DISTRIBUTION SYSTEM SERVICE RESTORATION USING A HEURISTIC SEARCH APPROACH

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Abstract — A heuristic search approach is developed for service restoration of a distribution system. The purpose is to devise a proper restoration plan after the location of a fault has been identified and the faulted zone has been isolated. Since service restoration is an urgent matter in distribution system operation, the restoration plan must be reached in a very short time. In addition, the out-of-service area must be minimized to enhance system reliability. To reach a restoration plan which satisfies all practical requirements, a set of heuristic rules are compiled through interviews with experienced operators at Taiwan Power Company. A heuristic search algorithm is developed for service restoration following a fault on distribution feeders. The effectiveness of the proposed heuristic search approach is demonstrated by the restoration of the electricity service following a fault in a underground distribution system within the service area of Taipei City District Office of Taiwan Power Company. It is found that the restoration plan can be reached very efficiently. Therefore, it can serve as a valuable tool to help distribution system dispatchers reach a proper restoration plan.

Keywords: distribution systems, restoration, heuristic search method.

1. INTRODUCTION

When a fault takes place in a distribution system, it is essential for system dispatchers to locate the fault, isolate the faulted zone, and restore the electricity service to the out-of-service area which is outside the faulted zone. In recent years, a lot of works have been reported on fault location identification [1–5] and service restoration [6–14]. The paper is concerned with the problem of service restoration based on the assumption that the fault location has been identified and the faulted zone has been isolated.

Our purpose is to determine a restoration plan for a fault on distribution feeders. Since the restoration plan reached in this work will be provided to system operators to help them make the final decision on how to restore the out-of-service area, it must meet the practical needs of system dispatchers as summarized below.

1. The restoration plan must be reached in a very short time. This is based on the practical consideration that the electricity service at the out-of-service area must be restored as soon as possible in order to avoid customers' inconvenience and enhance service reliability.
2. Restore as much load as possible within the out-of-service area.
3. The required number of switching operations in the restoration plan should be minimal. The main reason for allowing only minimal switching operations is that frequent operations may reduce the life expectancy of switches. In addition, it takes time for troubleshooters to operate a switch. This is especially a crucial factor in a crowded city such as Taipei because it may take the troubleshooters more than one hour to get to a place only one mile away. Therefore, the number of switches to be operated should be limited.

4. The configuration of the restored system should be as close to the original configuration as possible. In other words, only those switches which are close to the out-of-service area may be operated.
5. Radial system structure must be retained.
6. No components are overloaded.

Service restoration is a complicated combinatorial optimization problem because there are a great number of candidate switches in the distribution system. It may take a long time to reach a feasible restoration plan which satisfies all the aforementioned practical requirements if one tries to solve the problem using combinatorial optimization algorithms. Therefore, the dispatchers at many utilities including Taiwan Power Company tend to use their experience and heuristic rules to narrow down the potential candidates and reach a proper restoration plan in a short period. The important role of human experts in reaching a suitable restoration plan motivated some recent works [6–14] on the application of expert system approach and heuristic search approach to this field.

In this paper, the heuristic rules which are used by experienced dispatchers at Taiwan Power Company in conducting service restoration are first compiled. Based on these heuristic rules, a heuristic search algorithm is developed for service restoration following a fault on distribution feeders. The developed heuristic search algorithm has been tested on a distribution system within the service area of Taipei City District Office of Taiwan Power Company. It is found from the test results that the proposed heuristic search algorithm is capable of reaching proper restoration plans in a very efficient manner.

2. PROBLEM FORMULATION

To demonstrate the nature of service restoration problem, let's consider a typical distribution system configuration of Taiwan Power Company as shown in Fig. 1. Let's assume that there is a fault within the service area of feeder F1. It is observed from Fig. 1 that feeder F1 is connected with supporting feeder F2 through a normally open feeder tie switch (SW8). In addition, there are six laterals (LAT1, LAT2, LAT3, LAT4, LAT5, and LAT6) for feeder F1 with each lateral being connected with a supporting lateral through a normally open lateral tie switch. For example, lateral LAT1 is connected with lateral LAT7 through the lateral tie switch SW1. In addition, there is a loop switch SW7 between laterals LAT3 and LAT4.

When a fault takes place, the operators first identify fault location and isolate the fault. In a distribution system with feeder automation function, the fault locations can be automatically identified and isolated. But feeder automation projects in most utilities in the United States and other countries in the world such as Japan and Taiwan are still under way. In such systems where feeder automations have not been completed yet, the operators may have to identify the fault locations manually based on trouble calls and past experience. We have developed an expert system to assist the operators at Taiwan Power Company to identify fault locations [1]. In this paper, it is assumed that the fault location has been identified either manually by the operators or automatically by computers at the dispatching center of a system with feeder automation function. For example, consider the case where there is a fault at point J on feeder F1. The circuit breaker will trip and the switch at branching point I will be opened to isolate the fault. This will leave the service to the loads on the six laterals LAT1, LAT2, LAT3, LAT4, LAT5, and LAT6 interrupted. The operator now faces the problem of how to restore the electricity service to the six laterals within the out-of-service area as soon as possible. In other words, how can he dispatch the limited troubleshooters to proper locations to operate the switches such that the electricity service can be restored by the supporting feeder (F2) and supporting laterals (LAT7, LAT8, LAT9, LAT10, LAT11, and LAT12)?

Fig. 1 A sample distribution system used to demonstrate the heuristic search algorithm

It is obvious that the solution may be not unique. In fact, there are numerous solutions to this problem in most cases. Among these, a feasible restoration plan which meets all the six requirements as described in Section 1 must be picked out in a very short time. In current practice, the operators at Taiwan Power Company try to devise a proper restoration plan using their past experience and a set of heuristic rules. In this paper, a heuristic search algorithm which can be employed to devise proper restoration plans very efficiently will be developed based on these heuristic rules. A computer program is developed on a personal computer using the language C to demonstrate the effectiveness of the heuristic search method.

Before we proceed to the details of the heuristic search algorithm, let's give some comments on the loads which are essential for our heuristic search method. At present, the feeder automation project at Taiwan Power Company is still under way. Therefore, only feeder loads are available to system operators. In other words, we know the total load current of each feeder. When the feeder automation project is completed, the load for each section of the distribution feeder will be monitored and recorded. However, the loads on laterals and branching points are still not exactly known. Therefore, we need a certain means to estimate the loads on laterals and branching points. A convenient and popular (but not the best) way to do load estimation is based on the assumption of conforming loads where the individual loads change in the same proportion [13, 15]. This approach has been adopted in the present work. From the available feeder current I_{FD} , the load current of branching point i , $LOAD_i$, is estimated as

$$LOAD_i = I_{FD} \left(C_i / \sum_{i=1}^N C_i \right) \quad (1)$$

where

C_i = sum of the rated capacities of transformers at branching point i
 N = number of branching points that are supplied power from the feeder

It is noted that the loads as estimated by using eq. (1) are by no means very accurate. Unless we have a fully-automated distribution system where we put meters on every lateral and every distribution transformer, we will always need to estimate the loads. An approach based on neural networks [16] has been proposed to estimate the loads.

3. THE HEURISTIC SEARCH APPROACH

To make the heuristic search algorithm capable of generating a restoration plan which meets the practical needs of system operators at Taiwan Power Company, the heuristic rules that are followed by experienced operators in conducting service restoration are first compiled and are summarized as follows.

1. A feeder which is out-of-service can be supplied power from its supporting feeder by switching on the normally open feeder tie switch between the two feeders. But service restoration in this case can only be carried out when the supporting feeder has spare capacity margin. In other words, the supporting feeder should not be overloaded when it supplies power to the interrupted feeder.
2. If the supporting feeder does not have enough spare capacity to supply power to the entire out-of-service area, some laterals within the out-of-service area must be supplied power from their supporting laterals.
3. The supporting feeder with positive capacity margin must be dispatched before any supporting lateral is employed.
4. Support laterals can only be used to supply power to the out-of-service area in the corresponding interrupted lateral. They must not be used to supply power to feeder sections. For example, lateral LAT7 in Fig. 1 can only supply power to LAT1 by switching on SW1. It should not be used to supply power to other laterals or feeder sections.
5. Restore the loads on a lateral as a unit, if possible. In other words, avoid the situation where a lateral is supplied power from two separate sources.
6. If the electricity service within the out-of-service area can not be completely restored by using the supporting feeder and

- supporting laterals, transfer some loads on the supporting feeder to other feeders in order to increase its spare capacity.
7. If the out-of-service area can still not be completely restored after load transfer on the supporting feeder, try to restore as much load as possible.
 8. The required number of switching operations in the restoration plan must be minimal.
 9. The restoration plan should be reached in a very short period.

With these heuristic rules at hand, we can proceed to develop the procedures for reaching a proper restoration plan. As shown in Fig. 2, we first read in fault location and load currents. Then, the out-of-service area and the supporting feeder and laterals can be figured out from the network configuration which has been stored in the database. The available capacity margins for the supporting feeder and for each supporting lateral are computed before the heuristic search algorithm is executed to reach a proper restoration plan. Details of the heuristic search algorithm are described below.

As shown in Fig. 3, the algorithm begins with comparing the capacity margin of the supporting feeder (MF) with the total load within the out-of-service area $LOAD_T$. If MF is greater than $LOAD_T$, use RESTORATION ALGORITHM 1 to devise the service restoration plan.

RESTORATION ALGORITHM 1 (Use supporting feeder to restore power supply)

Close the feeder tie switch between the interrupted feeder and the supporting feeder and restore the power supply using the supporting feeder.

Example 1

Consider the distribution system in Fig. 1. For a fault that takes place at point J on feeder F1, circuit breaker CB1 will trip and the faulted zone is isolated by opening the switch at branching point 1. This will leave the loads on laterals LAT1, LAT2, LAT3, LAT4, LAT5, and LAT6 interrupted. Let $LOAD_i$ ($i = 1, 2, \dots, 6$) be the load for lateral LAT_i. The total load within the out-of-service area will be $LOAD_T = \sum_{i=1}^6 LOAD_i$. Since the supporting feeder in this case is feeder F2, we proceed to compare the capacity margin of F2, MF, with $LOAD_T$. If MF is greater than $LOAD_T$, we close feeder tie switch SW8 and the entire out-of-service area is supplied power from feeder F2.

If MF is less than $LOAD_T$, divide the laterals within the out-of-service area into two groups.

Group A: the laterals that can be completely restored by their corresponding supporting laterals.

Group B: the laterals that can not be completely restored by their corresponding supporting laterals.

Thus the load of a lateral in group A is less than the capacity margin of its supporting lateral while the load of a lateral in group B is greater than the capacity margin of its supporting lateral.

In block 2 of Fig. 3, we compute $LOAD_A$ which is the total load of the laterals in group A and $LOAD_B$ which is the total load of the laterals in group B. Note that $LOAD_B$ is equal to $LOAD_T - LOAD_A$. Then we compare MF with $LOAD_B$. If MF is greater than $LOAD_B$, use RESTORATION ALGORITHM 2 to devise the service restoration plan.

RESTORATION ALGORITHM 2 (Use supporting feeder and the supporting laterals for group A laterals to restore power supply)

Step 1. Use the supporting feeder to restore the electricity service on group B laterals and use the supporting laterals to restore the electricity service on group A laterals. The result is a temporary restoration plan.

Step 2. If MF is greater than $LOAD_B$, there is spare capacity on the supporting feeder. Therefore, we can use the supporting feeder to supply power to some laterals in group A. The process begins with modifying the temporary restoration plan by supplying power to the group A lateral with least

Fig. 2 Procedures for reaching a service restoration plan

Fig. 3 The heuristic search algorithm for service restoration

load from the supporting feeder. It is repeated until the supporting feeder's spare capacity is exhausted. This procedure is carried out in order to reduce the required number of switching operations. By supplying power to a lateral in group A from the supporting feeder, the number of switching operations can be reduced by two. Note that we start with the lateral with least total load in order to supply power to as many laterals as possible and reduce maximum possible number of switching operations. Take the distribution system in Fig. 1 as an example. Let lateral LAT1 be in group A. If this lateral is supplied power from its supporting lateral (LAT7), we will have to operate two switches at two different places (close switch SW1 and open the switch at branching point 1). If it is supplied power from the supporting feeder (F2), we do not have to operate any switch. Thus it is highly desirable to use the supporting feeder to supply power to as many group A laterals as possible in order to reduce the number of switching operations.

- Step 3. Reduce the number of locations that the troublemen need to visit to operate the switch in order to save the traffic time. This is achieved by giving priority to the switches in a branching point connected with two or more laterals. Let's demonstrate this point using Example 2.

Example 2

Consider the distribution system in Fig. 1 again. Assume once again that a fault takes place at point J on feeder F1. Let laterals LAT1, LAT2, LAT5, and LAT6 be in group A while laterals LAT3 and LAT4 be in group B. From the procedures in step 1, we obtain the following temporary restoration plan.

Temporary restoration plan 1 from step 1.

Laterals LAT3 and LAT4 are supplied power from the supporting feeder F2 while laterals LAT1, LAT2, LAT5, and LAT6 are supplied power from their supporting laterals LAT7, LAT8, LAT11, and LAT12, respectively.

Note that we need to operate 9 switches at 8 different locations as summarized in Table 1 if we employ this restoration plan.

Table 1. The switching operations for the temporary restoration plan 1 in Example 2

location	switch	switching operations
1. feeder tie switch for feeder F2	SW8	close
2. lateral tie switch for lateral LAT7	SW1	close
3. branching point 1	LAT1 switch	open
4. lateral tie switch for lateral LAT8	SW2	close
5. branching point 1	LAT2 switch	open
6. lateral tie switch for lateral LAT11	SW5	close
7. branching point 7	LAT5 switch	open
8. lateral tie switch for lateral LAT12	SW6	close
9. branching point 9	LAT6 switch	open

The number of switching operations can be reduced by employing the procedures in step 2. Let's assume that $LOAD_1 < LOAD_2 < LOAD_3 < LOAD_4$ and the supporting feeder has spare capacity to supply power to laterals LAT1 and LAT2. The temporary restoration plan 1 will be updated to temporary restoration plan 2 if the procedures in step 2 are executed.

Temporary restoration plan 2 from step 2

Laterals LAT1, LAT2, LAT3, and LAT4 are supplied power from the supporting feeder F2 while laterals LAT5 and LAT6 are supplied power from their supporting laterals LAT11 and LAT12, respectively.

It is observed from the switching operations in Table 2 that we now need to operate 5 switches at 5 different locations. The required number of switching operations has been reduced by 4.

Table 2. The switching operations for the temporary restoration plan 2 in Example 2

location	switch	switching operations
1. feeder tie switch for feeder F2	SW8	close
2. lateral tie switch for lateral LAT11	SW5	close
3. branching point 7	LAT5 switch	open
4. lateral tie switch for lateral LAT12	SW6	close
5. branching point 9	LAT6 switch	open

To further reduce the number of locations for switching operations, the procedures in step 3 are followed. Let's assume that feeder F2 has enough capacity to supply power to laterals LAT5 and LAT6. Since laterals LAT1 and LAT2 are connected with the same branching point 1, temporary restoration plan 2 will now be updated as follows.

Temporary restoration plan 3 from step 3

Laterals LAT3, LAT4, LAT5, and LAT6 are supplied power from the supporting feeder F2 while laterals LAT1 and LAT2 are supplied power from their supporting laterals LAT7 and LAT8, respectively.

It is observed from the switching operations in Table 3 that we need to operate 5 switches at 4 different locations. The number of different locations has been reduced by one.

Table 3. The switching operations for the temporary restoration plan 3 in Example 3

location	switch	switching operations
1. feeder tie switch for feeder F2	SW8	close
2. lateral tie switch for lateral LAT7	SW1	close
3. branching point 1	LAT1 switch	open
4. lateral tie switch for lateral LAT8	SW2	close
5. branching point 1	LAT2 switch	open

Since the out-of-service area has been completely restored without any component overloaded and the number of switching operations and locations can not be further reduced, the temporary restoration plan 3 is taken as the final restoration plan.

If MF is less than $LOAD_B$ in block 2 of Fig. 3, we try to operate loop switches, if there is any, in order to move some group B laterals to group A and reduce $LOAD_B$. Take the distribution system in Fig. 1 as an example. There is a loop switch SW7 between laterals LAT3 and LAT4. Let lateral LAT3 be in group A while lateral LAT4 be in group B. Assume that the capacity margin of supporting lateral LAT9 is greater than the sum of $LOAD_3$ and $LOAD_4$. If we open the lateral switches for laterals LAT3 and LAT4 at branching points 3 and 5, respectively and close lateral tie switch SW3 and loop switch SW7, laterals LAT3 and LAT4 will be supplied power from lateral LAT9. This is equivalent to moving lateral LAT4 from group B to group A.

By operating the loop switch, the total load of group B laterals, $LOAD_B$, will be reduced. If MF is now greater than $LOAD_B$, use RESTORATION ALGORITHM 2 to devise the restoration plan. Otherwise, the out-of-service area can not be completely restored using the supporting feeder and the supporting laterals for group A laterals. In this case, we need to use the supporting laterals for group B laterals in order to restore the electricity service completely. Each supporting lateral for a group B lateral is used to supply as much power as possible to that group B lateral until its spare capacity is exhausted. Consider the distribution system in Fig. 1 again. Let lateral LAT1 be in group B. The load at each branching point on lateral LAT1 and the capacity margin of its supporting lateral LAT7, M_7 , are shown in Fig. 4. It is observed from Fig. 4 that the supporting lateral LAT7 is capable of supplying power to branching points 16 and 17. The amount of restored load for lateral LAT1 is $RES_1 = 50$ while the amount of interrupted load is $LOAD_1 - RES_1 = 140 - 50 = 90$.

Fig. 4 The branching point loads of lateral LAT1 and the capacity margin of lateral LAT7

Let $RES_B = \sum_{i \in B} RES_i$ be the total restored load of group B laterals. Then the total interrupted load of group B laterals is equal to $LOAD_B - RES_B$ where $LOAD_B$ is the total load of group B laterals. In block 5 of Fig. 3, we proceed to check if MF is greater than $LOAD_B - RES_B$. If the answer is yes, the interrupted load of group B laterals can be completely restored by the supporting feeder. In this case, we use the RESTORATION ALGORITHM 3 to devise the restoration plan.

RESTORATION ALGORITHM 3 (Use supporting feeder and the supporting laterals for group A laterals and group B laterals to restore power supply)

- Step 1. Use the supporting laterals for group A laterals to restore the electricity service on these group A laterals.
- Step 2. Use the supporting laterals for group B laterals to restore as much load as possible on these group B laterals. Thus, for a lateral LAT_i in group B, part of the load, RES_i , is restored by its supporting lateral while the remaining load $LOAD_i - RES_i$ is supplied power from the supporting feeder. The resultant restoration plan is designated as the temporary restoration plan.
- Step 3. If the supporting feeder's spare capacity is not exhausted in the temporary restoration plan, try to use this spare capacity to modify the temporary restoration plan in order to reduce the required number of switching operations. The basic idea is to use this spare capacity to supply the amount of power, RES_i , that was restored by the supporting lateral in the temporary restoration plan. In doing so, the number of switching operations will be reduced by two. Take the distribution system in Fig. 1 and Fig. 4 as an example. In the temporary restoration plan, the loads at branching points 16 and 17 on lateral LAT1 are supplied power from supporting lateral LAT7 while the loads at the remaining branching points (18, 19, and 20) are supplied power from the supporting feeder F2. In this case, we will have to open the switch between branching points 17 and 18 and close switch SW1. If the entire lateral can be supplied power from the supporting feeder F2, we do not have to operate any switch.

To make the supporting feeder supply power to as many group B laterals as possible and achieve maximum reduction in the number of switching operations, the above procedure must begin with the group B lateral with smallest RES_i value. It is repeated for other laterals with small RES_i values until the spare capacity of the supporting feeder is exhausted.

Example 3

Consider the distribution system in Fig. 1. Let laterals LAT2, LAT3, and LAT6 be in group A and laterals LAT1, LAT4, and LAT5 be in group B. The temporary restoration plan from step 2 is described in Table 4 while the required switching operations are summarized in Table 5.

Table 4. The temporary restoration plan for Example 3

out of service area	restoration plan
1. LAT2	supplied by LAT8
2. LAT3	supplied by LAT9
3. LAT6	supplied by LAT12
4. part of LAT1 load (RES_1)	supplied by LAT7
5. part of LAT4 load (RES_4)	supplied by LAT10
6. part of LAT5 load (RES_5)	supplied by LAT11
7. remaining load of LAT1, LAT4, and LAT5	supplied by the supporting feeder F2

Table 5. Required switching operations in the temporary restoration plan for Example 3

location	switch	switching operation
1. lateral tie switch for lateral LAT2	SW2	close
2. branching point 1	LAT2 switch	open
3. lateral tie switch for lateral LAT3	SW3	close
4. branching point 3	LAT3 switch	open
5. lateral tie switch for lateral LAT6	SW6	close
6. branching point 9	LAT6 switch	open
7. lateral tie switch for lateral LAT1	SW1	close
8. a branching point on lateral LAT1		open
9. lateral tie switch for lateral LAT4	SW4	close
10. a branching point on lateral LAT4		open
11. lateral tie switch for lateral LAT5	SW5	close
12. a branching point on lateral LAT5		open
13. feeder tie switch for the supporting feeder F2	SW8	close

It is observed from Table 5 that we need to operate 13 switches at 13 different locations in the temporary restoration plan. The procedures in step 3 are now followed to reduce the number of switching operations. Assume that $RES_1 < RES_4 < RES_5$. If the spare capacity of feeder F2 is enough to supply both laterals LAT1 and LAT4 but not all the three laterals LAT1, LAT4, and LAT5 ($LOAD_1 + LOAD_4 + (LOAD_5 - RES_5) < MF < LOAD_1 + LOAD_4 + LOAD_5$), the total loads of laterals LAT1 and LAT4 are now supplied power from the supporting feeder F2. The resultant restoration plan and required switching operations are summarized in Table 6 and Table 7, respectively.

Table 6. Final restoration plan for Example 3

out-of-service area	restoration plan
1. LAT2	supplied by LAT8
2. LAT3	supplied by LAT9
3. LAT6	supplied by LAT12
4. LAT1	supplied by the supporting feeder F2
5. LAT4	supplied by the supporting feeder F2
6. part load of LAT5 (RES_5)	supplied by LAT11
7. remaining load of LAT5 ($LOAD_5 - RES_5$)	supplied by the supporting feeder F2

Table 7. Required switching operations in the final restoration plan for Example 3

location	switch	switching operations
1. lateral tie switch for lateral LAT2	SW3	close
2. branching point 1	LAT2 switch	open
3. lateral tie switch for lateral LAT3	SW3	close
4. branching point 3	LAT3 switch	open
5. lateral tie switch for lateral LAT6	SW6	close
6. branching point 9	LAT6 switch	open
7. lateral tie switch for lateral LAT5	SW5	close
8. a branching point on lateral LAT5		open
9. feeder tie switch for the supporting feeder F2	SW8	close

It is observed from Table 7 that the required number of switching operations has been reduced from 13 to 9 in the resultant restoration plan.

If MF is less than $LOAD_B - RES_B$ in block 5 of Fig. 3, we are not able to completely restore the electricity service on group B laterals without operating the loop switch. If there is loop switch between one lateral in group A and another lateral in group B, we can move the loop switch such that the load in the group B lateral is reduced. In this way, $LOAD_B$ is reduced and MF may become greater than $LOAD_B - RES_B$. Complete restoration is then achieved. Take the distribution system in Example 3 as an example. Assume, as we did in Example 3, that laterals LAT2, LAT3, and LAT6 are in group A while laterals LAT1, LAT4, and LAT5 are in group B. Consider the case where $MF < LOAD_B - RES_B$. Note from Fig. 1 that there is a loop switch, SW7, between LAT3 (a group A lateral) and LAT4 (a group B lateral). If the spare capacity of lateral LAT9 is not exhausted after it supplies power to lateral LAT3, we can move loop switch SW7 such that part of the load on LAT4 is supplied by lateral LAT9. In this way, $LOAD_B$ and $LOAD_B$ is reduced and MF may become greater than $LOAD_B - RES_B$. Complete restoration can then be achieved.

If there is no such loop switch or if MF is still less than $LOAD_B - RES_B$ after we operate the loop switch, the out-of-service area is not able to be completely restored unless we perform load transfer on the supporting feeder. If we decide not to perform load transfer on the supporting feeder in block 7 of Fig. 3, the restoration plan and out-of-service area are printed out. If we decide to transfer some loads on the supporting feeder, we go back to block 1 of Fig. 3 to determine the restoration plan. It is noted that load transfer on the supporting feeder is not carried out very often in current operation practice of Taiwan Power Company since it involves switching operations in a zone which is in normal service.

4. EXAMPLE

Based on the aforementioned heuristic search algorithm, a computer program is written on a personal computer using the language C. To demonstrate the effectiveness of the developed computer code, service restoration on a distribution system within the service area of Taipei City District Office of Taiwan Power Company is investigated. The results from a typical study are described below.

After a fault occurs at point A of Fig. 5, circuit breaker CB1 trips and the fault is isolated by opening the switch at branching point 7. To devise a proper restoration plan, we need the load currents on the feeder to be restored (SM64) and the supporting feeder (SU73) as listed in Table 8.

Table 8. The load currents and capacity margin of the interrupted feeder (SM64) and the supporting feeder (SU73) in Fig. 5

feeder	load current (A)	capacity margin (A) = 450 - load current
SM64	300	—
SU73	250	200

There are 12 laterals (LAT1–LAT12) in Fig. 5 to be restored electricity service. Among these, the eight laterals LAT1–LAT8 are connected with their supporting laterals through lateral tie switches. The feeder names for these supporting laterals are shown in Fig. 5. The capacity margins of these supporting laterals are listed in Table 9. Note that the capacity margin of a supporting lateral is given by $\min((450-x), (100-y))$ where y is the load current of the supporting lateral and x is the load of the feeder from which the supporting lateral is supplied power. The rated capacities of feeders and laterals are 450A and 100A, respectively.

The resultant restoration plan is described in Table 10. The required switching operations are depicted in Fig. 5.

Fig. 5 The restoration plan for a fault on a feeder

Table 9. The capacity margins of the supporting laterals

lateral	load current for the lateral (A)	capacity margin of the corresponding supporting lateral (A)
LAT1	5	100
LAT2	14	76
LAT3	15	74
LAT4	7	28
LAT5	26	63
LAT6	51	57
LAT7	33	42
LAT8	65	23
LAT9	47	—
LAT10	5	—
LAT11	27	—
LAT12	6	—

Table 10. The restoration plan for a feeder fault

switch	location	switching operation	description
SW10 SW5	33 14	open close	LAT5 is supplied power from its supporting lateral from feeder SM70
SW11 SW6	42 46	open close	LAT6 is supplied power from its supporting lateral from feeder ZH63
SW12 SW7	48 62	open close	LAT7 is supplied power from its supporting lateral from feeder ZH59
SW9	55	close	The remaining laterals are supplied power from the supporting feeder SU73

In a typical run on a personal computer, it takes about 2 minutes to load the system data, execute, and print out the results. For a distribution system which is not fully automated such as Taiwan Power System, it may take another 3 minutes for the operators to compile the load data in the field.

5. CONCLUSIONS

A heuristic search algorithm has been developed for the restoration of a distribution system following a fault on a feeder. In the development of the heuristic search algorithm, the practical needs of system dispatchers with regard to the restoration plan are first compiled. In order for the devised restoration plan to meet these practical needs, the heuristic rules that are employed by experienced operators are embedded in the heuristic search algorithm. The effectiveness of the proposed heuristic search algorithm has been demonstrated by service restoration of a distribution system within the service area of Taipei City District Office of Taiwan Power Company. It is found that a proper service restoration plan which meets all practical needs of system dispatchers can be achieved in a very efficient manner. Therefore, the proposed heuristic search algorithm can serve as a valuable tool for system dispatchers in conducting distribution system restoration.

In the present work, only the restoration following a fault on a feeder is considered. Service restoration following a fault on a lateral or a branching point will be investigated in our future work.

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