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## Fast restoration of large area breakdown for power distribution systems

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**Abstract:** An adjacent table-based simplified model of distribution networks containing medium voltage buses of a substation is established. Identification of bus outage and the condition to start fast restoration procedure are discussed. A complex load shading parameter is set up to describe various load shading schemes. The imaginary part of the load shading parameter describes the states of switches of load shading schemes while the real part is the corresponding amount of shaded load. A new concept of independent tripping operation is also put forward. The procedure to search the operation with the least amount of shaded load for a feeder and a connected domain are detailed. The procedure for fast restoration of a large area breakdown of the whole distribution network under emergency states is dealt with using a typical grid distribution network as an example. Results of analysis show that the direct load shading scheme under the most balanced topology is not always the optimal scheme. The proposed method can obtain the optimal operating mode with the least amount of shaded load thus showing its feasibility.

**Keywords:** Electric power engineering, Distribution systems, Distribution automation, Fault isolation and service restoration, Network reconfiguration

### 1 Introduction

Many papers have been published on fault isolation and restoration based on distribution automation system (DAS), most of which are for small interruptions such as fault on a certain feeder section [1–7]. The technique to safely transfer as many loads as possible to healthy power sources in case

of serious faults such as outages of a substation or a medium voltage bus was not mentioned.

Rethinking the large scope blackout of the interconnected North America power grid, we realized that although the possibility of disastrous interruption is very small, the harmful effects are very serious [8-9].

As for a robust distribution network, once a fault occurs resulting in several buses being de-energized, most of the affected loads may be transferred to adjacent healthy buses based on DAS.

Considering that modern distribution networks are so complicated, the study on algorithms to obtain the optimal load transferring scheme during fast restoration is necessary.

### 2 Modeling of distribution networks

A simplified model of distribution networks based on graph theory is described in Ref. [10], where switches are regarded as vertexes while feeder sections are regarded as edges. Assuming that the power factors of the loads are approximately the same, the loads can be described by the parameters of current. But adjacent matrixes are used in the model in Ref. [10] requiring a rather large size of storing space.

We improved the simplified model by defining a new type of vertex to describe medium voltage buses and using adjacent tables to replace adjacent matrixes in order to save the storing space.

The improved simplified model is detailed as follows:

1) Defining an adjacent table  $DT$  with  $N$  lines and 5 columns to describe the network structure.

The descriptions of the elements in  $DT$  are as follows:

$d_{i1}$  can be 0, 1, 2, 3 or 4 indicating the  $i$ th vertex to be a switch, a tapping point, a power source (i.e., circuit breaker in the substation), a terminal point or a medium voltage bus.

$d_{i2}$  can be 1, 2 or 3, indicating that the on/off state of the  $i$ th vertex is locked, load shading operation is made by tripping the  $i$ th vertex or load shading operation by tripping the  $i$ th vertex is forbidden.

As for a power source,  $d_{i3}$  indicates the sequence number

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of the medium voltage bus connected with it while  $d_{i4}$  indicates its downstream vertex.

As for a medium voltage bus,  $d_{i3} \sim d_{i5}$  have no meaning and can be of a value of  $-1$ , respectively.

As for the other types of vertexes,  $d_{i3} \sim d_{i5}$  describe the adjacent vertexes of the  $i$ th vertex.

The idle elements in  $DT$  should be  $-1$ .

2) Defining an adjacent table  $CT$  with  $N$  lines and 5 columns to describe the current operation mode.

The descriptions of the elements in  $CT$  are as follow:

$c_{i1}$  can be 0 or 1 indicating the  $i$ th vertex being tripped or closed.

As for a medium voltage bus,  $c_{i1} \sim c_{i5}$  have no meaning and can be of a value of  $-1$ , respectively.

As for a power source,  $c_{i2}$  indicates the sequence number of the medium voltage bus connected with it while  $c_{i4}$  indicates the terminal vertex of the arc taking the power source as its starting vertex.

As for the other types of vertexes,  $c_{i2}$  and  $c_{i3}$  describe the starting vertexes of the arcs taking the  $i$ th vertex as their terminal vertexes while  $c_{i4}$  and  $c_{i5}$  describe the terminal vertexes of the arcs taking the  $i$ th vertex as their starting vertexes.

The idle elements in  $CT$  should be  $-1$ .

3) Defining an adjacent table  $LT$  with  $N$  lines and 4 columns to describe the loads.

The descriptions of the elements in  $LT$  are as follow:

$l_{i1}$  indicates the load flowing through the  $i$ th vertex.  $l_{i2} \sim l_{i4}$  indicate the loads supplied from the edges with the  $i$ th vertex. The orders of the edges are in accordance with that in  $DT$ .

The idle elements in  $LT$  should be  $-1$ .

4) Defining an adjacent table  $ET$  with  $N$  lines and 4 columns to describe the rated loads.

The descriptions of the elements in  $ET$  are as follow:

$e_{i1}$  indicates the rated load of the  $i$ th vertex.  $e_{i2} \sim e_{i4}$  indicate the rated loads of the corresponding edges.

5) Defining an adjacent table  $L_nT$  with  $N$  lines and 4 columns to describe the normalized loads.

The elements in  $L_nT$  are:

$$l_{ni,j} = \frac{l_{i,j}}{e_{i,j}} \quad (1)$$

It is obvious that if an element in  $L_nT$  is larger than 1.0, the corresponding device is overloaded.

A connected domain (CD) is the sub-graph of a distribution network whose edges and vertexes are connected with-out considering the connection of medium voltage buses. Loads can be transferred in a connected domain.

$CT$  can be determined according to  $DT$  and the states of switches. Such procedure is called  $D$ -to- $C$  conversion. The algorithm of  $D$ -to- $C$  conversion is described in Ref. [10].

The loads of vertexes can be calculated according to  $CT$  and the loads of edges. Such procedure is called  $V$ -to- $A$  conversion. As for the  $m$ th vertex  $v_m$ , the load through it, i.e.,  $l(v_m)$ , can be written as

$$l(v_m) = \sum_{v_n \in \alpha} l(v_n) + \sum_{v_n \in \alpha} l(v_m, v_n) \quad (2)$$

where,  $\alpha$  is the set of all the son-vertexes of  $v_m$ ,  $(v_m, v_n)$  indicates the edge with end vertexes of  $v_m$  and  $v_n$ .

The loads of edges can be calculated according to  $CT$  and the loads of vertexes. Such procedure is called  $A$ -to- $V$  conversion. The algorithm of  $A$ -to- $V$  conversion is described in Ref. [10].

$DT$  is determined by the network structure.  $c_{i1}$ s and  $l_{i1}$ s are collected by RTUs and FTUs in real time. Once the state of a switch is changed,  $D$ -to- $C$  conversion is carried out to follow the change of grid topology.  $V$ -to- $A$  conversion is carried out at a regular interval to obtain the loads of edges to form the basic information for load transferring. Under emergency states,  $A$ -to- $V$  conversion is used to obtain the loads of vertexes for evaluation of restoration schemes.

### 3 Identification of outages of buses

In theory, if the voltage of a bus drops to zero and the currents through all of the power sources (i.e., circuit breakers) connected with the bus drops to zero at the same time, we can determine that there is an outage of the bus.

Considering the disturbance, the above identification criterion is modified as:

1) The voltage of the bus drops to approximately zero from its normal value.

2) The currents through more than  $N$  power sources connected with the bus together with their first stage feeder switches drop to approximately zero from their normal values.

Typically,  $N$  is a value between 2 and 5.

With the outage of buses being identified, the DAS saves the loads of edges before outage for evaluation of restoration schemes.

Once the dispatchers verify the requirement of restoring the loads by distribution network from a higher-level dispatching center, the fast restoration procedure is started.

The first step is to isolate faults by tripping the switches connected with the faulted buses. Such switches can be found by checking the elements of the third column in  $DT$ . Then, set the elements of the second column in  $DT$  of such switches to be a unit to lock them in the tripped state.

### 4 Minimum load shading approach

In case of light loads on the distribution network, directly closing the loop switches may restore all the loads affected by the fault. Such procedure is called as the direct-load-transferring.

In case direct-load-transferring does not guarantee that all the loads affected by the fault can be restored without causing overload, we should search for the restoration scheme with the minimum load shaded.

A load shading algorithm based on the operation mode with the most balanced loads is described in Ref. [11]. But in some cases the algorithm in Ref. [11] may not reach the optimal result.

Besides, in cases where no load control terminal units are on the demand side, the algorithm in Ref. [11] is not feasible.

To solve the above problem, we propose a new approach to minimum load shading.

#### 4.1 Load shading parameter

As for a feeder under a certain operation mode, the characteristic parameter of the  $i$ th load shading scheme, i.e.,  $\lambda_i$  is defined by

$$\lambda_i = \sum_{j=1}^M w_j 2^j \quad (3)$$

where,  $M$  is the number of switches of the feeder.  $j$  is the sequence number of vertexes.  $w_j$  is a characteristic number. If the  $j$ th vertex is closed,  $w_j = 1$ . Otherwise,  $w_j = 0$ .

It is obvious that a different load shading scheme has a different value of characteristic parameter.

According to load shading characteristic parameter  $\lambda_i$ , we can get the states of switches by

$$w_j = \text{int} \left[ \frac{\lambda_i - \sum_{m=j+1}^M w_m 2^m}{2^j} \right] \quad (4)$$

where,  $\text{int}[x]$  indicates the treatment that  $\text{int}[x] = 1$  in case  $x \geq 1$ , otherwise  $\text{int}[x] = 0$ .

We define a complex number  $\dot{s}$  to synthesize the characteristic parameter and the shaded load  $\Delta l$  of load shading schemes.  $\dot{s}$  is called as a load shading parameter, i.e.,

$$\dot{s} = \Delta l_i + j\lambda_i \quad (5)$$

The minimum shaded load  $\Delta l_{\min}$  is defined as the minimum value of load which should be shaded by tripping the existing operative switches to ensure the normalized load of the power source to be less than 1.0. The corresponding characteristic parameter is  $\lambda_{\min}$ .

#### 4.2 Independent tripping operation

As for a feeder, we can obtain  $m$  outage regions by tripping  $m$  switches, respectively. If the corresponding  $m$  regions are not overlapping, we call the tripping operations of the  $m$  switches as independent tripping operation (ITO). Otherwise we call it dependent tripping operation (DTO).

It is obvious that

$$c_{i2} + c_{i3} + c_{i4} + c_{i5} \neq -4 \quad (6)$$

the  $i$ th vertex is connected with the power source, i.e., the  $i$ th vertex is energized.

Therefore, the steps to identify ITO are:

**Step 1:** Trip the  $i$ th vertex. Execute  $D$ -to- $C$  conversion.

**Step 2:** According to  $CT$ , check whether the  $j$ th vertex is energized by Eq. (6).

**Step 3:** Trip the  $j$ th vertex. Execute  $D$ -to- $C$  conversion.

**Step 4:** According to  $CT$ , check whether the  $i$ th vertex is energized by Eq. (6).

**Step 5:** If the results of Step 2 and Step 4 are both true, the tripping operations of the  $i$ th vertex and the  $j$ th vertex is ITO. Otherwise they are DTO.

#### 4.3 Minimum load shading on one feeder

A family of sets  $S^{(k)}$  is introduced to represent the load shading schemes with  $k$  switches needed to trip. The minimum load shading on one feeder (MLSF) procedure consists of the following steps:

**Step 1:** Find out the total load (i.e.,  $\Delta L_{\Sigma}$ ) to be shaded by executing the  $A$ -to- $V$  conversion under the current topology.  $\Delta L_{\Sigma}$  is the load which should be shaded to ensure the normalized load of the power source to be less than 1.0, i.e.,

$$\Delta L_{\Sigma} = l_s - e_s \quad (7)$$

where  $l_s$  and  $e_s$  are the load and normalized load of power source, respectively.

It is obvious that if  $\Delta L_{\Sigma} \leq 0$ , no load needs to be shaded, the MLSF procedure can be stopped at once.

Let  $k = 1$ .

**Step 2:** Trip each switch and execute  $D$ -to- $C$  and  $A$ -to- $V$  conversion except for the ones with their  $d_{i2}$  being 1 or 3, respectively, forming a set of  $S^{(1)}$ .

**Step 3:** Execute the scheme in  $S^{(k)}$  and calculate the corresponding shaded load. Find the scheme guaranteeing safe operation (i.e., the total shaded load being larger than  $\Delta L_{\Sigma}$ ) in  $S^{(k)}$ . Label the scheme with the minimum load shaded ( $\Delta L_{k,\min}$ ) in such scheme as  $S_{\min}(k)$ . Obviously,  $S_{\min}(k)$  is the minimum load shaded scheme with  $k$  switches needed to trip. Save  $S_{\min}(k)$  into queue  $Q$ .

**Step 4:** Eliminate the scheme with shaded load larger than  $\Delta L_{k,\min}$  in  $S^{(k)}$  and  $S^{(l)}$  (because the new schemes with  $k+l$  switches tripping formed by such schemes must have larger shaded load than  $\Delta L_{k,\min}$ ). Add each switch in  $S^{(l)}$  to each scheme in  $S^{(k)}$ , respectively, and eliminate the DTO in the results forming a set of  $S^{(k+l)}$ .

**Step 5:** Go to Step 6 if  $S^{(k+l)}$  is an empty set ( $\emptyset$ ). Otherwise let  $k=k+1$  and return to Step 3.

**Step 6:** Compare among  $\Delta L_{l,\min}$  to  $\Delta L_{k,\min}$  and find the scheme ( $S_{\text{opt}}$ ) with the minimum shaded load ( $\Delta L_{\text{opt}}$ ), i.e.,

$$\dot{s}_{\text{opt}} = \Delta l_{\text{opt}} + j\lambda_{\text{opt}} \quad (8)$$

**Step 7:** Set the elements of the second column of  $DT$  of the switch vertexes for load shading to be 2, respectively.

#### 4.4 Minimum load shading in a CD

A connected domain (CD) consists of a lot of feeders. In order to obtain minimum load shaded scheme, network reconfiguration (i.e., changing of the positions of loop switches) should be considered besides the MLSF procedure for each feeder in a CD. Such procedure is called minimum load shading in a CD (MLSC).

Loop switches can be identified according to *CT*, i.e.,

If the in-degree of a vertex is 2 while its out-degree is 0, the vertex is a loop switch.

One-step-shifting procedure of a loop switch is defined as closing the loop switch and tripping one of the adjacent switches in the upstream direction to be the new loop switch. Since the in-degree of a loop switch is 2, one-step-shifting procedure may have no more than two feasible results.

Based on the one-step-shifting procedure, the steps of MLSC are as follows:

**Step 1:** Execute MLSF procedures for all feeders affected by the serious fault in the existing operation mode obtaining the total shaded load  $\Delta L_{\text{ref}}$  and the characteristic parameter  $A_{\text{ref}}$ . Let  $\beta = 0$ . Save all loop switches of the CD into queue  $R$ .

**Step 2:** Get a loop switch from  $R$  and execute one-step-shifting procedure. Based on the results, calculate the minimum shaded load  $\Delta L_{C,\text{min}}$  and the corresponding characteristic parameter  $A_{C,\text{min}}$ .

**Step 3:** If  $\Delta L_{C,\text{min}} < \Delta L_{\text{ref}}$ , let  $\Delta L_{\text{ref}} = \Delta L_{C,\text{min}}$ ,  $A_{\text{ref}} = A_{C,\text{min}}$ , let  $\beta = 1$ . Otherwise, reset the corresponding loop switch to its original position.

**Step 4:** If  $R$  is empty go to Step 5, otherwise, return to Step 2.

**Step 5:** Exist if  $\beta = 0$ . The optimal load shading scheme is  $\Delta L_{\text{ref}}$  and  $A_{\text{ref}}$ . Otherwise, reconfigure the distribution network according to  $A_{\text{ref}}$ . Save all loop switches in the new operation mode into queue  $R$ . let  $\beta = 0$  and return Step 2.

#### 4.5 Minimum load shading in total network

A distribution network consists of several connected domains. Considering that loads cannot be transferred between different connected domains, the minimum load shading scheme in the total distribution network is the sum-set of minimum load shading schemes in all connected domains.

The minimum load shaded in the total distribution network  $\Delta L_{D,\text{min}}$  is the summation of the minimum load shaded in the connected domains. The corresponding characteristic parameter  $A_{D,\text{min}}$  can be determined according to the corresponding characteristic parameters of the connected domains.

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### 5 Procedure of fast restoration

The procedure of fast restoration under emergency state is as follows.

**Step 1:** Fault isolation, which has been described in the end of Sect. 3.

**Step 2:** As for a certain connected domain, work out direct-load-transferring scheme if all the loads affected by the fault may be restored without overload.

**Step 3:** As for a certain connected domain, if direct-load-transferring is not feasible, work out the minimum load shading scheme according to the algorithm described in Sect. 4.

**Step 4:** Comparing the optimal operation mode with minimum load shaded of the total distribution network with the current operation mode, we may list the switches to be operated.

**Step 5:** Form a switch operation table by managing the switches to be operated in order according to the following principles:

1) The switch tripping operations to isolate faults should be executed at first.

2) As for the case that some load should be shaded, the switch tripping operation to shade loads should be executed secondly.

3) Match the rest of the switches to be operated into pairs, i.e., as for each switch to be tripped, find a corresponding switch to be closed meeting the requirements of no loop formed, no overload and energizing the outage parts due to the tripped switch. Execute such switches in pairs.

**Step 6:** Execute the operations in the switch operation table by tele-control measures. The fast restoration is reached.

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### 6 Discussions

Some researchers hold the opinion that the load shading should not be carried out on a healthy feeder. To meet such requirements, we just need to set the elements of the second column of *DT* to be 3 for the vertexes on the healthy feeders to forbid the corresponding load shading operation. The algorithm described in Sect. 4 is also feasible.

In the same way, the load shading on important customers can be avoided.

In order to guarantee not causing overload after load transferring, the rated load of a device can be set at a value lower than its electrical limitation or the setting value of relay protection.

Because the duration time of fast restoration is quite short, the loads can be considered without variation before and after the fault. But after restoration, the loads may raise to some extent to cause overload. In such case, network reconfiguration for load balancing should be executed, which are described in many literatures including [12–14] and will not be discussed in the paper.

## 7 An example

A typical distribution network is shown in Fig. 1. The data in brackets are the loads of edges ( $A$ ). The numbers beside vertexes are the sequence numbers of vertexes. The solid circles indicate the closed switches. The hollow circles indicate the tripped switches. The rated loads of all power sources are of the same value, i.e., 300 A. The distribution network consists of two connected domains. The 1st connected domain consists of vertexes 1, 3, 6, 9, 13, 17, 19, 20, 23, 25, 26, 27, 28 and 29. The 2nd connected domain consists of vertexes 2, 4, 5, 7, 10, 11, 12, 14, 15, 16, 18, 21, 22, 24, 30 and 31.

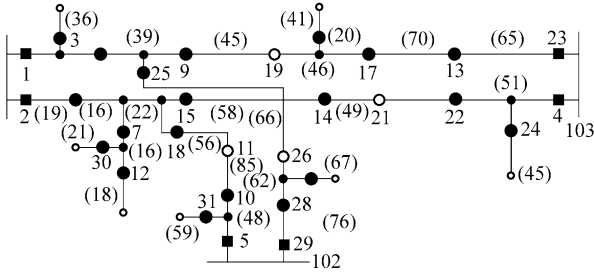


Fig. 1 A typical grid distribution network

Assuming that there is a fault on bus 101, the fault can be isolated by tripping the 1st and 2nd power sources. If we close loop switches 19 or 26 directly to transfer the loads supplied by the 1st and 2nd power source to the feeder supplied by the 23rd or 29th power source, after executing  $D$ -to- $C$  conversion and  $A$ -to- $V$  conversion, we find that the load of the 23rd or 29th vertex may reach 454 A or 437 A causing overload. Thus, the direct load transferring of the loads supplied by the 1st power source is not feasible. Similarly, the direct load transferring of the loads supplied by the 2nd power source is also not feasible.

After fault isolation, get the most balanced operation mode by the algorithm described in Ref. [10], i.e., the loop switches are vertex 15 and vertex 25.

As for the 1st connected domain, after executing  $D$ -to- $C$  conversion and  $A$ -to- $V$  conversion, we find the load of power source 23 and 29 are 388 A and 271 A, respectively. It is obvious that power source 23 is overloaded and  $\Delta L_{\Sigma} = 88$  A.

We recode the eight switches of the overloaded feeder, which is shown in Fig. 2 in brackets of  $\langle A \rangle$ . Tripping each of the eight switches and executing  $D$ -to- $C$  conversion, respectively, we obtain the set  $S^{(1)}$  of load shading parameters for each switch as:

$$\begin{aligned} \dot{s}_1 &= 36 + j(0111 \ 1111)_2; \dot{s}_2 = 82 + j(1011 \ 1111)_2; \\ \dot{s}_3 &= 121 + j(1101 \ 1111)_2; \dot{s}_4 = 166 + j(1110 \ 1111)_2; \\ \dot{s}_5 &= 41 + j(1111 \ 0111)_2; \dot{s}_6 = 253 + j(1111 \ 1011)_2; \\ \dot{s}_7 &= 323 + j(1111 \ 1101)_2; \dot{s}_8 = 388 + j(1111 \ 1110)_2. \end{aligned}$$

It is obvious that the minimum load shading scheme to ensure the normalized load of the power source to be less than the 1.0 in  $S^{(1)}$  is  $\dot{s}_3 = 121 + j(1101 \ 1111)_2$ . It is the

minimum load shaded scheme with one switch needed to trip. Save it into queue  $Q$ , i.e.,  $\dot{q}_1 = 121 + j(1101 \ 1111)_2$ .

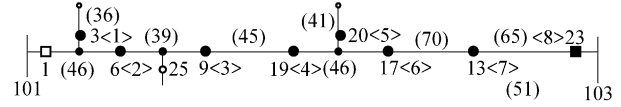


Fig. 2 Feeder with source node 23 and its recoding

Eliminating the elements with shaded load larger than 121 in  $S^{(1)}$ , the rest of the elements are  $\dot{s}_1 = 36 + j(1111 \ 1110)_2$ ,  $\dot{s}_5 = 41 + j(1110 \ 1111)_2$  and  $\dot{s}_2 = 82 + j(1111 \ 1101)_2$ . Combining such three elements in pairs and eliminating DTO, we have the set of  $S^{(2)}$ , i.e.,

$$\dot{s}_1^{(2)} = \dot{s}_1^{(2)} = \dot{s}_{1,5} = 77 + j(0111 \ 0111)_2$$

$$\text{and } \dot{s}_2^{(2)} = \dot{s}_2^{(2)} = \dot{s}_{2,5} = 123 + j(1011 \ 0111)_2$$

The minimum load shading scheme to ensure the normalized load of the power source to be less than the 1.0 in  $S^{(2)}$  is  $\dot{s}_2^{(2)} = \dot{s}_2^{(2)} = \dot{s}_{2,5} = 123 + j(1011 \ 0111)_2$ . It is the minimum load shaded scheme with two switches needed to trip. Save it into queue  $Q$ , i.e.,  $\dot{q}_2 = 123 + j(1011 \ 0111)_2$ .

Eliminating the elements with shaded load larger than 123 in  $S^{(2)}$  and  $S^{(1)}$ , the rest of the elements are  $\dot{s}_1^{(2)} = \dot{s}_{1,5} = 77 + j(0111 \ 0111)_2$  in  $S^{(2)}$ , and  $\dot{s}_1^{(1)}$ ,  $\dot{s}_2^{(1)}$ ,  $\dot{s}_3^{(1)}$  in  $S^{(1)}$ . Combining the elements in  $S^{(2)}$  and  $S^{(1)}$  in pairs and eliminating DTO, we have the set of  $S^{(3)} = \emptyset$ .

Since set  $S^{(3)}$  is empty, go to Step 6. Comparing  $\dot{q}_1$  with  $\dot{q}_2$ , we have  $\dot{s}_{\min} = \dot{q}_1 = 121 + j(1101 \ 1111)_2$ , i.e., the minimum load shading operation is to trip switch vertex 9 with the minimum shaded load of 121 A, i.e.,  $\Delta L_{\text{ref}} = 121$  A.

Executing one-step-shifting procedure on the 1st connected domain, we find that in case vertex 9 works as the loop switch, the loads of power source 23 and 29 are 267 A and 392 A, respectively. The minimum load shading scheme is to trip switch vertex 3 and 27 with the minimum shaded load of 103 A, which is superior to that based on the load balancing operation mode. But in case vertex 26 works as the loop switch, the minimum load shading scheme is to trip switch vertex 9 with the minimum shaded load of 187 A, which is not superior to that based on the load balancing operation mode. Thus,  $\Delta L_{\text{ref}}$  is changed to 103 A.

No further improvements can be made by continuing to execute the one-step-shifting procedure. Therefore, the final minimum load shading scheme for the 1st connected domain is vertex 9 working as loop switch and vertex 3 and 27 tripped with the minimum shaded load of 103 A.

It can be seen that the load shading algorithm based on the operation mode with the most balancing loads may not reach the optimal result.

Similarly, we obtain the minimum load shading scheme for 2nd is tripping vertex 7 with the minimum shaded load of 55 A.

The minimum shaded load for the total distribution

