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Subsystem Size Optimization for Efficient Parallel Restoration of Power Systems

Nuwan Ganganath†, Chi-Tsun Cheng†*, Herbert H. C. Iu‡, and Tyrone Fernando‡
†Dept. of Electronic and Information Eng., The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
‡School of Electrical, Electronic and Computer Eng., The University of Western Australia, Crawley, WA, Australia
*Email: chi-tsun.cheng@polyu.edu.hk

***Abstract*—It is essential to rapidly restore a power system after a blackout to minimize the economic losses and negative social impact. The most common approach of accelerating the restoration process is by restoring the complete network as several subsystems in parallel. Even though a parallel restoration process has obvious advantages over its sequential alternatives, sizes of the subsystems play key roles in controlling the overall restoration time. Existing network partitioning strategies for parallel restoration do not put control on the individual subsystem size. In this paper, we proposed a partitioning strategy that helps to accelerate the restoration process by minimizing the subsystem size differences. Case study results given in this paper illustrate the effectiveness of the proposed partitioning strategy in parallel restoration of the power systems.**

***Index Terms*—Network partitioning, blackout, parallel power system restoration, agglomerative clustering, constrained optimization.**

I. Introduction

The Northeast blackout of 2003 has drawn people's attentions to the safety and stability issues of our power systems [1]. The event has also triggered extensive researches in the last decade on the prevention of cascading failures in power networks. Although the robustnesses of our power systems were improved throughout the years, power outage is still unavoidable especially when the complexity of the network increases. The ability for a power system to be restored and recovered within a short period of time after a blackout thus becomes a crucial factor for reducing losses and damages [2].

A typical power plant requires external electric power for starting. Under normal operation, such power can be obtained from the grid. During a blackout, however, the required electric power will be relying on on-site generators, known as black-start generators. Power plants brought up by their black-start generators will become the cranking group and provide the cranking power to restore other plants in the outage area. The network will then be reconfigured for the cranking group to bring up plants and to connect loads sequentially [3]. The restoration process can be accelerated if multiple black-start generators, and so do cranking groups, exist in the blackout area, such that parallel restoration is possible. The whole power network can be restored back into a single entity by synchronizing the restored subsystems in the later stages of the process.

In [4], Kamwa *et al.* proposed a fuzzy-based algorithm for partitioning power systems. Their proposed idea relies on real-time data collected from phasor measurement units which, however, may not be applicable in a complete blackout scenario. Wang *et al.* in [5] proposed a multi-phase strategy for parallel restoration. Their solution is based on an ordered binary decision diagram which provides suggestions to human operators on how to carry out the restoration procedures. Lin *et al.* in [6] tackled the partitioning problem by exploiting complex networks properties in power systems. Their community detection-based algorithm can yield subsystems for parallel restoration without the aid of an expert system. Similarly, Quirós-Tortós *et al.* in [7] employed spectral graph theory to achieve the required clusters. The same group of authors used a constrained cut-set matrix in [8] to obtain multiple sets of subsystems for human operators to start with in a restoration process. Recently, Sun *et al.* in [9] formulated the partitioning problem as a mathematical programming problem. In their proposed solver, however, stability and synchronization issues were omitted. It is worthwhile mentioning that most power system partitioning methods presented in the last decade were only capable of dividing a network into two sub-networks. Repetitive executions of the methods are thus required if more than two subsystems are needed, which make it difficult to control the size of the resulting subsystems.

Assume it takes almost the same amount of time for a cranking group to bring up any power plant in a blackout area, having equal-sized subsystems can thus guarantee a shorter system-wide restoration time. Partitioning strategies that can yield subsystems with similar sizes are thus the key modules in a parallel restoration process. This paper proposes a partitioning strategy which optimizes the subsystem size while ensuring enough generation capability in each partition. The proposed strategy also ensures that the resulted subsystems satisfy some essential physical constraints related to operations of power systems. Those constraints are discussed in Section II along with other preliminaries. The proposed partitioning strategy is described in Section III and evaluated using two standard power system models in Section IV. Some additional properties of the proposed partitioning strategy are discussed in Section V. Concluding remarks and future directions are given in Section VI

II. Preliminaries

In this paper, a power system is represented using an undirected graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ that consists of $|\mathcal{V}|$ nodes and

$|\mathcal{E}|$ edges which respectively represent buses and branches of the power system. The generation-load difference at a node v_i can be obtained by

$$\widetilde{P}(v_i) = P_{\text{MG}}(v_i) - \alpha(v_i)P_{\text{LD}}(v_i), \quad (1)$$

where P_{MG} is the maximum active power generation capability, P_{LD} is the expected active power consumption, and α is the percentage of high priority loads to be restored before the synchronization of subsystems [7]. A set of nodes that represents the buses connected to critical loads are called critical nodes which is denoted by $\mathcal{V}^{\text{CL}}$. In accordance with [7] and [8], it is assumed that $\alpha(v_i) = 1.0$ if $v_i \in \mathcal{V}^{\text{CL}}$ and $\alpha(v_i) = 0.7$, otherwise.

Given a power system, a partitioning strategy will select a set of edges in $\mathcal{G}$, known as the cut-set $\mathcal{E}_{\text{CS}}$, to be removed in order to separate the system into multiple subsystems. The cut-set should be carefully selected to ensure each partition will be equipped with the necessary black-start capability to initiate the formation of their local cranking group [7]. Given that there are M black-start generators, a power system can be partitioned upto M subsystems for parallel restoration such that each subsystem consists of at least one black-start generator. Using (1), the generation-load difference of the kth subsystem can be given as

$$\varphi(\mathcal{V}_k) = \sum_{\forall v_i \in \mathcal{V}_k} \widetilde{P}(v_i), \quad (2)$$

where $\mathcal{V}_k \subset \mathcal{V}$ [7]. As each subsystem must be restored independently, $\mathcal{V}_i \cap \mathcal{V}_j = \emptyset$ for $i, j \in \{1, 2, \ldots, M\}$ and $i \neq j$. Moreover, $\mathcal{V}_1 \cup \mathcal{V}_2 \cup \ldots \cup \mathcal{V}_M = \mathcal{V}$. For evaluation purposes, the size of the kth subsystem is determined by the number of nodes in the corresponding subgraph, *i.e.* $|\mathcal{V}_k|$.

To ensure stability in the parallel restoration process, the selected cut-set should also ensure that the total power delivered by the local cranking group should satisfy the total demands of the local loads [10], [11]. Monitoring equipment should present at tie-lines among partitions to ensure synchronization during the merging process and a central monitoring centre should be there to monitor the operation of each partition continuously during the whole restoration process [8].

III. The Proposed Partitioning Strategy

It is essential to identify black-start generators and cranking groups before partitioning a power system for parallel restoration. An optimal black-start generator selection strategy is proposed in [12]. Cranking groups can be obtained using the method proposed in [13] which optimizes the duration of the cranking task. Identification of black-start generators and cranking groups are out of the scope of this paper. Here, it is assumed that the black-start generators and cranking groups are known prior to the start of the partitioning process.

Given that there are M parallel restoration processes, there should be an equal number of cranking groups available. Let the kth cranking group be denoted by $\mathcal{V}_k^{\text{CR}} (\subset \mathcal{V}_k)$. The non-black-start generators in a cranking group may not necessarily be connected to the black-start generator directly. In order to ensure the connectivity within a cranking group, the proposed strategy finds a shortest path tree $\mathcal{G}_k^{\text{SP}}$ using Dijkstra's algorithm [14] for all $k \in \{1, 2, \ldots, M\}$ such that the black-start and non-black-start generators in $\mathcal{V}_k^{\text{CR}}$ respectively represent root and leaf nodes in $\mathcal{G}_k^{\text{SP}}$.

Next, the proposed partitioning strategy ensures the satisfaction of the rest of the physical constraints. Let the union of sets of critical lines, lines without monitoring equipments, and any other lines which are unsuitable to be used as tie-lines between subsystems be denoted by $\mathcal{E}_E$. These lines should not be included in the cut-set [7]. Hence, in this step of the proposed strategy, nodes that are connected to a shortest path tree via an edge in $\mathcal{E}_E$ are clustered together with the nodes in the corresponding shortest path tree. These clusters are called primary sets. Note that there are M primary sets. If there are nodes that are connected to each other via the edges in $\mathcal{E}_E$ and not in primary sets, they are also clustered together. If there are any other nodes which are not considered under any of aforementioned criteria, each of those nodes is then considered to be a separate set. All these sets, except the primary sets, are called secondary sets. Now, we have two different types of node sets; each node in $\mathcal{V}$ belongs to only one type of the sets.

In the last step, the smallest primary set is combined with a candidate secondary set such that the generation-load difference of the resulted primary set is maximized. A candidate secondary set is a secondary set which always has at least one connection with the selected primary set. This process iteratively repeats until all secondary sets are combined with the primary sets. The nodes in each final set correspond to the buses in the final subsystems.

IV. Case Studies

In this section, the proposed partitioning strategy is compared with the spectral clustering based partitioning strategy proposed in [7]. The proposed strategy was implemented using MATLAB. Simulation results are summarized in TABLE I.

The first set of studies was carried out using IEEE 39-bus power system. In graph notations, v_{33} and v_{37} represent the black-start generators in this power system. Here, $M = 2$. Cranking groups are $\mathcal{V}_1^{\text{CR}} = \{v_{30}, v_{31}, v_{32}, v_{37}, v_{39}\}$ and $\mathcal{V}_2^{\text{CR}} = \{v_{33}, v_{34}, v_{35}, v_{36}, v_{38}\}$. Critical loads are $\mathcal{V}^{\text{CL}} = \{v_3, v_4, v_8, v_{16}, v_{20}\}$. Edges to be excluded from the cut-set are $\mathcal{E}_{\text{E}} = \{e_{(26,29)}, e_{(28,29)}, e_{(6,11)}, e_{(10,11)}, e_{(13,14)}, e_{(15,16)}, e_{(21,22)}, e_{(23,24)}, e_{(5,6)}, e_{(6,7)}\}$. The above parameters remained the same for both strategies under test. According to the simulation results, both algorithms returned identical subsystems with optimal sizes. The final subsystems are illustrated in Fig. 1. The cut-set is $\mathcal{E}_{\text{CS}} = \{e_{(3,18)}, e_{(14,15)}, e_{(25,26)}\}$. Obviously, non of the edges in $\mathcal{E}_{\text{E}}$ are included in $\mathcal{E}_{\text{CS}}$. Also, note that the generation-load difference of each subsystem is positive. That helps in maintaining the system frequency to be within a desirable range.

The second set of studies was carried out using IEEE 118-bus power system. Black-start generators in this

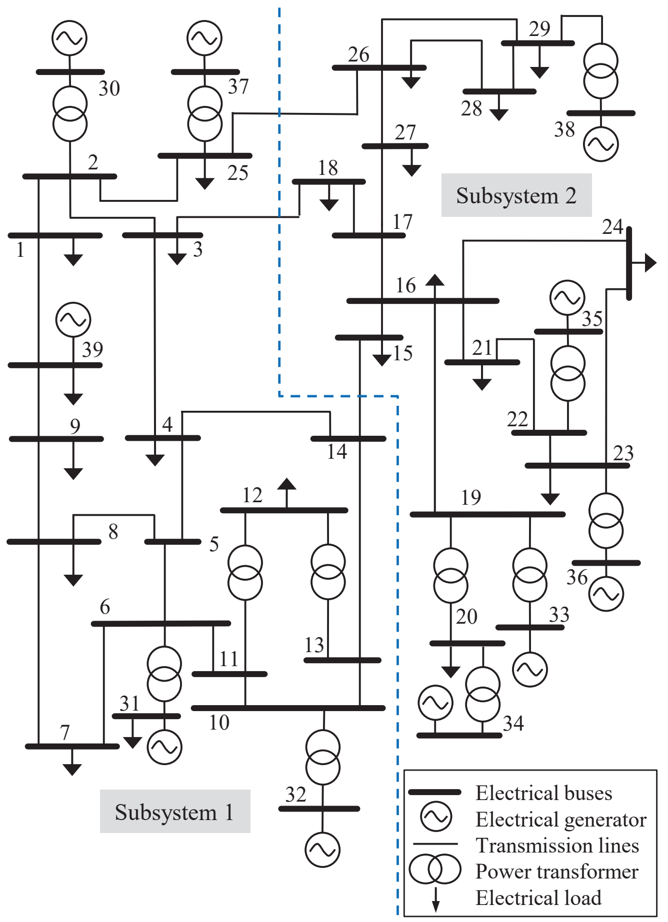

Fig. 1. Subsystems of IEEE 39-bus power system obtained by using the partitioning strategies under test.

power system are located at v_{31} and v_{87}. Cranking groups are $\mathcal{V}_1^{\text{CR}} = \{v_{10}, v_{12}, v_{25}, v_{26}, v_{31}\}$ and $\mathcal{V}_2^{\text{CR}} = \{v_{49}, v_{54}, v_{59}, v_{61}, v_{65}, v_{66}, v_{69}, v_{80}, v_{87}, v_{89}, v_{100}, v_{103}, v_{111}, v_{46}\}$. Critical loads are $\mathcal{V}^{\text{CL}} = \{v_{78}, v_{92}, v_6, v_{11}, v_{15}, v_{18}, v_{27}, v_{34}, v_{40}, v_{56}, v_{60}, v_{62}, v_{70}, v_{74}, v_{76}, v_{112}\}$. Edges to be excluded from the cut-set are $\mathcal{E}_{\text{E}} = \{e_{(5,8)}, e_{(8,9)}, e_{(9,10)}, e_{(34,43)}, e_{(37,38)}, e_{(38,65)}, e_{(40,42)}\}$. The above parameters remained the same for both strategies under test. The subsystems obtained using the proposed partitioning strategy are illustrated in Fig. 2. For comparisson, readers may refer to Fig. 5 in [7] for the illustration of subsystems obtained using the spectral clustering based partitioning strategy. According to the simulation results given in TABLE I, the subsystems obtained using either of the partitioning strategies under test report positive generation-load differences. Nevertheless, the proposed partitioning strategy has achieved a much smaller subsystem size difference compared to that achieved by the spectral clustering-based strategy. Therefore, the proposed partitioning strategy can considerably improve the overall restoration time of the IEEE 118-bus power system.

V. Discussion

In both of the above studies, the number of subsystems is defined as 2, which is constrained by the black-start power availability. Nevertheless, the agglomerative approach used in the proposed partitioning strategy enables it to produce more than 2 subsystems without repetitive executions if the black-start power requirements are satisfied. This can be considered as an advantage of the proposed partitioning strategy over other existing strategies, especially in restoration of large-scale power systems. If the generation-load difference of the complete power system is negative, the proposed strategy will fail to provide subsystems with all positive generation-load differences, which is in any other existing partitioning strategies. Finally, it is assumed that the power system is fully observable after the blackout. In practice, this may not be the case as some monitoring and communication modules can be offlined during the blackout.

VI. Conclusion and Future Work

This paper proposed a partitioning strategy for parallel restoration of power systems. The proposed strategy helps to accelerate the parallel restoration process by minimizing the subsystem size differences while satisfying some physical constraints. These constraints are vital in ensuring the independent restoration of each subsystem. The proposed strategy also optimizes the generation-load balance of the subsystems which is important in maintaining a desirable frequency in each subsystem before they are synchronized. Moreover, the proposed strategy is capable of partitioning a network into more than 2 subsystems depending on the availability of black-start generators. Performances of the proposed strategy need to be further analysed using large-scale power system data to justify its real-world applicability. Furthermore, the lack of full observability of power systems under restorations should be taken into account in future research.

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TABLE I
CASE STUDY RESULTS.

Power system	Partitioning strategy	Generation-load difference (MW)		Subsystem size	
		Subsystem 1	Subsystem 2	Subsystem 1	Subsystem 2
IEEE 39-bus power system	Spectral clustering based strategy [7]	1218.5	730.7	20	19
	Proposed strategy	1218.5	730.7	20	19
IEEE 118-bus power system	Spectral clustering based strategy [7]	746.8	2168.9	37	81
	Proposed strategy	416.6	2499.1	49	69

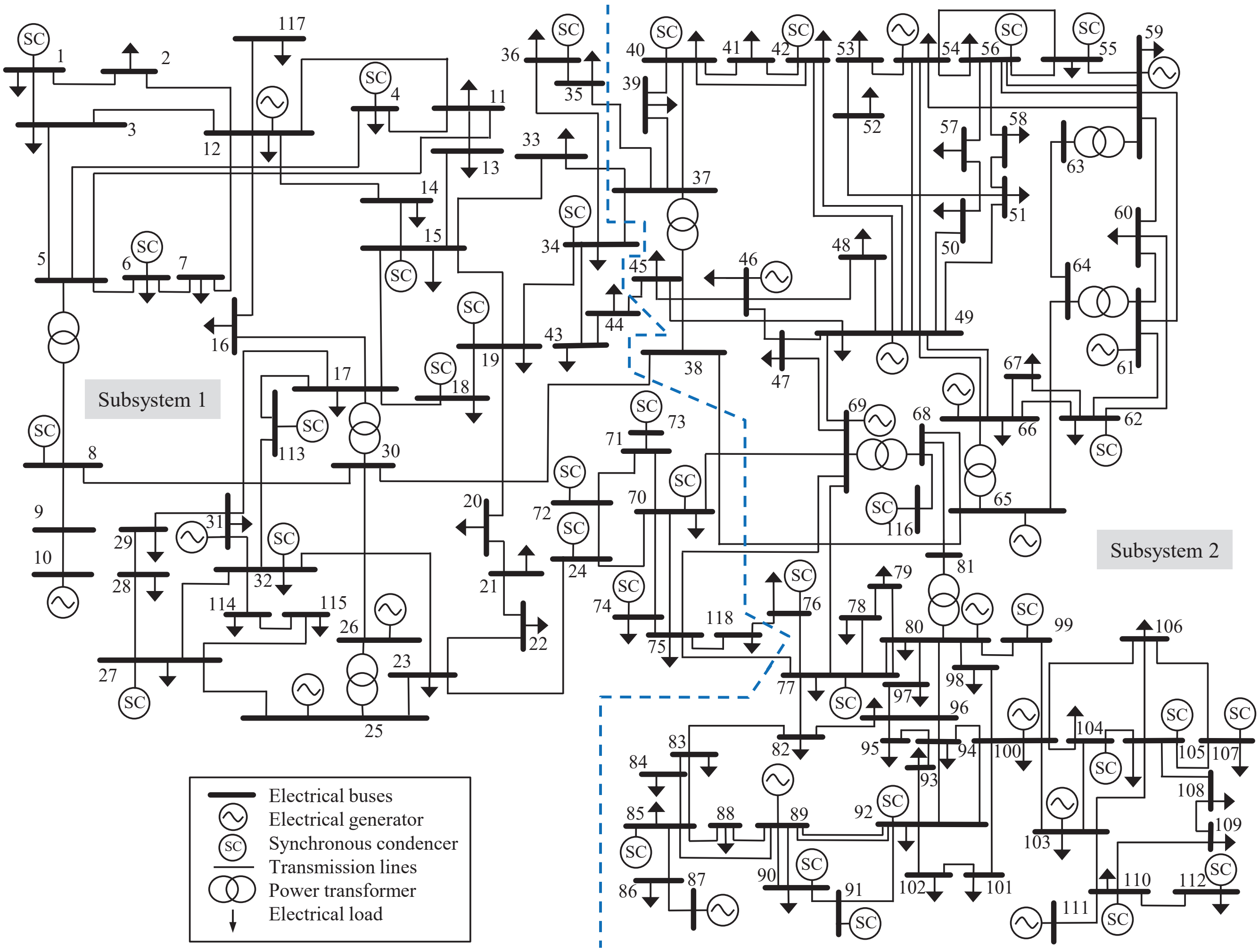

Fig. 2. Subsystems of IEEE 118-bus power system obtained by using the proposed partitioning strategy.

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