Selection of Multiple Credible Contingencies for Real Time Contingency Analysis

Sara Eftekharnejad
Department of Electrical and Computer Engineering
University of Idaho
Moscow, ID, USA
senejad@uidaho.edu

***Abstract*— The need to increase situational awareness in power systems is more evident than before. Increased power system complexity and integration of intermittent resources have contributed to the emerging need to monitor power systems in real time. Real time contingency analysis can increase situational awareness by monitoring the power system in real time and alarming the operators of the impending problems. Monitoring all multiple contingencies in real time is impossible and therefore, there is a need to reduce the number of monitored contingencies. This paper introduces a method for identifying most critical contingencies in power system for real-time monitoring.**

***Index Terms*— situational awareness, contingency analysis, security assessment, operations.**

I. Introduction

Power system's lack of situational awareness has been the main contributing factor to major widespread blackouts in the past two decades [1]. Power system 'situational awareness' has been the subject of recent studies [2-3]. Situational awareness is the ability of power system operators to observe the most recent status of the system and to identify the next contingency that will result in major overloads or voltage deviations. Identifying these impending failures provides operators with adequate time to prepare for the required mitigation that prevents additional cascading outages in the system. These mitigations are often pre-determined based on offline simulations of the system or can be determined as soon as the operator is informed of the impending contingencies.

Offline system simulations are based on system conditions that do not necessarily reflect the actual operating conditions. Therefore, the mitigations developed based on offline simulations are often overly conservative or inadequate to eliminate the adverse effects of the contingencies. One solution to this problem is to check the mitigations developed offline, such as the amount of load shed, with the real time model of the system that reflects the most recent load and generation profiles. When combined with the real time contingency analysis (RTCA), the power system operators can be alarmed of the real time contingencies that may jeopardize the reliability of the power systems in case of single or multiple contingencies. Hence, the operators are prepared for the unforeseen contingencies and may prevent those from impacting the neighboring systems.

RTCA provides the necessary means to monitor the systems in real time. However, it is extremely time consuming, expensive, and often impossible to monitor all multiple contingency in real time. Depending on the system size, the number of screened multiple contingencies are limited to the most critical contingencies to reduce the significant processing time required for contingency processing.

Recent studies have addressed the problem of reducing the number of contingencies [4]-[7]. Authors in [5]-[6] have investigated risk-based security assessment versus deterministic security assessment and have identified the problems associated with offline deterministic approaches. By limiting contingency analysis to those that expose the power systems to a higher risk, a comprehensive security assessment of the power systems is feasible. Lesieutre et al. have applied graph partitioning methods in [7] to identify the extreme events in power systems that are caused by the fewest number of transmission line outages.

This paper consists of two parts. The first part proposes a method that identifies the most critical single contingencies that are found based on real-time system conditions. The second part of this paper proposes a method that can be employed by RTCA systems in real time to identify the most credible multiple contingencies for screening by the RTCA systems.

The paper is organized as follows. Section II describes a measure that defines the criticality of a single contingency. A method to select credible multiple contingencies is introduced in section III. Simulation results are presented in section IV. Conclusions derived from this work are presented in section V.

II. Measure of Criticality

The main advantage of real time contingency analysis over offline simulations is the ability of the power system operators to estimate real time system conditions. By constantly monitoring power systems, operators are notified of the next contingencies that could drive the system above emergency thermal limits or beyond acceptable voltage stability limits. These conditions are often unseen by offline simulations and can jeopardize the reliability of power systems. The adverse impacts of some of these contingencies may be easier to mitigate by operating procedures already in place. However, contingencies that only became critical due to unprecedented system conditions demand more investigation time to identify proper mitigations. Thus, it is essential to identify those contingencies before they occur to have adequate time to prevent their potential adverse impacts, if they occur.

978-1-4673-8040-9/15/$31.00 ©2015 IEEE

The effectiveness of RTCA systems relies on the selection of contingencies that are monitored online. As discussed earlier, monitoring all multiple contingencies in real time is infeasible. The objective of this section is to introduce a contingency ranking method, based on system conditions, that identifies the optimal number of contingencies that should be monitored in real time.

The first step to identify monitored contingencies is to define a proper measure that can distinguish between critical contingencies and non-critical ones. Contingency ranking methods have been introduced in recent studies to rank contingencies based on their severity [8]-[10]. The method introduced in this research is inspired by the aforementioned studies; however, the proposed measure differs in multiple aspects. The *outage criticality index (OCI)* is defined based on the line flows of system transmission lines and is shown in (1). Although steady state bus voltages can also be used for screening the contingencies, throughout this work, it is assumed that the studied system is equipped with proper voltage regulation and VAR support equipment to regulate the steady state voltages.

$$OCI_{ij} = \begin{cases} \left[e^{\left(l_j - l_j^{Rate}\right)}\right] & ; l_j > l_j^{Rate} \\ 0 & ;\ l_j \le l_j^{Rate} \end{cases} \quad (1)$$

In (1) l_j^{Rate} is the rating of line *j*, and l_j is the flow of line *j* during the outage *i*. *OCI* quantifies the impact of various outages over other transmission lines. The *OCI* value calculated from (1) exponentially increases if the line flows exceed the line thermal ratings. System outage graphs are best formalized with graph representations. In Fig. 1, each node is a single bus and each edge is a transmission line. As stated in the literature [15], power networks differ from scale free networks and web traffic networks as they require electrical connections to be reflected in their graph representation. Therefore, a weighted graph is constructed where each edge weight is a function of the corresponding *OCI* values. Formally, weight w_{mn} is computed using the *OCI* calculated for the outage of line between buses *n* and *m* and quantifies the impact of this outage on the entire network. The weights are computed such that they consider the importance of an outage as follows:

1) The impact of an outage on other transmission lines: the higher the OCI_{ij} value, the more severe its impact on other lines, and
2) The number of times the outaged line is overloaded by the other single outages.

Based on the above mentioned two factors, w_{mn} values for all system transmission line outages (single outages) are defined as shown in (2).

$$w_{mn} = e^{2N_{mn}} + \sum_{i=1}^{N} OCI_{mn,i} \quad (2)$$

Where *N* is the total number of system transmission lines and $OCI_{mn,i}$ is the outage criticality index for outage of the line located between buses *n* and *m* and its impact on line *i*. Parameter N_{nm} is the number of times outage of the aforementioned line causes an overload on the rest of the transmission lines.

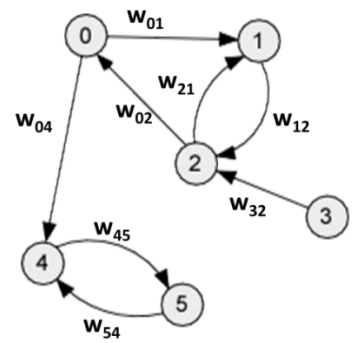

Figure 1. System outage graph

Once the outage graph of the system is constructed, the next step is to identify the critical single outages of the system that could result in relatively more severe consequences than other contingencies. To find critical outages of the system, the following questions are answered:

- What are the most *detrimental* outages in the power network?
- What are the *similar* outages?

The *degree of criticality* that is introduced in this work measures the level of criticality, influence and similarity among the single contingencies. In this definition outages with more impact on other lines are ranked higher in terms of criticality. However, having an impact on more lines does not by itself translate to criticality, rather being connected to more critical buses is better indication of criticality. Therefore, this method tries to generalize degree of criticality by incorporating the importance of the connected neighbors in the outage graph. In other words, a critical outage in this method is also the one that impacts the critical lines of the system.

According to the above mentioned assumptions, bus criticality in the outage graph is defined as the summation of the criticality of all other buses that are connected to it. Let C_i denote the criticality of bus *i*. Then, the criticality for bus *i* is the weighted summation of criticality of all buses such as *j* that are connected to *i*. The summation is normalized by a factor of $1/\lambda$. Hence, the criticality of node *i* is defined as,

$$C_i = \frac{1}{\lambda}\sum_{j=1}^{n} W_{ji}\, C_j \quad (3)$$

In (3), *n* is the total number of system buses. Further simplifying (3) yields,

$$\lambda C = W^T C \quad (4)$$

$$C = (C_1, C_2, \ldots, C_n)\ . \quad (5)$$

Where matrix *W* is the weight matrix and *C* and λ are the eigenvector and eigenvalues of that matrix respectively. Therefore, by calculating the *eigenvectors* of the *W* matrix the criticality of system buses are calculated. The above mentioned formulation is inspired by centrality measures in network science, and is called *eigenvector centrality* [11]. In eigenvector centrality positive eigenvectors are selected. It can be shown by using Perron-Frobenius theorem [18]-[20] that a

real square matrix with non-negative entries representing a strongly connected graph has a unique largest *real* eigenvalue and that the corresponding eigenvector has strictly real, non-negative components. Therefore, the largest eigenvalue of the weight matrix, W, will yield the corresponding positive eigenvector. This eigenvector is the measure of centrality that is used in this work. The weight matrix represents a strongly connected graph because for any two nodes in the network, there exists a path which connects those two nodes.

Application of centrality methods has been investigated in previous studies [15]-[17]. As Ernster et al. suggest in [16], centrality methods can be applied to power system for line outage rankings as compared to DC power flow methods. The proposed ranking method differs from previous studies as it introduces an edge weight definition and a methodology for selecting critical lines. The method presented thus far identifies critical system buses; however, the main objective of this work is to identify critical lines. Criticality index of *lines* are defined as follows,

$$C_{line} = C\,T \tag{6}$$

Where T is a $n \times m$ connectivity matrix and its elements are defined as,

$$T_{ij} = \begin{cases} 1 & \text{if line } j \text{ is connected to bus } i \\ 0 & \text{if line } j \text{ is not connected to bus } i \end{cases} \tag{7}$$

n: number of buses

m: number of lines

Line criticality defined as (6) assigns higher criticality to a line that is connected to critical nodes of the system. Although this method will identify the critical lines of the system, it might also assign high criticality to the lines that are connected to critical buses but are not necessarily critical. This is an acceptable trade-off as it ensures critical lines are guaranteed to be identified.

III. Case Study

The power system used in this research is the IEEE 30-bus (41 line) system that is widely used for power system studies. It is selected as it has sufficient number of buses and can represent a system with large number of multiple contingencies. The parameters for this test case are taken from [13] and [14]. Similar to [14], four levels of line thermal ratings are assigned to system transmission lines.

Offline contingency analysis (CA) is performed on the described system for all the single contingences. Overall, 41 line outages are simulated and the steady state line flows are calculated for each outage scenario. The OCI values are calculated for each outage and line pair based on (1) and the corresponding outage graph of the system is constructed. Using the approach described in section II, the most important buses of the system are identified and shown in Fig. 2.

For ease of comparison, the most critical nodes, i.e. buses, in the system graph are shown larger than the other nodes in Fig. 2. Table I lists these buses and the lines that are connected to them. Using (6) line criticalities are calculated and plotted in Fig. 3 for all the 41 lines in the system.

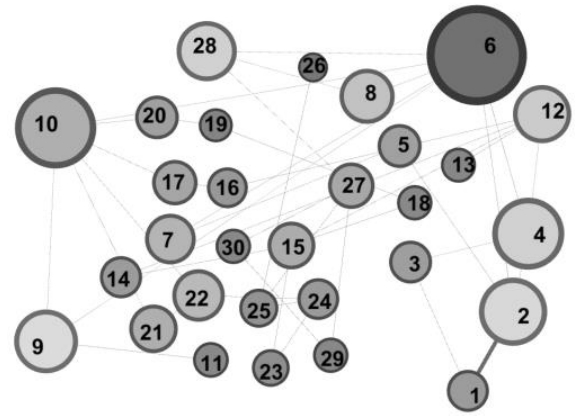

Figure 2. IEEE 30-bus system buses ranked based on eigenvector centrality method.

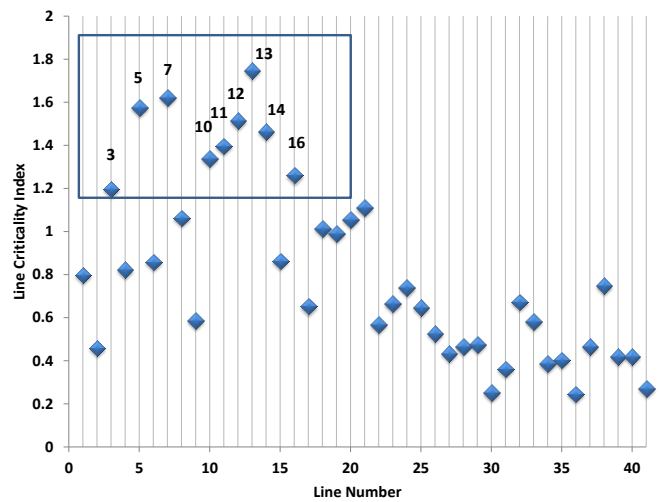

Figure 3. IEEE 30-bus single contingencies ranked based on line criticality index.

TABLE I. The Most Important Nodes of the IEEE 30-Bus Network and The Lines Connected to These Nodes

From Bus	To Bus	Line	From Bus	To Bus	Line	From Bus	To Bus	Line
6	2	5	**10**	9	16	**4**	2	3
6	4	7	**10**	17	18	**4**	3	6
6	7	10	**10**	20	19	**4**	6	7
6	8	11	**10**	21	20	**4**	12	8
6	9	12	**10**	22	21	**9**	11	17
6	10	13	**2**	1	1	**9**	6	12
6	28	14	**2**	5	4	9	10	16

IV. Identification of Credible Multiple Contingencies

A method to identify critical single contingencies was introduced in section III. In this section, a similar approach based on the outage graph is introduced that selects the credible multiple contingencies for real time monitoring. This method effectively identifies the clusters of outages that have similar impacts on the rest of the system. Therefore, any single transmission line outage from a cluster would approximately represent the impact of all the outages in the same cluster. This method significantly reduces the number of contingencies that need to be monitored in real time.

One method to find the node clusters in the outage graph is to find a group of system nodes and then verify whether the groups found could have emerged at random. The less likely these clusters are formed at random, the more robust would be the clusters of nodes that are found. Hence, one can aim to find clusters of nodes that are formed as far apart as random node clusters.

Assume in an outage graph, buses *i* and line *j* are connected to d_i and d_j number of lines, respecively. This translates to the fact that bus *i* will influence d_i lines in the actual system. Then the probability that bus *i* is connected to bus *j* at random is,

$$Pr_{random} = \frac{d_i d_j}{\sum_{j=1}^{n} d_j} \tag{8}$$

For any two buses *i* and *j*, the difference between the expected connection probability and the actual weight is:

$$W_{ji} - \frac{d_i d_j}{\sum_{j=1}^{n} d_j}. \tag{9}$$

For a combination of buses P_x, the difference is,

$$\sum_{i,j \in \mathrm{Px}} W_{ji} - \frac{d_i d_j}{\sum_{j=1}^{n} d_j}. \tag{10}$$

Therefore, for all *k* partitions in the graph, the difference is as shown in (11).

$$\sum_{x=1}^{k} \sum_{i,j \in \mathrm{Px}} W_{ji} - \frac{d_i d_j}{\sum_{j=1}^{n} d_j} \tag{11}$$

Moduarity finds the optimal partioning *($P_{x's}$)* of the graph such that the value calculated by (11) is maximized. Details of finding this optimal partitioning can be found in [11] and [12]. The optimal clustering of the nodes will identify cluster of lines that their outage will have similar impact on the rest of the power system. Each line outage in a single cluster will mostly affect the line flows that belong to the same cluster. Therefore, the highest ranked line outage in each cluster can represent the impact of all the line outages in the same cluster. To construct a reduced set of multiple contingencies, one representative line could be chosen from each cluster. These representative lines form a combined set of represenative outages for monitoring.

Next, the modularity method presented in this section is applied to the outage graph of the study case shown in Fig. 2. The node clusters of the system are identified in order to select the credible multiple contingencies of the system. The outage graph of the system with the clusters identified are shown in Fig. 4. As explained, the outages that belong to the same cluster have a similar impact on each other and also on the rest of the power system. Therefore, by selecting one *representative* outage from each cluster and combining those representative outages, one is able to find the reduced list of multiple contingencies. The representative line outage from each cluster is chosen as the *highest ranked* outage of each cluster, based on the criticality index defined as (6).

As seen from Fig. 4 there are three clusters of nodes that are identified by modularity maximization (shown in different colors). These clusters are listed in Table II.

TABLE II. Bus Clusters of IEEE 30-Bus Network

Cluster	Nodes
1	{30,29,28,27,26,25,24,23,22,21,20,19,18,17,16,11,10,9,8}
2	{13,12,6,4,3,2,1}
3	{5,7}

Further analyzing the results presented in Table II shows that there are some non-critical outages that are randomly assigned to different clusters. This will introduce an inaccuracy in the outcome of the clustering method. However, by selecting the most critical lines of each cluster, one can eliminate the impact of these inaccuracies on final contingency selection. Table III lists the corresponding lines that can serve as the best representatives of each cluster.

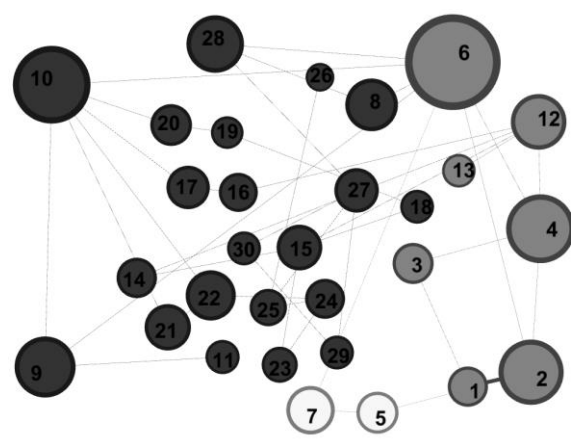

Figure 4. Outage clusters for the IEEE 30-bus system.

TABLE III. Best Contingencies for Identification of Credible Multiple Contingencies

Cluster	Representative Lines (contingency)	Buses connected
1	13	{10,6}
	14	{28,6}
	12	{9,6}
2	7	{6,4}
	5	{6,2}
	8	{4,12}
	3	{4,2}
3	4	{2,5}
	10	{7,6}

The single contingencies presented in Table III are not the absolute best representatives as some are not necessarily severe in terms of their impact. However, the most severe contingencies in each cluster are a subset of those presented in Table III. This points out to the fact that the proposed method can be further improved for more accurate results.

The credible multiple contingencies for the 30-bus network can be found by combining the contingencies presented in Table III. For the case study presented in this work, the number of double contingencies is reduced from 820 (all the 41 line outage combinations) to 36. This provides a significant improvement in time and computational needs for online security assessment of the power systems.

To test whether this method is effective in identifying the critical multiple outages, a few sets of contingencies from the list of contingencies presented in Table III are combined and the contingency analysis results are screened for the number of line flow violations. Table IV lists the number of violations for these credible contingencies versus non-credible contingencies. As seen from this table the credible contingencies, in general, illustrate more violations than the non-credible contingencies. It should be added that due to inaccuracies, there exist multiple contingencies in the list of non-credible contingencies that might be as severe as the credible contingencies for the reasons explained before.

TABLE IV. CREDIBLE VERSUS NON-CREDIBLE CONTINGENCY VIOLATIONS

Contingency (outaged lines)	**Number of line flow exceedances**
Credible	
{13,8}	7
{12,7}	4
{4,7}	10
Non-Credible	
{14,20}	3
{15,17}	0
{9,2}	3

V. CONCLUSIONS

This paper introduced a method for power systems that can rank contingencies and identify most credible multiple contingencies. The contingencies identified by this method can be used by the RTCA systems for real time system monitoring and operator alarming in case of impending thermal limit violations.

To illustrate the application of the method introduced in this work, IEEE 30-bus network is used as a test case. Simulation results show that modularity can effectively identify the single outages that are representatives of a group of outages. These methods can be applied on a seasonal or day ahead basis to the power system operating models to select and update the contingencies that are screened by the RTCA system in real time. Although proposed methods have been effective in identifying the credible contingencies, they could be improved to eliminate inaccuracies and further reduce the list of selected credible multiple contingencies.

REFERENCES

[1] FERC and NERC report, "Arizona southern California outages on September 8th 2011, causes and recommendations," April 2012. [Online]. Available: http://www.ferc.gov/legal/staff-reports/04-27-2012-ferc-nerc-report.pdf

[2] T. J. Overbye, "Visualization enhancements for power system situational assessment," in *Proc. IEEE Power and Energy Society General Meeting*, Pittsburgh, PA, July 2008.

[3] Y. Zhang, P. Markham, T. Xia, L. Chen, Z. Wu, Z. Yuan, L. Wang, J. Bank, J. Burgett, R. W. Conners, Y. Liu, "Wide-area frequency monitoring network (FNET) architecture and applications," *IEEE Trans. on Smart Grid*, vol. 1, no. 2, pp. 159-167, September 2010.

[4] A. Mittal, J. Hazra, N. Jain, V. Goyal, D. Seetharam, and Y. Sabharwal, "Real time contingency analysis for power grids, "in *Proc. Euro-Par 2011 Parallel Processing*, pp. 303-315, 2011.

[5] J.D. McCalley, V. Vittal, and N. Abi-Samra, "An overview of risk based security assessment," *in Proc. IEEE power engineering society summer meeting*, pp. 173-177, July 1999.

[6] M. Ni, J.D. McCalley, V. Vittal, and T. Tayyib, "Online risk-based security assessment," *IEEE Trans. on Power Systems*, vol. 18, no. 1,pp. 258-265, February 2003.

[7] B. C. Lesieutre, S. Roy, V. Donde, and A. Pinar, "Power system extreme event screening using graph partitioning," *in Proc. 38th North American Power Symposium*, pp. 503-510, September 2006.

[8] S. Eftekharnejad, G.T. Heydt, and V. Vittal, "Implications of smart grid technology on transmission system reliability," *in Proc. Power Systems Conference and Exposition*, March 2011, Phoenix, AZ.

[9] G. C. Ejebe, B. F. Wollenberg, "Automatic contingency selection," *IEEE Trans. on Power Apparatus and Systems*, pp. 97-109, vol. PAS-98, no. 1, January 1979

[10] G. Stefopoulos, F. Yang, G. J. Cokkinides, and A. P. Meliopoulos, "Advanced contingency selection methodology," *in Proc. 37th North American Power Symposium*, October 2005.

[11] R. Zafarani, M. A. Abbasi, and H. Liu, *Social Media Mining*, Cambridge University Press, 2014.

[12] V. D Blondel, J. Guillaume, R. Lambiotte, E. Lefebvre, "Fast unfolding of communities in large networks," *Journal of Statistical Mechanics: Theory and Experiment*, issue 10, October 2008.

[13] Illinois Center for a Smarter Electric Grid (ICSEG), "Power cases". [Online]. Available: http://publish.illinois.edu/smartergrid/power-cases/

[14] K. Sun, D. Z. Zheng, and Q. Lu, "Splitting strategies for islanding operation of large-scale power systems using OBDD-based methods," *IEEE Trans. on Power Systems*, vol. 18, no. 2, pp. 912-923, May 2003.

[15] P. Hines and S. Blumsack, "A centrality measure for electrical networks," *in Proc. the 41st Hawaii International Conference on System Sciences*, January 2008.

[16] T. Ernster and A. Sirvastava, "Power system vulnerability analysis towards validation of centrality measures," *in Proc. 2012 IEEE PES Transmission and Distribution Conference and Exposition*, May 2102.

[17] E. Zio and R. Piccinelli, "Randomized flow model and centrality measure for electrical power transmission network analysis," *Reliability Engineering and System Safety*, vol. 95, pp. 379-385, April 2010.

[18] C.D. Meyer, *Matrix Analysis and Applied Linear Algebra*, Society for Industrial and Applied Mathematics (SIAM), ISBN 0898714540, February 2001.

[19] G. Frobenius, "Uber matrizen aus nicht negativen elementen,*" S.B. Preuss Akad Wiss. Berlin*, pp. 456–477, 1912.

[20] O. Perron, "Zur theorie der matrizen," *Math. Ann.*, vol. 64, pp. 248-263, 1907.