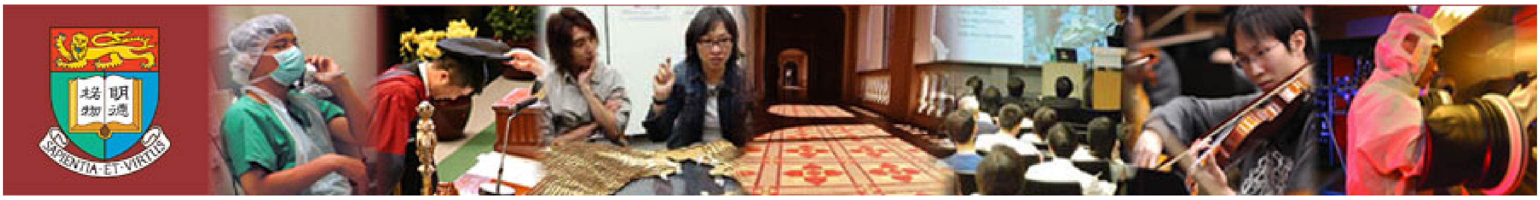

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Constructing Breaker Sequence based System Restoration Strategy with Graph Theory

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***Abstract*--This paper has proposed a mapping approach to serve as an interface between the branch-bus model and the breaker-based model. In order to find the specific optimal operation for breakers in substations according to the restoration strategies, firstly, the paper has established the breaker-based model for the substation by using graphic theory, and then the optimal operation sequence for breakers has been figured out by adopting Dijkstra algorithm. Finally, a case study for a realistic power system has been analyzed to demonstrate the feasibility and efficiency of the approach.**

***Index Terms*--restoration, breaker operation sequence, branch-bus model, breaker-based model, graph theory**

I. INTRODUCTION

Power system restoration has been well identified as a critical component for enhancing power system reliability [1]. As a multi-stage and multi-objective problem, a lot of complicated problems need to be solved. Consequently, power system restoration decision support tools are critically needed by system planners and operators. For restoration planning, some methodologies have been proposed to establish system restoration strategies based on branch-bus model [2-3], such as “System Restoration Navigator” (SRN) proposed in [3-4].

The branch-bus models have been widely used in power system analysis. Based on this model, restoration sequence for transmission lines and components (generating units and loads) on buses can be constructed. It can be used by restoration planners. More detailed model based on the sequence of breaker operation should be provided for operators. In the North American Electric Reliability Corporation (NERC)’s standards, the R1.8 and M1 in Standard EOP-005-2 clearly point out that the station service for substations is required in restoration operating process [5]. Thus, according to this standard, for the breaker-based model in substation, it is necessary to find out the specific operation in substation to realize the restoration strategies generated from branch-bus models. In other words, the interface that mapping the mathematical branch-bus model to the physical breaker-based model should be established so that the restoration plan can be validated and executed in realistic power system.

Up to now, for the breaker-based restoration, several categories of approaches have been proposed. Paper [6] has proposed the basic interactive techniques for substation automation by describing the topological models and computational techniques. Moreover, [7] has added the action strategies to re-establish the normal conditions for critical elements, and [8] has presented a practical restoration aid expert system for Korean 145kV substations. Paper [9] has utilized the Petri nets to fast achieve the service restoration plan of a substation on-line, and [10] has revised the approach by using hierarchical colored Petri net in a safe, reliable, fast and efficient way. Paper [11] has proposed a new approach using Artificial Intelligence techniques to search the optimal restoration actions. Therefore, the above general approaches indeed provide much enlightenment to the substation restoration.

The purpose of this paper is to extend the branch-bus based restoration strategy to the realistic breaker-based models. According to the characteristics of the branch-bus model and different categories of breakers, auxiliary equipment and their associated standards, the breaker-based model of power plants and transmission substations for system restoration will be established. Upon this model, the approach for mapping branch-bus based model to breaker-based model will be developed. Furthermore, due to different operation regulations and realistic requirements, such as maintenance, forced outage, operation constraints, the specific operation actions need to be modified accordingly [16-18]. Hence, the sequence of operating actions for a restoration strategy will be generated. This sequence can be operated on realistic power grids, which will finally provide a major step to update the restoration strategies from an off-line decision support system to an on-line self-healing system.

Therefore, the remainder paper is organized as follows. Section II establishes a detailed model set of realistic power system operations for a substation restoration, including the equivalent problem in graphic theory and the modeling process. Section III presents the algorithm adopted to find the optimal operation actions based on the proposed model. Section IV gives out an illustrated case and a practical case on a realistic system to demonstrate the approach proposed in this paper. The conclusions is shown in Section V.

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II. BREAKER-BASED MODEL FOR SYSTEM RESTORATION

In this section, a detailed model set of realistic power system operations for substation restoration will be established. This is a critical step to put the off-line restoration strategy into realistic on-line operation and, ultimately, to implement a closed-loop self-healing power grid. Currently, few, if any, systematic restoration tools have been established. In these tools, the power system is based on a set of abstract system model, i.e., branch-bus based model. The connection of a power grid can be roughly described with this model. However, a realistic power system operating strategy should be implemented with a series of breaker operations in substations. To fill this gap, the detailed model during a system restoration for breaker operations in transmission substations will be established. The model set should involve the major operating standards and constraints associated with the breakers. Specifically, the remainder of the section presents the construction of the model.

A. Equivalent model in graphic theory

With the restoration strategies generated by branch-bus model, the energizing order for restored buses can be figured out. The key point of this part is to realize this energizing sequence of buses by operating the breakers in the substation. In general, we usually hope that this energizing process can be accomplished by the operations of breakers as few as possible.

To solve this problem, we need to make some equivalent transformation for the substation. In graphic theory, if we regard the buses as nodes and the lines as the branches, the topological graph of the substation can be drawn out. Then energizing the buses in certain sequence becomes the equivalent problem to traverse the nodes in sequence. Furthermore, because there must be a priority operation order of breakers due to the operating standards and constraints, in order to indicate this priority operation order of breakers, we need to evaluate the branches in the topological graph with different weighted values, where the lower value stands for the higher priority.

Thus, the topological graph of the substation becomes the weighted graph, where the weighted value can be viewed as distance between two nodes. Consequently, the optimal operation sequence for breakers is equal to find out the shortest path from the start node to the end node in the weighted graph, mathematically.

B. Model construction

In realistic substation restoration, the order of restoration buses may be different in various scenarios according to the calculating results from branch-bus model. Thus, for the on-line operation, in order to figure out the breakers operation sequence for all scenarios, it is necessary to consider the shortest path for every two buses mathematically. Hence, it is convenience to utilize the matrix for weighted graph to indicate this equivalent graphic model.

To construct the weighted incidence matrix, firstly, we need to evaluate all of the branches. Assuming the number of nodes is n and the nodes inside the graph are denoted by v_i. The weight incidence matrix can be described by a $n \times n$ matrix **W**, where the a_{ij} elements in **W** is defined as (1)

$$w_{ij} = \begin{cases} 0, & if \;\; i = j \\ a_{ij}, & if \;\; i \neq j, node\ v_i\ and\ node\ v_j\ are\ connected \\ \infty, & if \;\; i \neq j, node\ v_i\ and\ \ node\ v_j\ are\ not\ connected \end{cases} \quad (1)$$

To the substation system, because the branches of the equivalent topological graph can be viewed as the lines with breakers, the weighted values of the branches represent the priority sequence for operating the breakers. For the directly connected nodes, the weighted value is nonnegative integer. Otherwise, the weighted value is infinite because there is no line to connect them. The specific operation requirements and constraints for the breakers also influence the operation priority for breakers, and it is necessary to revise the weighted value accordingly.

Moreover, in the realistic substation, the incidence matrix for a certain part of the substation, such as a certain type of configuration, has been already generated off-line. When the operation order of the restoration buses is generated, according to the specific combination of the different types of configurations, the incidence matrix for the combination must be figured out as fast as possible on-line. Hence, we need to know how to create the incidence matrix for the combination, under the assumption that the elements of the combination have already existed. To create the incidence matrix for the combination, usually we have 3 steps.

Step 1: The dimension of the new matrix is determined by the nodes in the new system. Usually, the dimension can be calculated by the (2), where D_{new} is the dimension of the new incidence matrix for the combination. $D_{original}$ is the dimension of the i^{th} original incidence matrix.

$$D_{new} = \sum_{\substack{number\ of \\ original\ matrix}} D_{original\ i} \quad (2)$$

Step 2: Arrange the original matrix as the diagonal elements for the new matrix, shown in (3) where $\mathbf{O_i}$ denotes the i^{th} original matrix.

$$\mathbf{W} = \begin{bmatrix} \mathbf{O_1} & & & & & \\ & \mathbf{O_2} & & & & \\ & & \cdots & & & \\ & & & \mathbf{O_i} & & \\ & & & & \cdots & \\ & & & & & \mathbf{O_n} \end{bmatrix} \quad (3)$$

Step 3: Pay special attention to the elements that represent the newly connected nodes resulted from the combination. According to (1), revise the weighted value for the newly connected nodes correspondingly. For the other elements in the new matrix, the weighted value is ∞ because of the non-connection between the nodes. Obviously, the new matrix **W** is sparse.

Finally, with the initial weighted incidence matrix for the basic configurations in substations, the weighted incidence matrix for any combination of the basic configuration units can be generated. Therefore, when the order of energizing buses is given out, the breaker-based model indicated by weighted incidence matrix for the connection inside the substation can be figured out immediately.

III. OPTIMAL OPERATION SEQUENCE FOR BREAKERS

In mathematics, to find the shortest path, there are many algorithms, such as Dijkstra algorithm, Bellman-Ford algorithm, Floyd-Warshall algorithm and SPFA algorithm [15]. Among them, Floyd-Warshall algorithm deals with the shortest problem for multi-source and positive weighted branch, but time complexity and space complexity is high [12]. Bellman-Ford algorithm can be used to solve the shortest path problem in dense graph [13] [15], whereas Dijkstra algorithm is usually adopted in sparse graph [14-15]. Meanwhile, Dijkstra algorithm is the most popular and sophisticated one, with high timeliness. SPFA algorithm can be used when the weighted value of the branches is negative [16]. In the specific equivalent shortest path problem, because the graph for the breaker-based model is sparse and all the weighted value is nonnegative, we use Dijkstra algorithm to solve this problem.

A. *Optimal operation sequence for breakers*

Based on the order of energizing buses determined by restoration strategies generated by SNR, by utilizing the Dijkstra algorithm, we can find out the optimal operation sequence for breakers, which is equal to find out the shortest path for the equivalent graph for the breaker-based model.

First of all, assuming that the weighted incidence matrix has been formed, the shortest distance for each node to any other nodes need to be found. The calculation flow chart is shown in Fig. 1, and the calculation steps are shown as follows.

Step 1: Input the $n \times n$ weighted incidence matrix, denoted as **W**, and two same dimension matrices **R** and **V** where the elements are all zero. **V** is the value of the shortest distance and **R** is the specific shortest route.

Step 2: For the row *i* (at first *i*=1). With the Dijkstra algorithm, calculate the shortest path for the node *i* to the rest nodes.

Step 3: Store the distance value, calculated in Step 2, into the corresponding position in matrix **V**.

Step 4: Store the specific shortest route calculated in Step 2, into the corresponding position in matrix **R**.

Step 5: Go to the next row *i*=*i*+1. If the traversal has covered all the nodes (*i*=*n*), then finish the algorithm and output the matrices **V** and **R**. Otherwise, go back to Step 2.

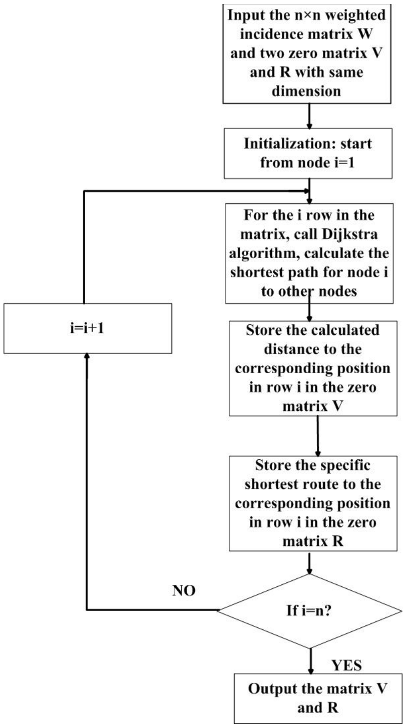

Fig. 1 Flow chart of shortest path calculation for weighted incidence matrix

Therefore, the operation decision of the breakers can be obtained by the output matrix **V** and **R**. From matrix **V**, we can obtain the value of the shortest distance. From matrix **R**, we can obtain the specific operation route for the breakers.

B. *Modification of operation action*

Due to different operation regulations and realistic requirements, such as maintenance, forced outage, operation constraints, the specific operation actions need to be updated accordingly [17-18]. A certain weighted incidence matrix used above is in corresponding to a certain operation scenario. Thus, the weighted incidence matrix needs to be updated if the states of the breakers or the restoration strategies are changed.

Specifically, according to different operation regulations and realistic requirements, such as maintenance, forced outage, operation constraints, etc., the elements in weighted incidence matrix need to be updated. For example, if the calculating result of branch-bus model shows that some certain lines must be energized, and then the corresponding elements in the matrix should be revised to 0, which means they have been already connected before any restoration operations. Also, with respect to some operation constraints of the breakers stated before, the elements in the matrix should be revised correspondingly, which means that the operation of breakers is subjected to the constraints. After revising the elements according to specific scenario, the input weighted incidence matrix **W** can be used to calculate the objective matrix **R** and **V**.

Finally, through the approach discussed above, shortest path of any nodes to the other nodes can be obtained. In the realistic substation, it means that we can figure out the optimal operation order of the breakers for any combination of the configuration in substation.

IV. CASE STUDY

In this section, two cases will be analyzed to illustrate the calculating process of the approach proposed above. One of them is a combination of two double bus-single breaker configurations. The other one is a case study for a realistic substation system to demonstrate the restoration process for a realistic system with 70 buses and 12 generators. All the restoration strategies are previously generated by SRN [3-4].

A. *Case study 1*

If the calculation results of SRN show that two Double Bus-single Breaker Configurations in Fig. 2 must be connected to each other, in this case, we will show how to generate the weighted incidence matrix **W**, the shortest distance matrix **V** and the shortest route matrix **R** for the combination of two double bus-single breaker configurations.

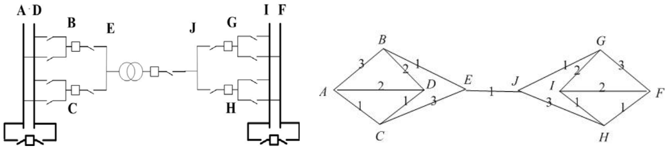

Fig. 2 Combination of two Double Bus-single Breaker Configurations
(a) Physical System (b) Topological Graph

According to the operation priority of the breakers, we assume that all of the breakers are weighted with some different nonnegative values, and the weighted incidence matrix for Double Bus-single Breaker Configuration is shown as (4):

$$\mathbf{O}_1 = \mathbf{O}_2 = \begin{bmatrix} 0 & 3 & 1 & 2 & \infty \\ 3 & 0 & \infty & 2 & 1 \\ 1 & \infty & 0 & 1 & 3 \\ 2 & 2 & 1 & 0 & \infty \\ \infty & 1 & 3 & \infty & 0 \end{bmatrix} \tag{4}$$

where $\mathbf{O}_1$ and $\mathbf{O}_2$ stand for the incidence matrix for the two Double Bus-single Breaker Configurations respectively.

According to the existent matrix $\mathbf{O}_1$ and $\mathbf{O}_2$, we can calculate the final incidence matrix **W** for this combination shown in (5) according to (1)(2)(3):

$$\mathbf{W} = \begin{bmatrix} 0 & 3 & 1 & 2 & \infty & \infty & \infty & \infty & \infty & \infty \\ 3 & 0 & \infty & 2 & 1 & \infty & \infty & \infty & \infty & \infty \\ 1 & \infty & 0 & 1 & 3 & \infty & \infty & \infty & \infty & \infty \\ 2 & 2 & 1 & 0 & \infty & \infty & \infty & \infty & \infty & \infty \\ \infty & 1 & 3 & \infty & 0 & \infty & \infty & \infty & \infty & 1 \\ \infty & \infty & \infty & \infty & \infty & 0 & 3 & 1 & 2 & \infty \\ \infty & \infty & \infty & \infty & \infty & 3 & 0 & \infty & 2 & 1 \\ \infty & \infty & \infty & \infty & \infty & 1 & \infty & 0 & 1 & 3 \\ \infty & \infty & \infty & \infty & \infty & 2 & 2 & 1 & 0 & \infty \\ \infty & \infty & \infty & \infty & 1 & \infty & 1 & 3 & \infty & 0 \end{bmatrix} \tag{5}$$

Hence, by running the Dijkstra algorithm, the value of the shortest path matrix **V** and shortest route **R** can be obtained, where the elements in matrix **V** stands for the shortest distance value from any node to other nodes and **R** stands for the specific route, shown in (6)(7):

$$\mathbf{V} = \begin{bmatrix} 0 & 3 & 1 & 2 & 4 & 9 & 6 & 8 & 8 & 5 \\ 3 & 0 & 3 & 2 & 1 & 6 & 3 & 5 & 5 & 2 \\ 1 & 3 & 0 & 1 & 3 & 8 & 5 & 6 & 6 & 3 \\ 2 & 2 & 1 & 0 & 3 & 8 & 5 & 6 & 6 & 3 \\ 4 & 1 & 3 & 3 & 0 & 5 & 2 & 4 & 4 & 1 \\ 9 & 6 & 8 & 8 & 5 & 0 & 3 & 1 & 2 & 4 \\ 6 & 3 & 5 & 5 & 2 & 3 & 0 & 3 & 2 & 1 \\ 8 & 5 & 6 & 6 & 3 & 2 & 3 & 0 & 1 & 3 \\ 8 & 5 & 6 & 6 & 3 & 2 & 2 & 1 & 0 & 3 \\ 5 & 2 & 4 & 4 & 1 & 4 & 1 & 3 & 3 & 0 \end{bmatrix} \tag{6}$$

$$\mathbf{R} = \begin{bmatrix} AA & AB & AC & AD & ACE & ACEJHF & ACEJG & ACEJH & ACEJGI & ACEJ \\ BA & BB & BDC & BD & BE & BEJHF & BEJG & BEJH & BEJGI & BEJ \\ CA & CDB & CC & CD & CE & CEJHF & CEJG & CEJH & CEJGI & CEJ \\ DA & DB & DC & DD & DCE & DBEJHF & DBEJG & DBEJH & DBEJGI & DBEJ \\ ECA & EB & EC & ECD & EE & EJHF & EJG & EJH & EJGI & EJ \\ FHJECA & FHJEB & FHJEC & FHJEBD & FHJE & FF & FG & FH & FHI & FGJ \\ GJECA & GJEB & GJEC & GJEBD & GJE & GF & GG & GIH & GI & GJ \\ HJECA & HJEB & HJEC & HJEBD & HJE & HF & HIG & HH & HI & HJ \\ IGJECA & IGJBE & IGJEC & IGJEBD & IGJE & IHF & IG & IH & II & IGJ \\ JECA & JEB & JEC & JEBD & JE & JGF & JG & JH & JGI & JJ \end{bmatrix} \tag{7}$$

Therefore, if it is required that the bus F and bus A should be connected, then the route with the fewest operation times of breakers is $F \longrightarrow H \longrightarrow J \longrightarrow E \longrightarrow C \longrightarrow A$, with the operation value equal to 9. Actually, according to practical scenarios, there may be some requirements to certain breakers such as maintenance and force outages. This can be solved by changing the weighted value of **W**, so the **V** and **R** will be changed accordingly.

B. *Case study 2*

This part presents a realistic system to show the feasibility and efficiency of the proposed mapping approach.

When this realistic system is in a blackout, SRN can provide a sequential strategy based on a black-start generator. The total strategy includes 11 steps to restore all generators. The original system in blackout is shown in Fig. 3, where the lines in pink denote the line need to be restored and the red circle denotes the first restoration step. In each step, there are several buses need to be energizing according to the restoration strategies provided by the SRN. We need to realize the buses restoration by breakers operation inside the specific substations. Here we just show the step 1 for illustration.

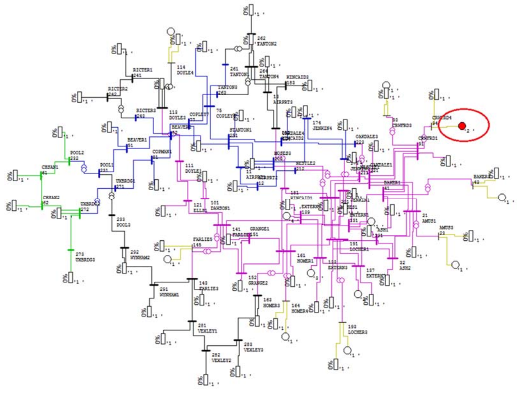

Fig.3 Original system topology

Step 1: The transformer between buses 91 and 93 and the transformer between buses 91 to 94 should be restored. The topology of buses in the CRWFRD station is shown in Fig. 4. Bus 94 is a Double Bus-single Breaker Configuration.

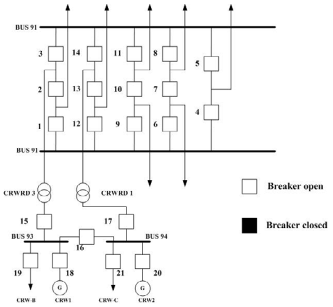

Fig. 4 Topology of buses in the CRWFRD Station

According to the proposed approach, **V** and **R** can be obtained, which denotes the operation decision of breaker sequence is 20-17-14-3-15-18. The topology after operations is shown in Fig. 5. The red bold lines denote the restored lines.

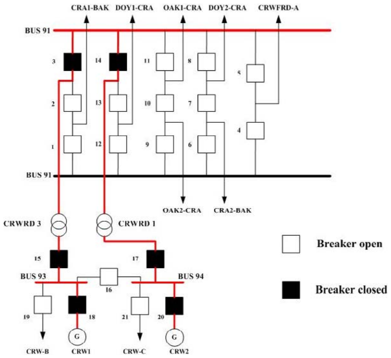

Fig. 5 Switching operations in the CRW station

Finally, after 11 steps similar to step 1, the whole system has been restored, shown in Fig. 6, where the pink bold lines denote the restored lines and transformers.

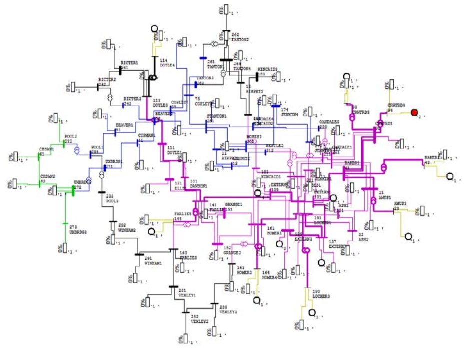

Fig. 6 System topology after 11restoeration steps

V. CONCLUSIONS

This paper has proposed an approach that serves as an interface between the branch-bus model and breaker-based model. Based on the graphic theory, the graphic topology for breaker-based model has been constructed. With the graphic topology, according to the characteristics of different categories of breakers, auxiliary equipment and their associated standards, the sequence of operating actions in substations for realizing the self-healing strategy have been generated, which can be operated in realistic power grids. The simulation results of a realistic power system also show the efficiency of the approach.

Furthermore, the accomplishments of this paper will contribute significantly to applications in industry on the self-healing smart grid construction. It will provide a major step to update the off-line decision support system to an on-line self-healing system. As a result, the closed-loop self-healing tool for a power system is expected.

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