is proposed in [18] which propose islanding strategy by identifying coherent groups of generators. Another slow coherency based algorithm combined with a graph theoretic islanding algorithm is presented in [19] to prevent cascading outages and simulated with the August 14th 2003 blackout scenario.

This paper introduces a novel method to predict cascade event outage at early stage and mitigate it with proper control strategy. In the first step, methodology employs sparsely located phasor measurement units to detect disturbances using electromechanical oscillation propagation phenomena. The obtained information is used to update system topology and power flow results. Then, a constrained spectral k-embedded clustering method is hired to determine vulnerable areas which might be prone to cascade event outages, and if needed, list suggest switching action to intentionally divide system into islands. With the implementation of proposed method, one can minimize amount of load to be shed, maintain voltage profile of the network, and therefore avoid cascading event outages which can result in major blackouts.

II. Proposed Methodology

A. Online Generation/Load Outage Detection

Electromechanical wave originated following a disturbance travels with finite velocity in the network. Electromechanical waveforms are characterized by phase angle modulation of voltages and currents with low frequency (0.1–10.0 Hz) [20]. These oscillations could be detected by looking into phasor measurement captured by PMUs or other IEDs which can report phasors.

Once the time of arrival (ToA) of electromechanical wave is obtained at selected buses where PMUs are installed, it can be used to determine where the generation/load outage occurred. It has been proven that the speed of electromechanical wave propagation through the network solely depends on system parameters and can be obtained as follows [20].

$$v = \sqrt{\frac{\omega \sin\theta}{2h|z|}} \tag{1}$$

where ω is the nominal system frequency, θ is the line impedance angle (~90°), h is the inertia constant of generator and $|z|$ is the line impedance. Therefore, the propagation delay of each line in the network can be calculated by:

$$T_{delay-L} = \frac{x_L}{\sqrt{\frac{\omega \sin\theta}{2h|z|}}} \tag{2}$$

where L=1,…,l represents each transmission line in the network and x_L is the total length of line L. Assuming that types and lengths of all transmission lines in power system are known, one can determine the wave propagation delay for each transmission line using (2).

For instance, let's assume for a sample network as depicted in Fig. 1, PMUs are located at buses A, B, C and D, while the outage occurred at an unknown bus k. The propagation delay of electromechanical wave to reach bus A can be obtained by:

$$t_{Ak} = t_A - t_k \tag{3}$$

where t_k represents outage initiation time at bus k, t_A represents ToA of electromechanical wave at bus A and t_{Ak} is the propagation delay of electromechanical wave to arrive at bus A. However, as the outage initiation time (t_k) is unknown, it is impossible to obtain t_{Ak}. Suppose that bus A is the first to receive the propagated wave, it can be used as the time reference. Therefore, the wave propagation delay from bus k to bus B with respect to ToA of electromechanical wave at bus A (t_A) can be defined as:

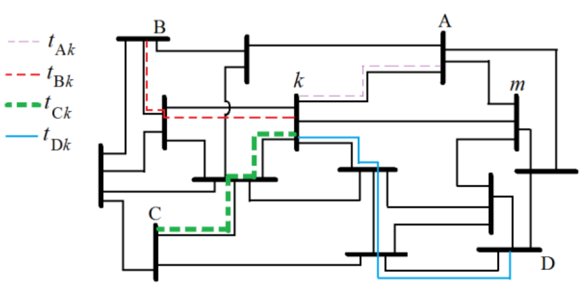


Fig. 1. Illustration of calculation of theoretical and measured delay matrixes

$$t_{BA} = t_{Bk} - t_{Ak} = t_B - t_k - (t_A - t_k) = t_B - t_A \tag{4}$$

The wave propagation delay from bus k to other buses with respect to ToA of electromechanical wave at bus A (t_A) can be defined similar to (4). Hence, the measured propagation time delay vector matrix can be defined as:

$$T_{meas} = \begin{bmatrix} t_{BA} & t_{CA} & t_{DA} \end{bmatrix} \tag{5}$$

Since the propagation delay of each transmission line is known by (6), one can compute the following vector of time differences resulting from the shortest travel times.

$$T_{sp-x} = \begin{bmatrix} \tau_{Bx} - \tau_{Ax} & \tau_{Cx} - \tau_{Ax} & \tau_{Dx} - \tau_{Ax} \end{bmatrix} \tag{6}$$

where τ_{Ax}, τ_{Bx}, τ_{Cx} and τ_{Dx} are the theoretical shortest time delay paths from buses A, B, C and D to any arbitrary bus x, respectively. It can be rewritten as:

$$T_{sp-x} = \begin{bmatrix} \tau_{BAx} & \tau_{CAx} & \tau_{DAx} \end{bmatrix} \tag{7}$$

The shortest time delay path for each bus pair is computed utilizing the Dijkstra's algorithm [21].

Since the outage occurred at unknown bus k, the calculated T_{sp-k} should identically match T_{meas} captured by ToA detectors. Therefore, one can define P_k as follows and then check it for all buses to find the bus corresponds to minimum P_k value.

$$P_x = Min\left(\left\| T_{sp-x} - T_{meas} \right\|\right) \qquad x = 1,\dots,n \tag{8}$$

where x=1,…,n is the total number of buses and P_k is the minimum norm associated with bus k.

B. Controlled Islanding Scheme

After several disturbances occurred in power system, the system gradually drifts to instability region. Consequently, the power system may enter the stage of fast cascading outages which will result in large-area blackouts. Instantly, generators with strong dynamic coupling swing together and are called coherent generators, whereas generators with weak dynamic coupling swing against each other [22]. Hence, islands must be intentionally formed to ensure that coherent generators are within the same islands to improve the transient stability and decrease the possibility of further outages. In this paper, we assumed that the generator coherency information is obtained from approaches such as the one described in [23].

The controlled islanding problem can be evaluated as a graph-cut problem using constrained spectral clustering. The objective function used in this paper is defined based on minimal power flow disruption which secures minimum change on transmission lines power flow pattern compare to pre-disturbance situation. In the constrained spectral clustering two types of constraints can be defined as Must Link (ML) and Cannot Link (CL) [24]. A ML constraint between two buses assures that those buses will be in the same island. However, a CL constraint guarantees that those buses will be in different islands. In our study, generator coherency information is used to determine ML and CL constraints. If the generators are coherent, there is ML between them, and if they are not coherent, the link between them is CL. To apply constraints into spectral clustering problem, constraint matrix Q is defined as below:

$$Q = \begin{cases} -1 & if \quad (x_i, x_j) \in CL \\ +1 & if \quad (x_i, x_j) \in ML \\ 0 & else \end{cases} \tag{9}$$

To determine if the constraints are properly attained by the clustering solution, the following index is defined:

$$u^T Qu = \sum_{i,j} u_i u_j q_{ij} \tag{10}$$

where $u \in \{-1, +1\}^N$ is called cluster indicator vector. The above encoding scheme can be further extended by relaxing u and Q such that:

$$u \in R^N \,,\; Q \in R^{N \times N} \tag{11}$$

If nodes i and j are related to the same cluster then $Q_{ij} > 0$; if nodes i and j are related to separate clusters then $Q_{ij} < 0$. The normalized constraint matrix Q_N and the Laplacian matrix L_N is defined as:

$$\begin{aligned} L_N &= D^{-1/2} L D^{-1/2} \\ Q_N &= D^{-1/2} Q D^{-1/2} \end{aligned} \tag{12}$$

where L, the un-normalized Laplacian of the graph which represent power system, is defined as:

$$L = \begin{cases} -w_{ij} = -\dfrac{|P_{ij}| + |P_{ji}|}{2} & i \neq j \\ d_i & i = j \end{cases} \tag{13}$$

$$d_i = \sum_{j=1}^{n} w_{ij}$$

P_{ij} and P_{ji} are the active power flow between buses i and j. The matrix L can be written as $L = D - W$, where D is a diagonal matrix with nonzero entries d_i.

Then, the constrained spectral clustering can be defined as a constrained optimization problem with the following definition [24]:

$$\begin{aligned} &\arg\min \quad v^T L_N v \\ &s.t. \quad v^T Q_N v > \beta,\; v^T v = vol,\; v \neq D^{1/2} 1 \end{aligned} \tag{14}$$

where $vol = \sum_{i=1}^{N} d_{ii}$ is the volume of the graph and β is the threshold value defined to confirm the constraints satisfaction. $v^T L_N v$ is the cost of the cut, $v^T v = vol$ is defined to normalize v and $v \neq D^{1/2} 1$ rules out the trivial solution.

The objective function in (14) can be solved using Karush-Kuhn-Tucker theorem [25]. After a few mathematical steps described in [24], optimal solution of (14) could be obtained by solving the generalized eigenvalue problem as below.

$$L_N v = \lambda \left(Q_N - \frac{\beta}{vol} I \right) v \tag{15}$$

The proposed spectral k-Embedded clustering method can be implemented within following steps.

- Defining k (total number of clusters) based on generator coherency information.
- Computing normalized Laplacian (L_N) and constraint matrix (Q_N).

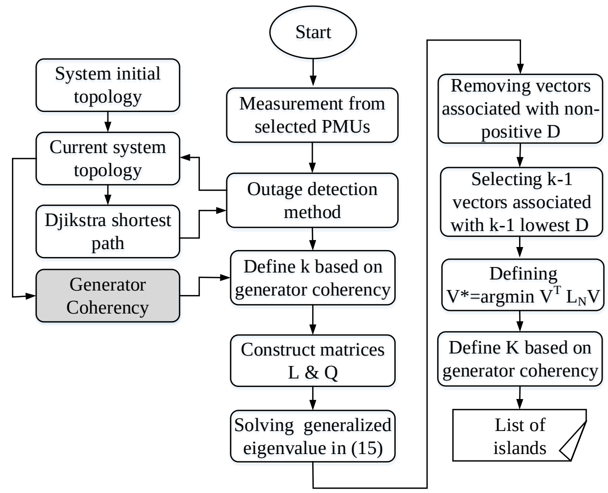


Fig. 2. Flowchart of the proposed cascade event prevention method

- Solving the generalized eigenvalue system in (15)
- Removing eigenvectors associated with zero or negative eigenvalues.
- Selecting k-1 eigenvectors ($v_1, ..., v_{k-1}$) related to the k-1 lowest eigenvalues.
- Defining $V^* \leftarrow \arg\min V^T L_N V$ where $V \in R^{n \times k-1}$ is the matrix containing vectors $v_1, ..., v_{k-1}$ as columns.
- Clustering nodes using k-medoids algorithm [26].

In summary, Fig. 2 shows the flowchart of the proposed cascade event prevention method.

III. Test Results

In this section, IEEE118 bus test system is used to test the performance of proposed methodology. Fig. 3 shows the location of PMUs in the system as suggested in [27].

A. Cascade Scenario

In this subsection, a series of outages are simulated using IEEE118 bus test system to create a cascading event outage scenario which finally leads to system blackout. The sequence of events is described as follows:

- Generator 10 is out of service at t=5 sec.
- Double phase fault occurred at t= 50 sec on line 30-38.
- Generator at bus 12 is disconnected after it losses synchronization with the rest of the network at t=52 sec.
- Due to overload on line 26-30, corresponding relays mis-operate at their third zones at t=55 sec (see Fig. 4a).

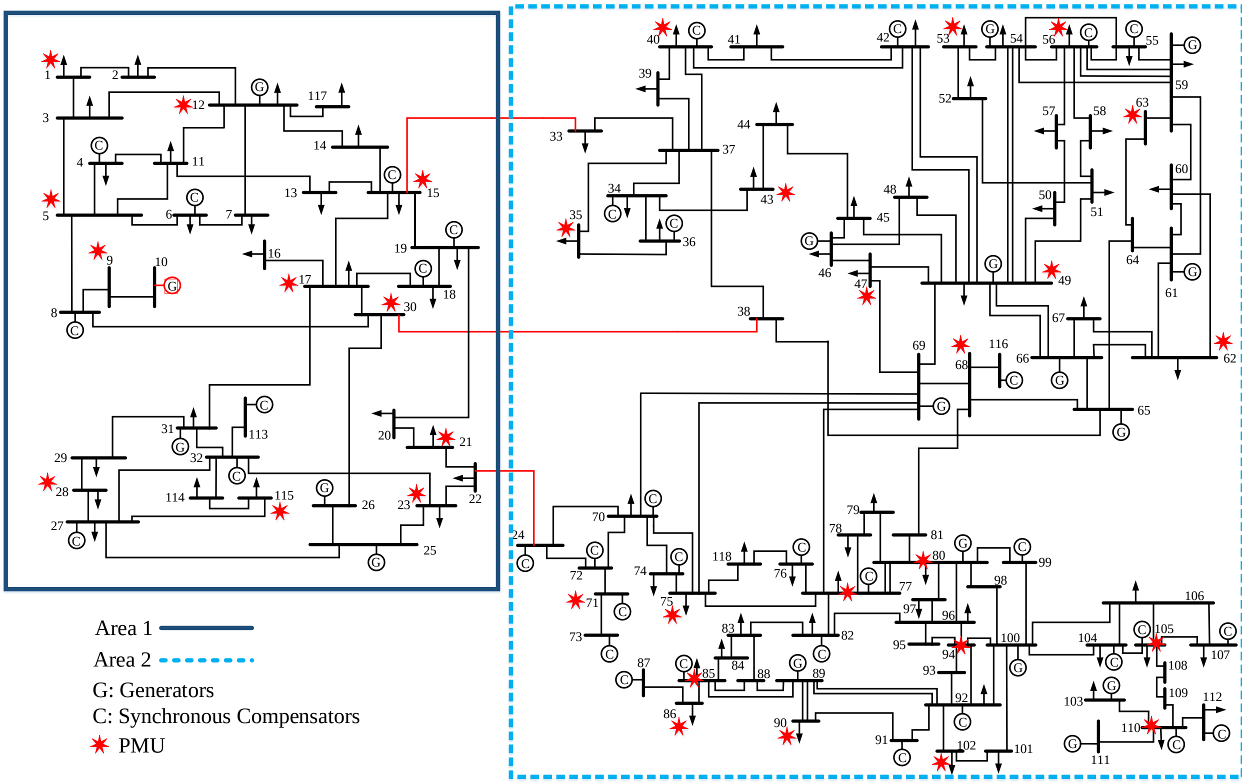
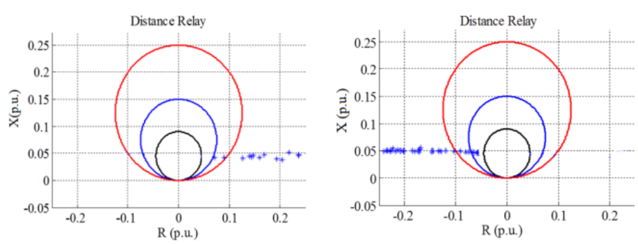


Figure 3. IEEE 118-bus test system



(a) (b)

Fig. 4. Distance relays mis-operation, a) overload on line 26-30, b) power swing on line 22-24

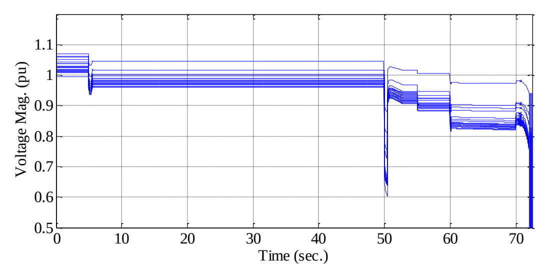


Fig. 5. Voltage profile during cascade event outages

- Line 22-24 is de-energized due to mis-operation of relays under power swing condition at t=60 sec (see Fig. 4.b).
- Lines 17-31, 15-33 and 19-20 are de-energized due to third zone mis-operation of relays under heavily overloaded condition after t=70 sec.
- Finally the voltage profile of the system collapses at t= 72 sec, and blackout occurs.

Fig. 5 shows the voltage profile obtained from buses where PMUs are installed. It can be seen that successive tripping of lines due to faults and relay mis-operations leads to voltage collapse and system blackout. Next subsection demonstrates how the proposed methodology can prevent cascading outages and save the system from blackout.

B. Cascade Event Prediction

Figs. 6 represent phasor angles captured by PMUs following outage of generator at bus 10 (only 5 phasor angles of PMUs were plotted to maintain readability of plot). As can be seen, the electromechanical wave oscillation (pick value) is first detected at bus 9 (at t=5.23 sec) and then detected at buses 1, 17, 15 and 21, respectively. Once, ToAs are detected at PMU locations, T_{meas} is calculated from (5). Then, P_k is calculated using (8), which leads to detection of generator outage at bus 10. Next, the topology updates from online outage detection module triggers the islanding module.

The generator coherency information determines that generators at buses 12, 25, 26 and 31 are coherent while the rest of generators are in the other coherency group. The suggested cutset to create intentional islands include lines (15-33, 22-24 and 30-38) which are shown in Fig. 3 with different color. By switching out these lines, IEEE 118 bus system is the total cost of suggested cutsets is 1.72 p.u. Since, coherent generators are grouped within the same island; the suggested islanding solution satisfies generator coherency constraints. In addition, the load-generation balance could be preserved without any need of load shedding. As it can be seen in table I, the active and reactive loads in both islands are less than the active and reactive generation capacity. As shown in Fig. 6, all bus voltages are higher than 0.95 pu after switching lines suggested by cascade event mitigation module at t=51 sec.

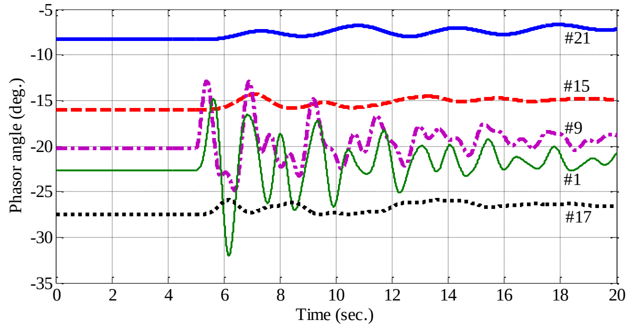


Fig.6. Electromechanical wave oscillation propagation

TABLE I. IEEE 118-BUS SYSTEM LOAD-GENERATION BALANCE

Island no.	Active Load (P_L)	Active Gen Capacity (P_G)	Reactive Load (Q_L)	Reactive Gen Capacity (Q_G)
1	9.63*	14.69	3.45	±23.18
2	36.08	45.86	10.93	±56.65

*Values are in p.u. base of 100MVA.

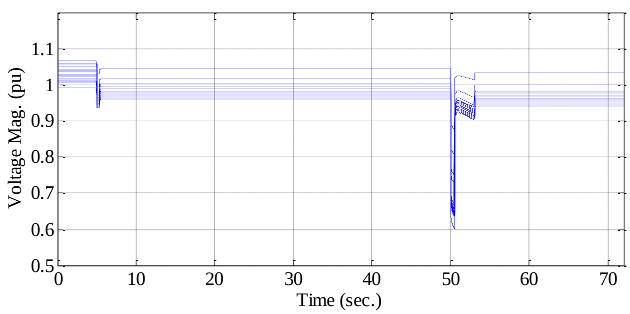


Fig. 7. Voltage profile during cascade event outages considering the proposed method.

IV. CONCLUSION

The main advantages of the proposed method over previously established ones could be itemized as follows.

- Due to topology update information from online outage detection module, the proposed method does not rely on information from topology processor or state estimator.
- The proposed spectral k-embedded clustering solution is computationally efficient so it can be used to predict and mitigate cascade events in a real-time condition.
- Defining objective function based on minimal power-flow disruption along with constraint matrix formed by generator coherency information resulted in creation of stable islands; meanwhile it reduced the complexity of islands' re-connection.
- This overall method can be implemented to work automatically with or without operator supervision, and can serve as a decision support tool for real time operation or operator training purpose.

REFERENCES

[1] "Final report on the August 14, 2003 blackout in the United States and Canada: causes and recommendations," *U.S.-Canada Power System Outage Task Force*, April 5, 2004.

[2] R. Baldick et al., "Initial review of methods for cascading failure analysis in electric power transmission systems," *IEEE PES General Meeting*, Pittsburgh, PA, USA, Jul. 2008.

[3] U.S. Department of Energy, "Federal Power Commission, The Con Edison power failure of July 13 and 14, 1977," June 1978.

[4] A. Esmaeilian, M. Kezunovic, "Impact of Electromechanical Wave Oscillations Propagation on Protection Schemes," *Electric Power Systems Research*, pp. 1-7, Jan. 2016.

[5] J.C. Tan, P.A. Crossley, P.G. McLaren, "Application of a wide area backup protection expert system to prevent cascading outages," *IEEE Trans. Power Deliv.*, Vol. 17, No. 2, pp. 375-380, 2002.

[6] D. C. Elizondo, J. deLa Ree, A.G. Phadke, S. Horowitz "Hidden failures in protection systems and their impact on wide-area disturbances," *IEEE 2001 PES Winter Meeting*, Vol. 2, pp. 710-714, 2001.

[7] A. Esmaeilian, M. Kezunovic, "Fault Location Using Wide Area Measurement of Electromechanical Wave Propagation," *Early Access in IEEE Trans. Power Delivery*, Vol. PP, No. 99, pp. 1-9, Dec. 2015.

[8] C. -C. Liu, J. Jung, G. T. Heydt, V. Vittal, A. G. Phadke "The strategic power infrastructure defense (SPID) system: a conceptual design," *IEEE Control Syst. Mag.*, Vol. 20, No. 4, pp. 40-52, 2000.

[9] G. C. Ejebe and B. F. Wollenberg, "Automatic contingency selection", *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-98, no. 1, pp. 938 – 109, Jan/Feb 1979.

[10] G. C. Ejebe, H. Van Meeteren, and B. F. Wollenberg, "Fast contingency screening and evaluation for voltage security analysis", *IEEE Trans. on Power Systems*, Vol. 3, No. 4, pp. 1582-1590, Nov. 1988.

[11] A. P. S. Meliopoulos, C. S. Cheng, and F. Xia, "Performance evaluation of static security analysis methods", *IEEE Trans. on Power Systems*, Vol. 3, No. 4, pp. 1441-1449, Aug. 1994.

[12] C. A. Castro and A. Bose, "Correctability of voltage violations in on-line contingency analysis," *IEEE Trans. on Power Systems*, vol. 9, pp. 1651-1657, Aug. 1994.

[13] Y. Chen and A. Bose, "Security analysis for voltage problems using a reduced model," *IEEE Trans. on Power Systems*, Vol. 5, Aug. 1990.

[14] L. Srivastava, S. N. Singh, and J. Sharma, "Knowledge-based neural network for voltage contingency selection and ranking," *Gen., Trans. & Dist., IEE Proceedings*, Vol.146, No.6, pp.649-656, Nov 1999.

[15] H. Song, M. Kezunovic, "A new analysis method for early detection and prevention of cascading events," *Electric Power Systems Research*, Vol. 77, No. 8, pp. 1132–1142, Jun. 2007.

[16] L. Mili, Q. Qui, A.G. Phadke, "Risk assessment of catastrophic failures in electric power systems," *International Journal of Critical Infrastructures*, Vol. 1, No. 1, pp. 38-63, 2004.

[17] K. Sun, D. Zheng, and Q. Lu, "Splitting strategies for islanding operation of large-scale power systems using OBDD-based methods," *IEEE Trans. Power Syst.*, Vol. 18, No. 2, pp. 912–923, May 2003.

[18] H. You, V. Vittal, and X. Wang, "Slow coherency-based islanding," *IEEE Trans. Power Syst.*, Vol. 19, No. 1, pp. 483–491, Feb. 2004.

[19] 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 Trans. Power Syst.*, Vol. 21, No. 4, pp. 1840–1847, Nov. 2006.

[20] J. Thorp, C. Seyler, A. Phadke, "Electromechanical Wave Propagation in Large Electric Power Systems," *IEEE Trans. on Circuits and Systems*, Vol. 45, No. 6, Jun. 1998.

[21] E. W. Dijkstra, "A note on two problems in connexion with graphs," Numer. Math., vol. 1, pp. 269–271, 1959.

[22] M. A. M. Ariff, B. C. Pal, "Coherency identification in interconnected power system -An independent component analysis approach," *IEEE Transactions on Power Systems*, vol. 28, no. 2, May 2013.

[23] C. Juarez, A. R. Messina, R. Castellanos, G. Espinosa-Perez, "Characterization of multi-Machine system behavior using a hierarchical trajectory cluster analysis," *IEEE Transactions on Power Systems*, vol. 26, no. 3, pp. 972-981, Aug. 2011.

[24] X. Wang, B. Qian, I. Davidson, "On constrained spectral clustering and its applications," *Data Mining and Knowledge Discovery*, pp. 1-29, Sep. 2012.

[25] H. Kuhn, A. Tucker, "Nonlinear programming," *ACM SIGMAP Bulletin*, pp.6-18, 1982.

[26] http://www.mathworks.com/help/stats/kmedoids.html

[27] L. Ding, F. M. Gonzalez-Longatt, P. Wall, V. Terzija, "Two-step spectral clustering controlled islanding algorithm," *IEEE Transactions on Power Systems*, vol. 28, no. 2, May 2013.

[28] S. Azizi, A. Dobakhshari, A. N. Sarmadi and A. M. Ranjbar, "Optimal PMU Placement by an Equivalent Linear Formulation for Exhaustive Search," *IEEE Transactions on Smart Grid*, Vol. 3, No. 1, Mar. 2012.