Heuristic Optimal Restoration Based on Constructive Algorithms for Future Smart Grids

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***Abstract*-- This paper proposes a heuristic optimization algorithm for online restoration for future smart grids based on constructive approaches to reinstate supply to the loads following a fault. The algorithm tries to minimize the total switching operations for the post-fault restoration strategy. This algorithm is also compared with the one in a previous work which tends to minimize the loading imbalance among all available substations. The proposed algorithm is based on the constructive network tracing approach that comes up with the final network restoration strategy. This is achieved by determining the switching sequences of switchable components such as circuit breakers, reclosers, sectionalizers, or intelligently controlled switches. Sample systems are studied to demonstrate the method. The results obtained from the constructive methods are compared with the ones from the enumeration method. The comparison verifies the effectiveness of the proposed method.**

***Index Terms*- Constructive algorithm, distribution automation, online restoration, heuristic optimization, smart grid.**

I. Introduction

The recent legislation and initiative about Smart Grid mandates a need of high quality and reliability of electricity service meeting the standard of 21st century through modern communication and control technologies. Fast and efficient service restoration is clearly an important goal of future Smart Grid, especially considering that up to 90% of power system outage events originates in distribution systems.

When there is a fault in system, some of the loads are interrupted for certain time during the fault, but the out-of-service loads except in the faulted section should be restored immediately. And the restoration should not violate the operating constraints such as capacity ratings and radial topology which is dominant configuration in US utilities.

Smart Grid encourages intelligent electronic devices (IEDs), and advanced communication systems, which will open up the areas to implement automatic methods for harmonics, fault diagnostics and isolation, system restoration [1-7]. The future system may be upgraded with more complicate configurations [8]. More complicate configuration means more difficult to coordinate than in the past without the penetration of IEDs. Hence, there is a great possibility of improving the system reliability by quickly restoring the supply after faults.

There are previous works about distribution restoration or reconfiguration based on various computer-aided approaches such as the heuristic search based algorithms [9-12], fuzzy methods and intelligent searches like genetic algorithms and simulated annealing separately or in some combination [13-17], and mathematical-programming-based approaches [18-19]. These algorithms can be good at the planning stage when their efficiency is less concerned. When applied to online post-fault restoration, it may not be fast enough to be comparable with switching operations in a few cycles. Since the system will have one count of momentary interruptions as long as the outage duration is within a minute or so, it is sensible to perform complicated algorithms through extensive optimization techniques. However, under the Smart Grid initiative, this needs to be improved. The goal of this paper is to develop fast algorithms for distribution service restoration under possible complicated configurations with multiple backup substations connected through normally open switches.

With the above motivation, this paper proposes an efficient constructive approach targeting minimal switching operations. The constructive approach originated from the constructive approach used in [20], which aims to minimize losses of reconfiguration for planning purpose, while this work is for online restoration for minimizing switching operations. The proposed method is complementary to the method proposed in [21], which is also based on constructive approach but tends to minimize loading imbalance.

The remaining part of the paper is organized as follows: Section II describes the overall methodology adopted in developing both algorithms. Section III reviews the algorithm for minimizing loading imbalance with case studies. Section IV proposes the algorithm for minimizing switching operations with case studies. Section V benchmarks the results from two constructive algorithms with global enumerations. Section VII concludes the paper.

II. Background of Restoration

A. Assumptions

The basic underlying assumptions for the proposed algorithm are as follows:

- The substations are assumed to have a fixed capacity in terms of ampere rating with constant voltage.
- Loads are considered to be constant power.
- The impedances of the feeder sections connecting to the switches are ignored.
- There is a distribution control center that collects real time data from remote sensors.

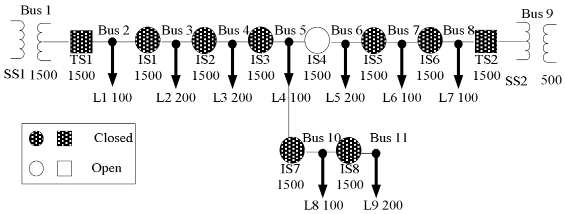

Fig. 1 Sample Distribution Feeder

B. General Background of Restoration

The proposed algorithms result in the restoration strategy which ensures the radial nature of the distribution feeder and also checks the violation of the network components.

A simple sample distribution feeder is taken as an example system to demonstrate the restoration strategies. The feeder comprises of substations, tie-switches and isolation switches and the loads as shown in Fig. 1.

Both of the proposed algorithms require the information about the configuration of the distribution feeder in terms of the location of switches, circuit breakers considering the direction of power flows. This information can be readily available in real time through IEDs. The data is given by a connectivity matrix of a specific system. The matrix created for the system shown in Fig. 1 is as given in TABLE I.

In TABLE I, the buses are classified as “From Bus” and “To Bus” considering the direction of supply. The corresponding switches which are placed in between these two buses are considered and the position of these switches in reference to the “From Bus” and “To Bus” are determined. For example, TS1 is downstream to Bus1 or substation1 and upstream to Bus2 or Load1. Hence, the corresponding position of TS1 considering “From Bus” i.e. Bus1 and “To Bus” i.e. Bus2 is indicated by the strings “DWS” for downstream and “UPS” for upstream respectively.

It should be noted that “TS” here stands for tie switch, which means connecting a feeder with a substation. Also, “IS” here stands for isolation switch. In short, a TS is connected to a source while a IS is a switchable component sectionalizing the feeder.

The restoration strategy should ensure a radial configuration of the system which means each load is supplied by a single source and the flow at each component is less than its respective capacity limit. Since a substation, i.e., source, is usually the bottleneck, the total power supplied by the source is calculated for capacity limit verification. It should be noted that line losses are ignored here since it is typically less than 10% of the load in distribution systems. In fact, the flow calculated at the substation can simply be scaled up by 10% as the estimated loss. Otherwise, the strategy will be much more time-consuming for an online task to achieve super-fast restoration. Plus, even if there is slight short-term overloading, it is acceptable since the system is expected to be restored to normal configuration after the fault reparation which usually takes only a few hours. Nevertheless, Section V discusses the consideration of losses.

TABLE I INPUT DATA SHOWING FEEDER CONFIGURATION

BusFrom	BusTo	Switch	PositionBusFrom	PositionBusTo
1	2	TS1	DWS	UPS
2	3	IS1	DWS	UPS
3	4	IS2	DWS	UPS
4	5	IS3	DWS	UPS
5	6	IS4	DWS	UPS
6	7	IS5	DWS	UPS
7	8	IS6	DWS	UPS
8	9	TS2	DWS	UPS
5	10	IS7	DWS	UPS
10	11	IS8	DWS	UPS

C. Motivation of the Constructive Approach

The main idea of the constructive restoration is to hypothetically assume all switches are open. The algorithm then gradually closes the switch from source to downstream and flags all energized components. If closing a switch reaches an already energized component, then this switch cannot be closed. Hence, radial topology is ensured without any time-consuming global topology search. After the final status of switchables is identified, the actual open/close action will be performed to those components that need a change. However, a challenge still remains: *how to determine which switch should be closed next?* The answer to this question is critical to the proposed algorithm which will be elaborated in the following sections.

III. Review of Restoration Method for Minimal Loading Imbalance with Case Studies

A. Review of the Previous Algorithm

The objective of the algorithm for minimal loading imbalance based on constructive approaches can be found in [21]. It is briefly reviewed in this subsection, with a set of updated case studies in the next subsection for comparison with the new algorithm in Section IV, as well as global enumeration.

The objective here is to achieve minimal loading imbalance among all backup sources for post-fault restoration. In other words, this is to avoid one source taking too much load while other sources take much less. It is desired to utilize the remaining capacity of each source as much as possible.

Here we take the definition of imbalance similar to [22]. That is, the imbalance is the difference between the highest and lowest capacity factors (CFs) of sources. Here CF is defined as:

$$\textit{Capacity Factor (CF)} = L_{sum} / SS_{cap} \quad (1)$$

where L_{sum} is the sum of all the loads served by the substation transformer and SS_{cap} is the substation capacity.

Considering the operational constraints of radial topology and substation rating limits, the problem formulation may be given as follows:

$$Min:\ f = (\max(CF_i) - \min(CF_i)) + Penalty * UL;\ i = 1 \sim n_{ss}. \quad (2)$$

Subject to:

$$SS_{cap}(i) <= \max(SS_{cap}(i));\ i = 1 \sim n_{ss}. \quad (3)$$

$$Src(L_i) <= 1;\ i = 1 \sim n. \quad (4)$$

Here, n_{ss} is the number of substations and n is the number of buses. CF_i is the capacity factor of substation i, L_i is load at Bus i, and $Src(L_i)$ represents the number of substations serving load L_i. *UL* is the total unserved load and *Penalty* is the penalty, usually high, for unserved load. This high penalty ensures the model to find a possible solution to serve all loads. The constraint (3) is a substation capacity constraint and (4) means that the load is either un-served or served by only 1 substation to ensure radial topology.

The flowchart of the proposed algorithm is as shown in Fig. 2. The details of the algorithm can be found in [21]. An important feature of the proposed reconfiguration strategy is that the radial topology of the feeder is ensured since the post-restoration search starts with the assumption that all of the isolation switches downstream of the fault are hypothetically open and start to close one by one.

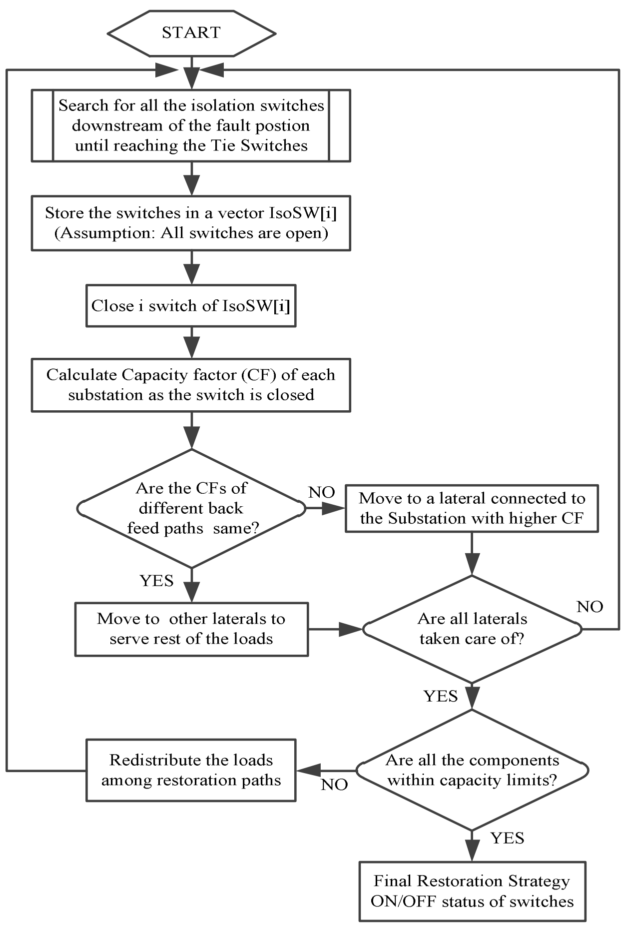

Fig. 2 Flowchart of the restoration algorithm for balancing loads.

B. Case Studies

The normal circuit topology of example system considered is as shown in Fig. 3. In normal state, SS1 serves all loads. As distribution system is complex, it should be noticed that SS2, SS3 and SS4 are serving other branches which are not shown in the figure. Then, three case studies are illustrated next.

<u>Case 1</u>: When there is a fault at L4 as shown in Fig. 4, the fault is isolated by opening the immediate switches IS3, IS4, IS10 and IS7. Since the downstream substations SS2, SS3 and SS4 have sufficient capacity to take up the isolated loads in their respective restoration paths, the tie-switches TS2, TS3 and TS4 are closed so that the supply is restored to all the remaining loads as shown in Fig. 4. In this situation, the load balancing cannot be considered because the fault location is such that the feeder is divided into four different paths without any alternatives.

<u>Case 2</u>: When the fault is at L6 as shown in Fig. 5, the post restoration strategy according to the algorithm shows that the fault is isolated by opening the isolation switches IS5 and IS6. The feedback path should be selected such that the loading level is balanced among the substations. Even though SS1 has a capability of serving all the loads in its restoration path, the algorithm utilizes all sources to supply the load to reduce the stress of SS1. Again, this is based on the consideration that a reduced system stress is desired when a fault has already occurred. The algorithm closes the tie-switch TS4 and opens IS11 so that SS4 serves the loads L11 and L12 in its restoration path. Also, TS3 is closed so that SS3 can serve L7. Similarly, SS2 serves the loads L9 and L10. This leaves the capacity factor of all the substations as close as possible.

<u>Case 3</u>: When the fault is at L1 as shown in Fig. 6, the fault is isolated by TS1 and IS1. Here SS4 capacity is increased to 1000 for better demonstration to avoid irrestorable load due to insufficient capacity. The loads which were served by only SS1 are then divided among SS2, SS3 and SS4. It can be observed from Fig. 6 that the switches IS4 and IS7 are opened and the loads are served such that loading levels of SS2, SS3 and SS4 are almost balanced.

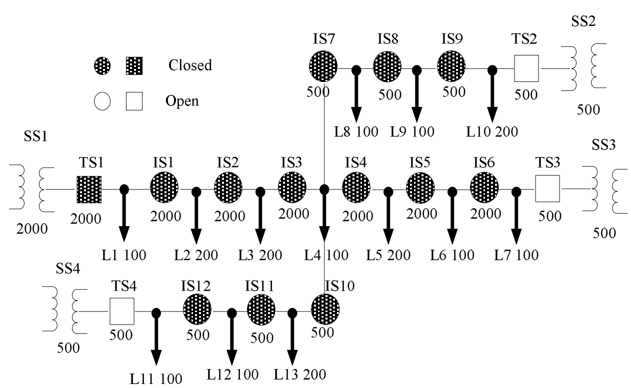

Fig. 3 Normal topology of example system

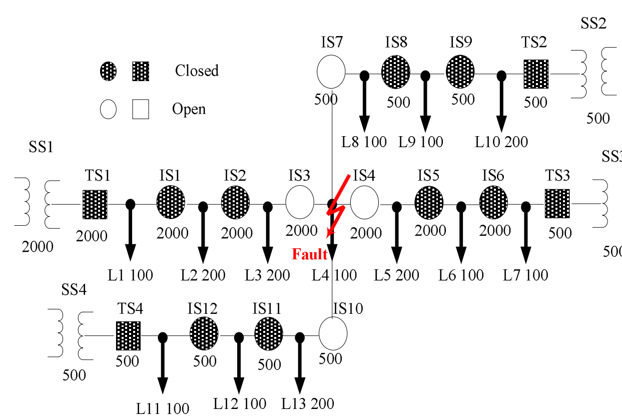

Fig. 4. Post Fault Restoration strategy for Case 1.

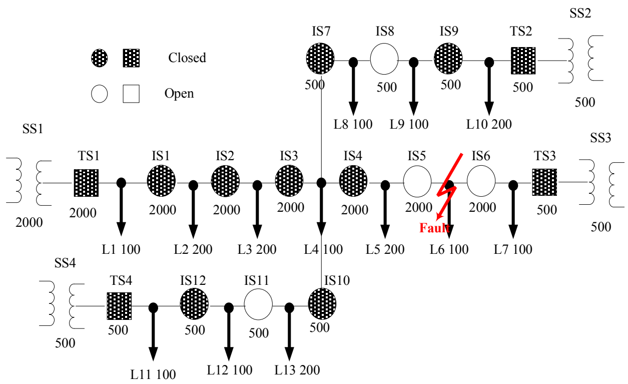

Fig. 5. Post Fault Restoration Strategy for Case 2.

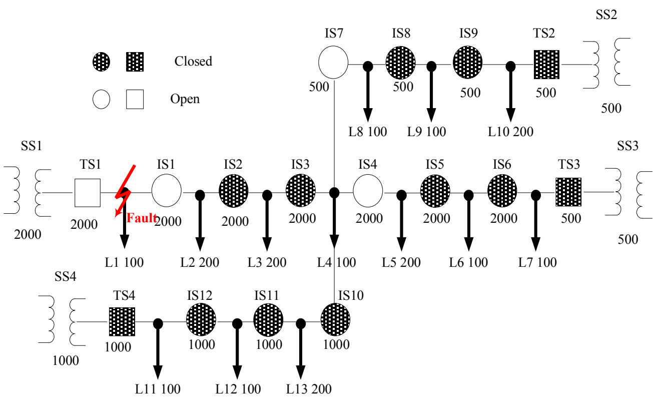

Fig. 6. Post Fault Restoration Strategy for Case 3.

IV. Restoration for Minimal Switching Operations

A. Problem Formulation

The previous section discusses the restoration algorithm for minimizing loading imbalance among all substations. However, sometimes utilities may be interested in reducing the number of switching operations during post-fault restoration due to limited lifetime switches. This is sensible when system loading level is not a major concern.

Hence, the problem formulation for minimizing the total number of switching operations is as below.

$$\text{Minimize: } f = NSO + Penalty*UL \quad (5)$$

$$\text{Subject to: } SS_{cap}(i) <= \max(SS_{cap}(i));\ i=1\sim n_{ss}. \quad (6)$$

$$Src(L_i) <= 1;\ i=1\sim n. \quad (7)$$

where NSO is the number of switching operations.

B. Algorithm Description

All the assumptions made in the algorithm for minimizing loading imbalance also apply to this algorithm except the goal is to minimize the switching operations.

Step 1: Algorithm searches for immediate isolation switches downstream and upstream of fault location. These switches are stored in a vector IsoIm[i] and should be open to isolate fault.

Step 2: Then, the algorithm starts searching the tie switches of each back-feed path. All the candidate tie switches are stored in vector TieSW[i].

Step 3: For each TieSW[i], the algorithm searches all isolation switches in back feed restoration path and stores them in vector IsoSW[i].

Step 4: While finding downstream switches, it also checks if it encountered two or more immediate downstream switches. If so, the node is considered as a T-node and each of downstream switches is considered as a representative of possible back feed restoration path. Each of the isolation switches corresponding to restoration paths is stored in IsoTnode[i].

Step 5: The algorithm then also searches all the isolation switches in back feed restoration path for each element of IsoTnode[i] and again stores in IsoSW1[i].

Step 6: Then, each of the isolation switches in vector IsoSW[i] are started to close with loads being added one by one. At each step, capacity factor of the respective substation is calculated to see if the substation is able to take up the loads.

Step 7: In this course, if a T-node is encountered in back feed restoration path, the algorithm closes the switches stored in IsoSW1[i] to see if all loads can be served by single substation.

Step 8: If a substation is found to be incapable of taking up loads any further, then that particular isolation switch in IsoSW[i] or IsoSW1[i] is opened and the algorithm repeats similar procedure for other elements of TieSW[i].

Step 9: At each step of closing the switches in IsoSW[i], the current carrying capability of each components are checked. If there is any violation, the switch to be closed is chosen until there are no more limit violations. The remaining unserved loads would be supplied by searching among remaining substations by repeating the same procedures described above.

Step 10: Once the algorithm results in the determination of respective restoration paths, the switches with a change of status need to be opened or closed. The actual open or close operation of switches except main substation circuit breakers will be performed simultaneously; then the substation circuit breakers will be operated.

This algorithm also automatically guarantees radial configuration of the system. This algorithm attempts to reduce switching operation as much as possible.

C. Case Studies

The proposed algorithm for online distribution restoration considering the minimization of switching operations is demonstrated using the example systems similar to the ones used in Section III.

Case 4: When the fault is at L4 as shown in Figure 7, according to the proposed algorithm, immediate downstream switches IS3, IS4, IS7 and IS10 are opened to isolate the faulted area of the system and the remaining loads are served by the respective substations SS1 through SS4. There is no other option to serve all the loads because of the location of the fault in this case. Hence, this post restoration strategy looks similar to the one obtained from the load balancing algorithm.

Case 5: When the fault is at L6 as shown in Fig. 8, SS1 has enough capacity to take up all the loads of the feeder except the load L7. The algorithm hence first isolates the faulted part by opening the isolation switches IS5 and IS6 and SS1 takes up all other loads and SS3 serves L7. It can be observed that with this algorithm, only two isolation switches have to be opened and one tie switch TS3 needs to be closed in the post restoration strategy.

Case 6: When the fault is at L1 as shown in Fig. 9, IS1 and TS1 are open to isolate fault. SS4 with the largest capacity tries to pick up loads as much as possible. Thus, SS4 is able to take up L11, L12, L13, L4, L3, L2 and L8 so that rest of the loads need to be supplied by SS2 and SS3. Thus, TS2 and TS3 need to be closed, and IS8 and IS4 need to be opened to maintain the radial configuration.

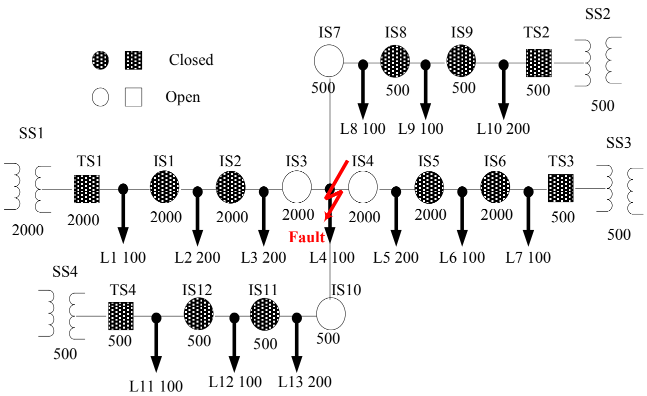

Fig. 7. Post Fault Restoration Strategy for Case 4.

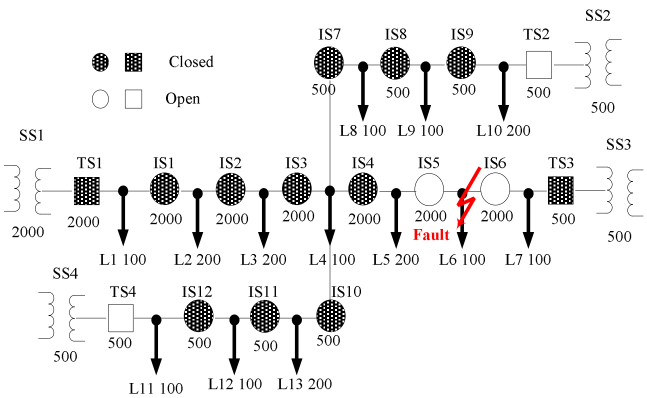

Fig. 8. Post Fault Restoration Strategy for Case 5.

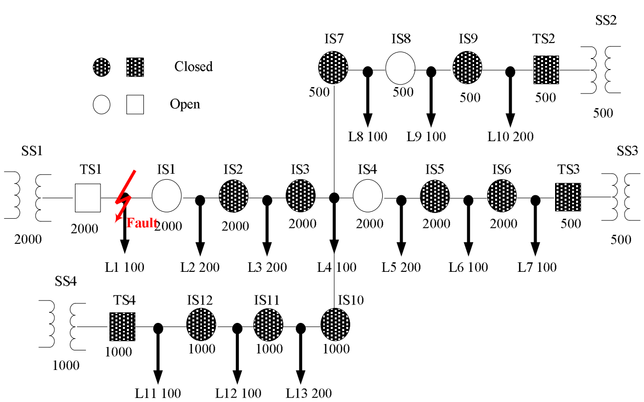

Fig. 9. Post Fault Restoration Strategy for Case 6.

V. Comparison with Enumerative Approach

In this section, a global search is implemented using the enumerative approach to benchmark with the constructive approach. The enumerative approach simply checks all possible combinations of the status of switchable components. Assuming there are 16 switchables in system, there will be up to 2^{16}=65,536 combinations. In the enumerative approach, each of combinations is checked to ensure radial topology and capacity constraint. The enumeration results for Cases 1 to 3 are discussed as follows.

Case 1: There is only one valid combination (as shown in Table 2) and all other combinations violating constraints or unable to serve all loads not in the faulted section.

Case 2: There are altogether 40 combinations that can serve all loads. Among them, 13 violate radial topology limit, 18 violate capacity limit, and 9 are valid as shown in Table III.

Case 3: There are altogether 43 combinations that can serve all loads. Among them, 26 violate radial topology limit, 25 violate capacity limit, and 2 are valid as shown in Table IV.

It can be observed from Tables II through IV that the topologies resulting from the constructive algorithm for minimizing loading imbalance always rank the 1st in enumerative approach. Similar results are obtained for the cases of minimizing switching operations. Tables V through VII show the ranking of the valid combinations obtained for three different locations of the fault. Each solution for Cases 4-6 from the constructive approach ranks the 1st among all corresponding valid combinations from enumerative approach.

This benchmark study shows that the proposed constructive approach is effective in identifying the best solution.

It is also worthwhile to mention that the constructive algorithms for the cases discussed in this paper take less than 0.02 seconds, which is even faster than most switching operations. Therefore, the proposed algorithms are promising for implementing post-fault restoration in a complicated distribution system under the future Smart Grid.

TABLE II Loading Imbalance with Enumerative Approach for Case 1

Rank	Open Switches	f in (2)
1	IS3, IS4, IS7, IS10	0.55

TABLE III Loading Imbalance with Enumerative Approach for Case 2

Rank	Open Switches	f in (2)
1-T	IS5, IS6, IS8, IS11	0.4
1-T	IS5, IS6, IS8, IS12	0.4
1-T	IS5, IS6, IS9, IS11	0.4
4	IS5, IS6, IS9, IS12	0.45
5-T	IS5, IS6, IS7, IS10	0.6
5-T	IS5, IS6, IS7, IS11	0.6
5-T	IS5, IS6, IS7, IS12	0.6
5-T	IS5, IS6, IS8, IS10	0.6
5-T	IS5, IS6, IS9, IS10	0.6

TABLE IV Loading Imbalance with Enumerative Approach for Case 3

Rank	Open Switches	f in (2)
1-T	IS1, TS1, IS4, IS7	0.1
1-T	IS1, TS1, IS4, IS8	0.4

TABLE V Switching Operations with Enumerative for Case 4

Rank	Switches with Status Changed	f in (5)
1	IS3, IS4, IS7, IS10	7

TABLE VI Switching Operations with Enumerative for Case 5

Rank	Switches with Status Changed	f in (5)
1	TS3, IS5, IS6	3
2-T	TS2, TS3, IS5, IS6, IS7	5
2-T	TS3, TS4, IS5, IS6, IS8	5
2-T	TS2, TS3, IS5, IS6, IS9	5

2-T	TS2, TS3, IS5, IS6, IS10	5
2-T	TS3, TS4, IS5, IS6, IS11	5
2-T	TS3, TS4, IS5, IS6, IS12	5
8-T	TS2, TS3, TS4, IS5, IS6, IS7, IS10	7
8-T	TS2, TS3, TS4, IS5, IS6, IS7, IS11	7
8-T	TS2, TS3, TS4, IS5, IS6, IS7, IS12	7
8-T	TS2, TS3, TS4, IS5, IS6, IS8, IS10	7
8-T	TS2, TS3, TS4, IS5, IS6, IS8, IS11	7
8-T	TS2, TS3, TS4, IS5, IS6, IS8, IS12	7
8-T	TS2, TS3, TS4, IS5, IS6, IS9, IS10	7
8-T	TS2, TS3, TS4, IS5, IS6, IS9, IS11	7
8-T	TS2, TS3, TS4, IS5, IS6, IS9, IS12	7

TABLE VII SWITCHING OPERATIONS WITH ENUMERATIVE FOR CASE 6

Rank	Switches with Status Changed	f in (5)
1-T	TS1,TS2,TS3,TS4,IS1,IS4,IS7	7
1-T	TS1,TS2,TS3,TS4,IS1,IS4,IS8	7

VI. CONCLUSIONS

The Smart Grid initiative mandates a high quality of electricity supply meeting even higher standard. Through the prospective large-scale deployment of IEDs, real-time system information will be readily available such that a more complicated system with multiple backup sources can be built. Considering the technology gap in the vision of Smart Grid and present industrial practice, this paper reviews a previous algorithm based on constructive approach and then presents a new one, for efficient heuristic optimal restoration.

The objective of the first algorithm is to balance loads among all available substations. This is more suitable when the system is heavily loaded, especially considering that the stress has already lead to a fault. The second algorithm considers the minimization of switching operations with the goal of preventing expensive switching equipment from worn out. This is more suitable when the system has a light to medium load.

The constructive nature of both algorithms guarantees the radial topology of the system such that there is no time-consuming topological check. This makes the algorithm simple, efficient, and suitable for online restoration for a complicated distribution system with multiple backup sources. This is an integrated part of full implementation of future Smart Grids.

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