A Novel Slow Coherency Based Graph Theoretic Islanding Strategy

Bo Yang, Vijay Vittal and Gerald T. Heydt

Department of Electrical Engineering

Arizona State University

Tempe, AZ, 85287

{byang6, vijay.vittal, heydt}@asu.edu

Arunabha Sen

Department of Computer Science & Engineering

Arizona State University

Tempe, AZ, 85287

asen@asu.edu

Abstract **– Slow coherency analysis is used to effectively determine the slowly coherent generator groups among weak connections for any given power system. A novel graphic theoretic method is proposed in this paper to simplify a large scale power system into a smaller network without losing optimal solutions. A multi-level recursive bisection graph partition method is employed to partition the reduced network into desired sub-networks with minimum generation-load imbalance. The relevant simplification rules and partitioning procedure are presented. The strategy is tested on the pre-cascading August 14, 2003 scenario for the Eastern Interconnection. The simulation results show that the proposed islanding strategy is effective.**

Index Terms – Slow coherency based grouping, Power System Stability, Graph simplification, multi-level graph partition.

I. Introduction

Power systems are being operated closer to stability limits as a result of competition in the market and other factors that include growth in generation and demand without the concomitant transmission system expansion. Stressed system conditions together with inadequate situational awareness, ineffective vegetation management and insufficient diagnostic support can cause catastrophic failures as demonstrated by the August 14, 2003 blackout [1]. In the literature, several approaches to deal with large disturbances have been proposed. Several of these tools are critical components of modern energy management systems. In general, the tools employed to defend against catastrophic failure can be categorized as either a) preventive control techniques or b) corrective control techniques.

In [2-4], a corrective control strategy that splits the system into controlled self-sustaining islands using a slow coherency approach has been presented. The islands are created based on a minimum load-generation unbalance criterion. The criterion takes into account aspects of restoration related to black start and reactive power capabilities. A load-shedding scheme based on the rate of frequency decline is applied to prevent frequency instability in load rich islands. In [3], an analytical approach to automatically determine the islands from the identified slowly coherent groups of generators using an exhaustive cut set approach was developed. Reference [4] further refined the automatic island determination scheme using a max-flow min-cut, graph theoretic approach with capabilities to merge adjoining slowly coherent groups, or break coherent groups based on the location of the disturbance. Reference [9] proposed a timing schedule for controlled islanding and a possible implementation based on decision tree technology. A controlled islanding strategy was tested using the extended transient-midterm stability program (ETMSP) [5] on a 179- bus, 29-generator equivalent of the WECC system and showed potential in mitigating the impact of disturbances and preventing cascading outages. The work reported in [12] demonstrated the slow coherency based islanding strategy on a realistic large scale power system. A maximum flow algorithm was employed to form the boundary between two islands. Simulation results demonstrated that the frequency of the island with generation shortage could recover to acceptable values via proper load shedding.

The advantage of the slow coherency criterion in capturing the structural characteristics of generators is critical when used for identifying the slowly coherent generator groups in [2-4, 12] while various graph theoretic methods are adopted to decide islands boundaries consistently.

The power system could be converted into a graph by denoting buses and transmission lines as vertices and edges respectively. The power system islanding problem then turns into the following graph partitioning problem: splitting the graph into connected and balanced sub-graphs according to properly defined vertex weights under the constraint that the net weights on boundary of each sub-graph is minimized. A breadth first search (BFS) algorithm is introduced in [14] for island detection and isolation. Reference [15] presents a graph splitting method using the OBDD technique. Boolean variables are used to determine whether a vertex belongs to an island or not. A software package called 'BUDDY' [16] is used to solve the Boolean equations under constraints that load and generation imbalances are within limit in each island. Reference [4] proposes a strategy to partition the graph using minimal cut sets with minimum net flow.

The author would like to acknowledge the National Science Foundation through its grants NSF EEC-9908690 and the DOE through a CERTS project through Power System Engineering Research Center for the support of this work.

Several efforts based on graph theory have been applied to solve this specific graph partitioning problem. However, there are still some issues that need to be addressed. Firstly, most of the graph theoretic methods are demonstrated on reduced size systems. Since the graph partitioning problem has been proved to be an NP-hard problem [13, 21] the computational complexity of this problem would be extremely high for large scale power systems. Therefore graph network reduction while preserving useful information is required. Reference [20] gives several clues of graph simplification after power system characteristics. Secondly, most of the boundary solutions obtained from the above mentioned islanding strategy are sub-optimal within some limits. Therefore improving accuracy of the obtained feasible solutions is still necessary.

This paper identifies the slowly coherent generator groups based on the slow coherency criterion and then determines the boundary of each island with a novel graph theoretic method. The proposed graph theoretic approach includes two parts: a graph simplification method based on the characteristic of the graph formed from a power system to reduce the computational burden and a multi-level graph partitioning method to solve the graph partitioning problem. The approach is qualitatively demonstrated on the August 14, 2003 blackout scenario. The demonstration is characterized as "qualitative' because a 2004 summer peak load Eastern Interconnection base case was altered to represent the condition during the 2003 blackout based on the information available from the joint US-Canada task force final report [1]. As a result, the reconstruction is presumed to closely resemble actual conditions prior to the blackout. However, the reconstruction does not exactly replicate the system state that existed prior to the blackout because these details were not provided in [1] and, indeed, the full set of data may not exist.

The 2004 summer peak load Eastern Interconnection case consists of 30000-buses and nearly 5000-generators. All the model detail provided in the available data remains un-changed as obtained from AEP. The slow-coherency method available in EPRI's DYNRED package [6] is used to identify the generator groups. The proposed graph theoretic method is applied to simplify the original graph and the boundary of island is determined based on the disturbance location taking into account the load-generation unbalance. A rate of frequency decline based load-shedding scheme is then applied to the load rich island.

This paper is organized as follows: Section II provides a brief overview of the slow coherency based generator grouping algorithm and rate of frequency decline based load-shedding scheme. Section III gives graph simplification rules and the details of the multi-level graph partitioning method. Section IV describes the recreated August 14, 2003 scenario from [12] and the simulation results of the demonstration of the proposed strategy. Section V presents discussion and conclusions.

II. Slow Coherency Based Islanding and Load-Shedding

In the controlled slow coherency based islanding approach, the determination of sub-regions of the electric power system, or *islands*, is a critical step. A slow coherency method [7] based on two-time-scale theory is utilized. A modification called tolerance based slow coherency [8] is used to deal with large systems and achieve more precise results. In the tolerance based approach to coherent generator identification, the user can specify tolerance values, the number of slow modes, and the number of eigenvalues of the linearized dynamic system equations being calculated. After having determined the groupings of generators using slow coherency and taking into account the location of a disturbance, an automatic controlled islanding algorithm is applied that takes into account certain physical constraints in forming islands. In these methods, two assumptions are made: 1) The coherent groups of generators are independent of the size of disturbance so that the linearized model could be used to determine the coherency group; 2) The coherent groups are independent of the level of detail used in modeling the generator unit so that a classical generator model can be considered [9].

One of the most important requirements for islanding is to minimize the real power imbalance within the islands to facilitate restoration. A graph theoretic technique has been developed in which the graph is partitioned with balanced vertex weights and minimized net flows. Once an island is formed, the net flow in the lines that must be interrupted is an indicator of the load – generation imbalance. It is assumed that losses can be ignored.

Once the islands are formed, some of the islands will be load rich and some of the islands will be generation rich. In the load rich islands, the decline in frequency becomes a serious issue and an adaptive load shedding scheme has been developed and demonstrated in [2-3] to shed load based on a rate of frequency decline. A load shedding scheme based on the rate of frequency decline is used here to identify the magnitude of the disturbance. At the same time, conventional load shedding is modified in a two-level load shedding algorithm [3]. Normally, load frequency relays are used to implement a conventional load shedding scheme. Conventional load shedding has long time delays and lower frequency thresholds which can be used to prevent inadvertent load shedding in response to small disturbances. If the system disturbance is large and exceeds the signal threshold [3], a second layer will be activated and the load shedding scheme based on the rate of frequency decline will take effect. This layer of the load shedding will shed load quickly to prevent the cascading events in the island. Thus the two levels of load shedding consists of conventional under frequency load shedding (slow response time), and rate of frequency decline load shedding (rapid response time).

III. Graph Simplification and Graph Partitioning

Having obtained the slowly coherent generator groups, the graph theoretic islanding method consists of two parts:

1) graph simplification; 2) graph partitioning. The flow chart is shown in Fig. 1.

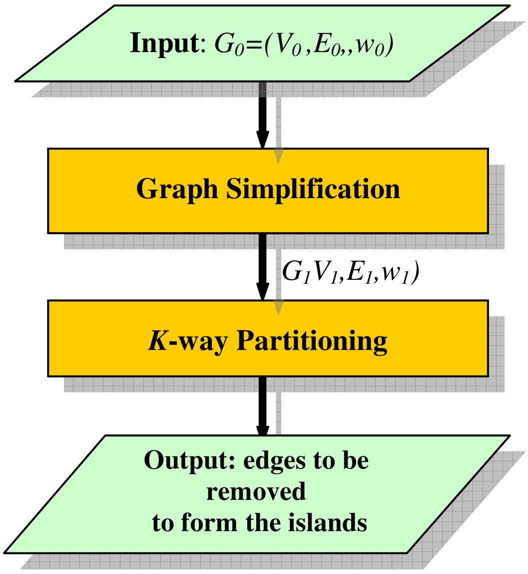

Fig. 1. Flow chart of the proposed method.

A. *Graph Simplification*

The motivation for graph simplification is easy to understand. The graph partitioning problem is NP-hard [13]. The computational complexity is high for large sized graph even for heuristic solutions. Simplifying the graph without losing too much useful information is necessary and efficient in order to speed up the simulation.

In general the process of partitioning a given graph consists of finding a group of edges which when removed will split the original graph into desired numbers of connected sub-graphs with minimized net flow. The simplification is aimed at decreasing the volume of the vertex and edge space for searching while conserving useful information. Converting the power system into a graph with vertices and edges could give a clear view of the total solution space. Network reduction could be conducted based on some features of the graph.

The simplification procedure consists of two aspects: 1) reducing the size of vertices and 2) reducing the size of edges.

The degree of a vertex is the number of edges connected to this vertex. It could be any positive number other than zero. Since the goal of partitioning is to form connected sub-graphs, edges of vertices of degree one would not be included in the feasible solutions.

The weight of a vertex is defined as the active power that flows out of it. For a vertex converted from a generator bus, the weight is positive. The weight is negative if the vertex corresponds to a load bus. The weight of a vertex could be zero if the input power flow equals to the output flow. This type of vertex is very common for long distance transmission lines. They are defined as 'energy conserving' in this paper.

A tree is a graph in which any two vertices are connected by exactly one edge. A properly designed tree could include desired vertices with least information. A shortest path tree (SPT) could guarantee that the number of undesired vertices included is minimized and the least redundant vertex and edge information would be adopted.

Based on the characteristics of graphs obtained from power systems, the following simplification rules are proposed:

1. *Remove vertices of degree one*

Taken as vertices in a graph, generators and loads are connected to a bus in the power system through transmission lines. In a graph, these vertices are vertices of degree one at the end of an edge. As shown in Fig. 2, they could be removed from the graph without changing the total vertex weights by adjusting the weight of vertex connected to them. Also the partitioning solution is going to split the graph into a connected sub-graph and the edge with a vertex of degree one will not be among the feasible solutions. Rule No.1 could reduce the both the size of vertices and edges of a graph.

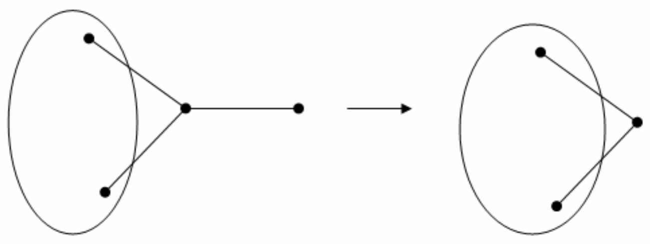

Fig. 2. Simplification rule No. 1: remove vertices of degree one.

2. *Contract energy conserving vertices of degree two*

For buses at which no loads and generators are connected, the power flow into the buses should equal to the power flow out if power loss along the transmission lines are ignored. For long distance power transmission, the power loss along lines is low compared to the total amount of power transmitted. Such buses could still be considered as energy conserving. The vertex weight of such buses would be defined as zero and they could be contracted without changing net flow of the island as shown in Fig. 3. Rule No. 2 could also reduce both the amount of vertices and edges.

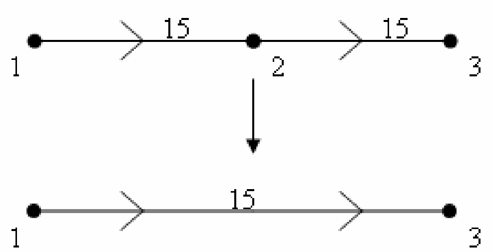

Fig. 3. Simplification rule No. 2: contract energy conservative vertices of degree two.

3. *Tree node collapsing*

Generator groups are identified based on slow coherency to capture the structural dynamics among generators within one island. In the graph partitioning problem, vertices corresponding to these generators within one coherent group are not intended to be split into different sub-graphs. One approach to realize this is to form a shortest path tree (SPT) with all generators in one slowly coherent group and allow only generator vertices to appear at the end of the branches. Collapsing the whole tree into one multi-mode would significantly reduce the numbers of vertices and edges as shown in Fig. 4.

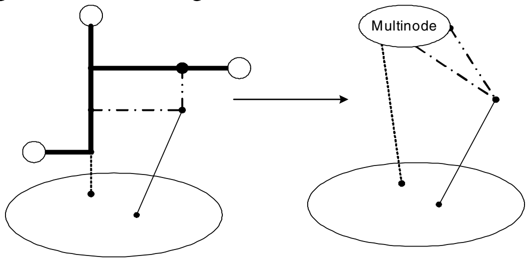

Fig. 4. Simplification rule No. 3: tree node collapsing.

There are other physical constraints that should be considered in islanding, which could further reduce the size of the graph. For example, within a given area which should not be interrupted during islanding, the whole area could be collapsed into one multi-mode. The vertex weight would be the total weights of vertices within the area and the edges connected to the area would be connected to the multi-node directly without changing edge weights.

Following the above three simplification rules, the complexity of a graph would be reduced and hence the computational cost of the original graph partitioning problem would be lowered.

B. Graph Partitioning

Graph partitioning is an important topic in graph theory. Several techniques in this field have been adopted to find solutions for the specific power system splitting problem [5, 12, and 17]. However, the islanding problem is not exactly the same as traditional graph partitioning problem.

The islanding problem can be formally stated as: given a graph $G=(V,E)$ with weight $w(v)$ and $w(e)$ associated with each vertex $v \in V$ and each edge $e \in E$ respectively, for given vertex sets $U_1, U_2 ... U_n$, partition the vertex set V into n subsets $V_1, V_2, ... V_n$, such that:

1) The n sub-graphs induced by $V_1, V_2, ... V_n$ are connected;

2) $U_i \in V_i, i = 1...n$;

3) $w(V_i) = \frac{w(V)}{n}$, $i = 1...n$ Where $w(V_i)$ is the summation of vertices weights in vertex set V_i;

4) $w(e_i)$, $i = 1...n$ is minimized for each sub-graphs, where $w(e_i)$ is the total edge weights for edges on the boundary.

The multi-level recursive spectral bisection algorithm is employed to partition the graph into n sub-graphs [18]. Each graph $G=(V,E)$ is associated with a Laplacian matrix L, where matrix $L := (l_{i,j})_{m \times m}$ satisfies:

$$l_{i,j} := \begin{cases} w(v_i) & if\ i = j \\ w(e_{i,j}) & if\ i \neq j\ and\ (v_i, v_j) \in E \\ 0 & otherwise \end{cases} \quad (1)$$

The eigenvector Y corresponding to the second smallest eigenvalue of L is computed. Let r be the median of y_i with $Y = [y_1, y_2 ... y_m]$. Those vertices of $y_i < r$ would be in a different vertex subset from those of $y_i > r$. In this way, the graph could be partitioned into two equal parts [18]. Recursive spectral bisection leads to the required number of partitions consistently.

Unfortunately the computational cost of Y is expensive. A multi-level approach is applied to omit the calculation for the whole matrix L directly. The matrix L is coarsened stepwise to an acceptable smaller sized matrix L' using graph theoretic methods. The corresponding eigenvector Y' is solved and interpolated back to the original size. The approximation of Y' could be further improved using iterative methods.

IV. Simulation Results

A. August 14, 2003 blackout scenario overview

In reference [12], the scenario before August 14, 2003 blackout is recreated. The slow coherency algorithm available in DYNRED [6] is then applied to find the slowly coherent generator groups based on the power flow obtained from the scenario recreated and the given dynamic data. No simplifications were made and all modeling details provided in the data are included. As noted in [12], First Energy (FE) forms a slowly coherent group by itself.

The initiation of the cascading event started with the trip of the Sammis-Star line on a Zone 3 relay setting as detailed in [1]. This was the primary disturbance which caused the cascade to spread across the system.

Reference [12] also shows that islanding within FE area is feasible and efficient to prevent disturbances escalation. This information was used in the initiation of the proposed graphic theoretic islanding strategy which identifies the islands with the minimum load generation unbalance. In general the criterion of when to island will be determined by conducting off-line analysis.

B. Network simplification and partitioning for the Eastern Interconnection

The 2004 summer peak load Eastern Interconnection case consists of 30000-buses and nearly 5000-generators. When converted into a graph, it has 26552 vertices and 37839 edges. For the FE area, there are 708 vertices and 1018 edges. A number of edges and vertices of the graph could be eliminated and the computational cost for graph partitioning would be reduced. Fig. 5 shows the efficiency of proposed graph simplification rules.

With the simplified graph, the multi-level recursive bisection method available in the METIS package [19] is employed to form the island imposing the minimal net flow constraint on the boundary. As shown in Fig. 6, the region around Cleveland near Lake Erie in the FE area is split from the rest of the system and forms an island.

Compared to the island in [12], more generators and loads are included. The island by the proposed strategy is still around Cleveland area. 20 lines are tripped to form the island. They include 7, 345 kV lines, 9, 138 kV lines and 4, 69 kV lines. The total generation in the island is 6259.23 MW and the total load is 8309.07 MW. This load rich island has a power shortage of 2049.84 MW, which is lower than the result obtained in [12] which was 2262.1 MW.

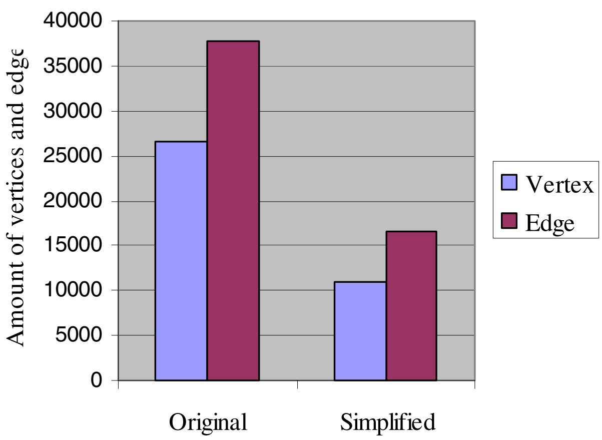

Fig. 5. Comparison of graph size

Under frequency load shedding is applied to prevent frequency decline in the island. With a bigger island geographically than in [12] and a comparable power shortage, it is easier to stabilize the dynamic behavior of the Cleveland area than it was in [12]. The under frequency load shedding relay operates and sheds a total of 23% (1911.09) MW of load. The time domain simulation results related to selected system states are shown in Fig 7-13.

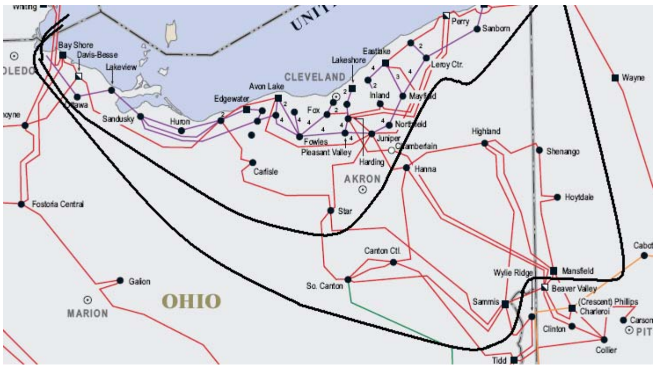

Fig. 6. Line connection of FE area: the outer boundary includes the FE area coherent group; the inner boundary shows the island.

C. *Dynamic simulations*

As described in [1], a primary disturbance of tripping the Sammis-Star 345 kV transmission line initiated the cascading events by overloading several other 345 kV transmission lines. The proposed islanding strategy islands the Cleveland area. The active power flow on these key 345 kV lines is examined. Line active power is compared between the fault only case and the islanding case in Fig. 7-9. Since the island boundary includes the 345 kV line between Sammis and Star, the line is opened and will not be overloaded as in the fault only case in Fig. 7. Moreover, the line flow on both Fostoria to Lima in Fig. 8 and Wayne to E. Erie in Fig. 9 are reduced by islanding, which indicates that islanding at least minimized the impact of disturbances on both the western and eastern portion of the system.

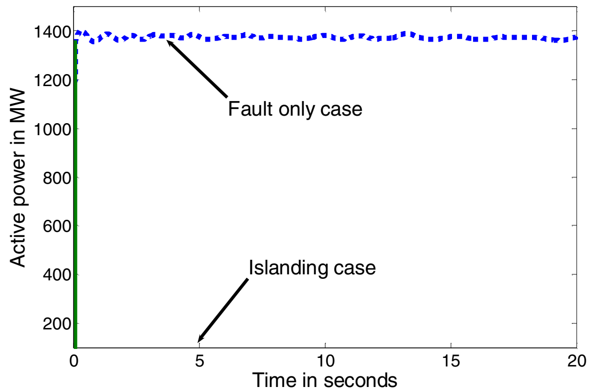

Fig. 7. Active power on Sammis-Star.

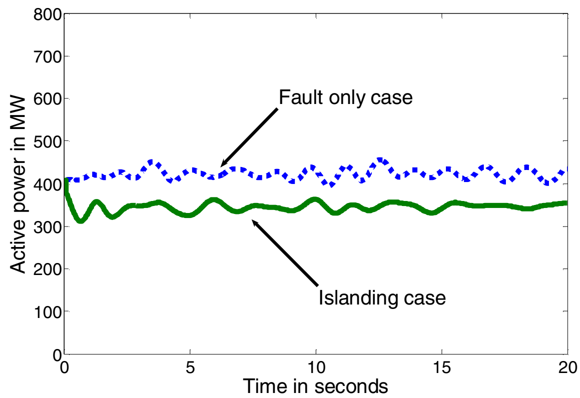

Fig. 8. Active power on Lima-Fostoria

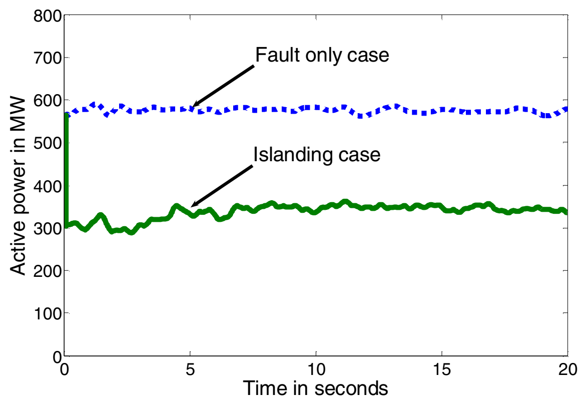

Fig. 9. Active power on Wayne-E. Erie

Impacts of islanding on frequency and voltage are also examined in Fig. 10-11. Frequency at the Burger bus outside the island is stable and around 60 Hz and rises a small amount after islanding as shown in Fig. 10. In the load rich island, frequency at Edgewater drops to 58.5 Hz and stays below 60 Hz for a few seconds. It bounces back to around 60 Hz after proper load shedding in Fig. 11.

Voltage at Sammis located outside the island is slightly improved after islanding compared with the fault only case in Fig. 12. Note that the voltage at Mansfield stays solid in both cases as described in Fig. 13. Islanding benefits the voltage at Starr by raising the voltage magnitude from below 0.9 pu up to 1.09 pu and stabilizes at 1.03 pu in Fig. 14.

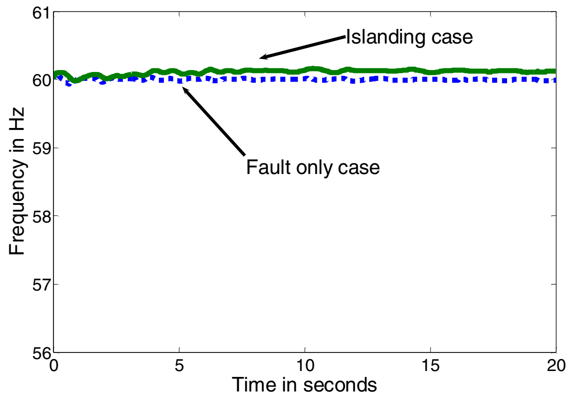

Fig. 10. Frequency at Burger

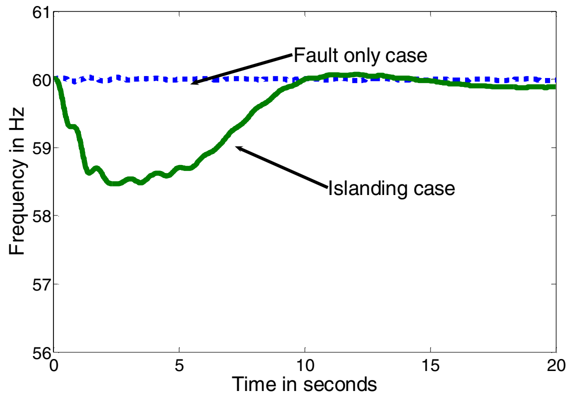

Fig. 11. Frequency at Edgewater.

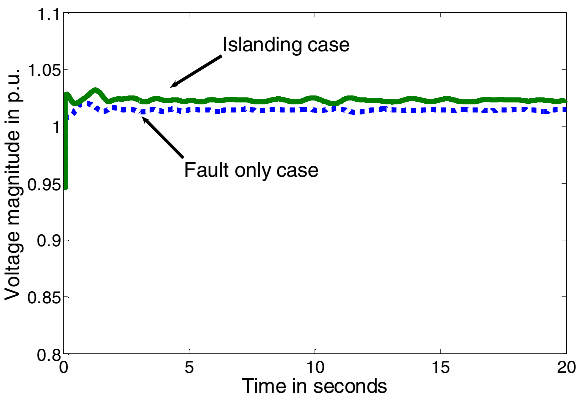

Fig. 12. Voltage magnitude at Sammis

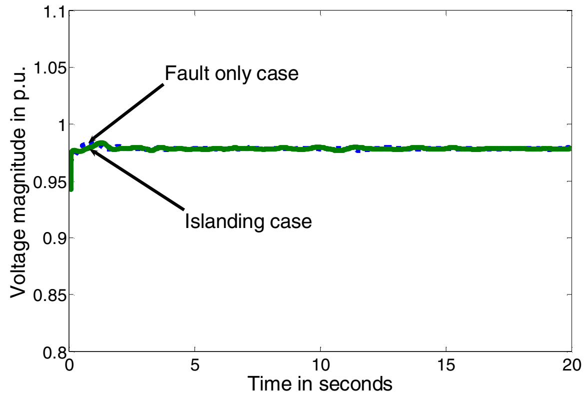

Fig. 13. Voltage magnitude at Mansfield

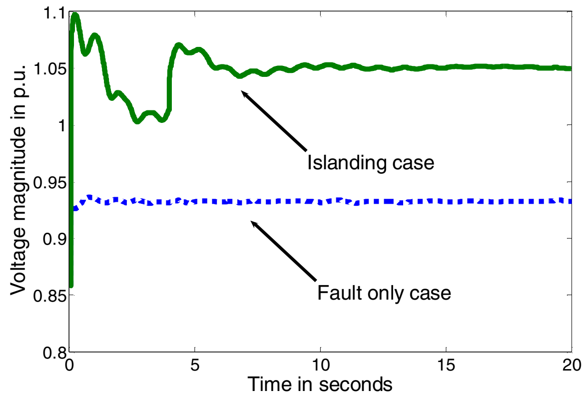

Fig. 14. Voltage magnitude at Star

The relative angle of Burger to the east of the Cleveland area is also examined in Fig. 15. It is observed that the impact of disturbances in the eastern portion of the system is low.

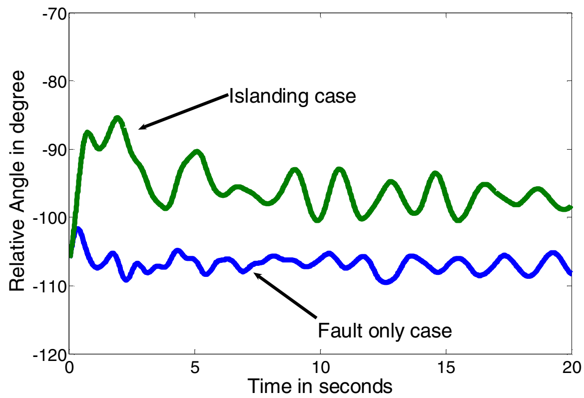

Fig. 15. Relative angle of Burger

V. Conclusions and Discussions

This paper presents a slow coherency based graph theoretic islanding strategy. Generator groups are identified by slow coherency criterion considering both structural and dynamic characteristics. Simplification rules are proposed to reduce the network and lower the computational complexity. The multi-level recursive spectral bisection method available in METIS [19] is adopted to determine the boundary of islands with minimal net flow.

The impacts of islanding are inspected in detail on the August 14, 2003 blackout scenario. Simulation results reveal the efficacy of proposed islanding strategy on containing disturbances from spreading to the system and potentially preventing initiate cascading events. Islanding has small effect on the system outside the island. The load rich island formed could also be stabilized by load shedding.

In the future, the advantages of the proposed islanding strategy would be compared with previously employed strategies.

REFERENCES

[1] U.S.-Canada Power System Outage Task Force, "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," April 2004. - https://reports.energy.gov/ BlackoutFinal-Web.pdf

[2] H. You, V. Vittal, and Z. Yang, "Self-Healing in Power Systems: An Approach using Islanding and Rate of Frequency Decline-Based Load Shedding," *IEEE Trans. on Power Systems*, vol.18, No.1, pp 174-181, Feb. 2003.

[3] H. You, V. Vittal, and X. Wang, "Slow Coherency-Based Islanding," *IEEE Trans. on Power Systems*, vol. 19, No. 1, pp 483-491, Feb. 2004.

[4] X. Wang and V. Vittal, "System Islanding Using Minimal Cutsets with Minimum Net Flow," *Proceedings of the 2004 IEEE PES Power System Conference and Exposition*, New York, October 2004.

[5] Electric Power Research Institute, "Extended Transient-Midterm Stability Program (ETMSP)," vol. 2, EPRI TR-102004-V2R1, May 1994, Version 3.1, User's Manual (Rev. 1).

[6] Ontario Hydro, "Dynamic Reduction," vol. 2, EPRI TR – 102234 - V2R1, May 1994, Ver. 1.1, User's Manual (Rev. 1).

[7] J. H. Chow, Time-Scale Modeling of Dynamic Networks with Applications to Power Systems. New York: Sprinter-Verlag, 1982, vol. 46.

[8] W. Price et al., "Improved Dynamic Equivalencing Software," GE Power Systems Engineering, Final Report, EPRI TR-105919 Project 2447-02, Dec. 1995.

[9] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*, Piscataway, NJ: IEEE Press, 1994.

[10] N. Senroy, G. T. Heydt, "A Conceptual Framework for the Controlled Islanding of Interconnected Power Systems," accepted for publication, *IEEE Trans. on Power Systems*, 2005.

[11] NPCC Supplement to Specification for Electrical Installations, Electric System Bulletin # 756B, April 2004- http://www.nationalgridus.com/non_html/shared_construction_esb756 b-2004.pdf

[12] 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. On Power Systems*, vol. 21, No. 4, pp. 1840-1847, Nov 2006.

[13] A. Sen, P. Ghosh, V. Vittal and B. Yang, "A New Min-Cut Problem with Application to Electric Power Network Partitioning," The 44th Annual Allerton Conference, Sep 27-29, Allerton, IL.

[14] J. S. Thorp and H. Wang, Computer Simulation of Cascading Disturbances in Electric Power Systems, Impact of Protection Systems on Transmission System Reliability Final Report, PSERC Publication 01-01. May 2001.

[15] K. Sun, D. 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.

[16] BUDDY: A Binary Decision Diagram library – http://sourceforge.net/projects/buddy

[17] T. Bi, Y. Ni, C. M. Shen and F. F. Wu, "Efficient Multiway Graph Partitioning Method for Fault Section Estimation in Large-scale Power Networks", *IEE Proc-Gener. Trans. Distrib.* Vol 149, No. 3, May 2002.

[18] T. Zorner, "Multilevel Spectral Bisection", Master Thesis, University of Massachusetts, Amherst, MA, 1997.

[19] METIS: Serial Graph Partitioning and Fill-reducing Matrix Ordering - http://glaros.dtc.umn.edu/gkhome/metis/metis/overview

[20] K. Sun, D. Zheng and Q. Lu, "Searching for Feasible Splitting Strategies of Controlled System Islanding", IEE Proceedings Generation, Transmission & Distribution, vol. 153, No. 1, pp, 89-98, 2006

[21] Q. Zhao, K. Sun, D. Zheng, J. Ma and Q. Lu, "A Study of System Splitting Strategies for Island Operation of Power System: A Two-phase Method Based on OBDDs", IEEE Transactions on Power Systems, vol. 18, No.4, pp. 1556-1565, Nov 2003

Bo Yang (S'03) received the B.S and M.S. degree from Shanghai Jiaotong University, Shanghai, China, in 2000 and 2003 respectively. She is currently pursuing the PH.D in the department of Electrical Engineering at Arizona State University, Tempe. Her research interests are in the area of power system dynamics and control.

Vijay Vittal (S'78-F'97) received the B.E. degree in electrical engineering from Bangalore, India, in 1977, the M.Tech. degree from the Indian Institute of Technology, Kanpur, India, in 1979, and the Ph.D. degree from Iowa State University, Ames, in 1982.

Currently, he is the Ira A. Fulton Chair Professor in the Electrical Engineering Department at Arizona State University, Tempe and the Director of .PSERC a National Science Foundation, Industry University Cooperative Research Center. From 1982- 2004 he was on the faculty at the Electrical and Computer Engineering Department, Iowa State University. Dr. Vittal received the 1985 Presidential Young Investigator Award and the 2000 IEEE Power Engineering Society Outstanding Power Engineering Educator Award.

Dr. Vittal is a member of the National Academy of Engineering.

Gerald T. Heydt (M'64–SM'80–F'91) received the Ph.D. degree in electrical engineering from Purdue University, West LaFayette, IN.

Currently, he is the site director of PSERC a National Science Foundation, Industry University Cooperative Research Center at Arizona State University, Tempe, where he is a Regents' Professor. His industrial experience is with the Commonwealth Edison Company, Chicago, IL, and E. G. & G., Mercury, NV. He is a registered professional engineer in Indiana.

Dr. Heydt is a member of the National Academy of Engineering.

Arunabha (Arun) Sen received his bachelor's degree in Electronics and Tele-Communication Engineering from Jadavpur University, Kolkata, India and PhD degree in Computer Science from University of South Carolina, Columbia, South Carolina. He is currently an Associate Professor in the department of Computer Science and Engineering at Arizona State University. He also serves as the Associate Chairman of the department responsible for Graduate Programs and Research. His research interest is in the area of resource optimization problems in networks. He primarily studies the algorithmic issues related to the problems in these domains and utilize graph theoretic and combinatorial optimization techniques to find solutions. He has published over eighty research papers in peer reviewed journals and conferences on these topics and served many IEEE and ACM workshops and conferences either as a Program Committee member or as the Chair of the Program Committee.