DYNAMIC SERVICE RESTORATION OF DISTRIBUTION SYSTEMS

BASED ON LOAD CURVES

A Project

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by

Jinqiu Li

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Department of Electrical and Electronic Engineering

Abstract

of

DYNAMIC SERVICE RESTORATION OF DISTRIBUTION SYSTEMS

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Jinqiu Li

A dynamic service restoration (DSR) method based on load curve variations, is proposed in this project. The application of the time variable load is considered to make an effective service restoration plan for affected distribution systems. Based on the available load curves of Sichuan provincial power system in China, the proposed method identifies the optimal candidate network configurations. The network configuration is altered for each hour over the restoration period. A service restoration plan with global dynamic characteristics is formed. The established distribution systems DSR is a constrained multi-objective mathematical model. Computation complexity is reduced by a two-stage solving methodology. A couple of case studies of a 70-node distribution system are presented in the paper. The simulation results indicate that, the proposed method will provide a fast, secure and reliable service restoration plan of the distribution.

________________________, Committee Chair
Atousa Yazdani, Ph.D.

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Date

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I am highly indebted to Prof. Yazdani for her guidance, patience. I would also like to thank Prof. Kumar for his advices and help. Finally, I dedicate this project to my parents and girlfriend who provided me support at any time. You are my proud, and, I will try my best to make you proud.

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CHAPTER 1

INTRODUCTION

1.1. Background of the Project

Power System reliability and finding methodologies to reduce the number and duration of outages have always been one the areas of concern in power system engineering. Utility operators are responsible for fast and efficient allocation of faults and also providing effective fault isolation and service restoration. The main objective in service restoration procedures is to maximize load restoration transferring the outage loads to healthy part of the network utilizing network reconfiguration. The network reconfiguration is performed without violating operation and security constraints. The effective service restoration is designed to reduce the unaffected outage area caused by the fault. Also, the design is intended to shorten the outage duration of customers.

1.2. Review of the Literature

The distribution systems service restoration can be mathematically formulated as a combinatorial, nonlinear, and constrained optimization problem, considering the Network topology and loads [4], [5]. Adopting different load models results in obtaining different service restoration plans. Constant load models and variable load models are studied in different research references. The constant load model usually refers to pre-faulted load using neural network [6],multi-agent system [7]–[10], fuzzy logic [11]–[13], graph theory [14]-[16].heuristic methods [17],[18], mathematical programming [19]-[21], and expert system [22], [23] The variable load model refers to formulate the service restoration plan based on the peak load transfer over the fault restoration period [26, 27]. Service to some loads may not be restored when using the constant maximum load. While using the load value for the pre-fault condition may result in overloads in some branches during the fault restoration period. Thus adopting the variable load model ensures no overloading in branches.

1.3. Goals of the Project

Major work of this project is described as follows:

A DSR methodology of distribution systems based on load curves is proposed in this project to provide fast restoration of the system by adopting variable loads.

A couple of cases have been studied in the project to prove the proposed method will provide a fast, secure and reliable service restoration plan of the distribution.

1.4. Layout of the Project

In this project, The DSR methodology of distribution systems based on load curves is proposed in this report. Chapter 2 establishes a constrained multi-objective mathematical model for DSR. Utilizing the model provided in the previous section, Chapter 3 provides a case study with application of the proposed methodology. Chapter 4 summaries the work in form of a conclusion..

CHAPTER 2

DYNAMIC SERVICE RESTORATION OF DISTRIBUTION SYSTEMS

2.1. Introduction to Chapter 2

In the chapter, the concept of dynamic service restoration in distribution systems is proposed, and a multi-objective mathematical model is established for the DSR of distribution systems.

2.2. The Mathematical Model of the DSR

After isolating the fault successfully, service to the unaffected outage area shall be restored as soon as possible [2, 4, 26, 26-29]. Service restoration can be performed as long as the available ampacity of the supporting feeder exceeds the amount of load that is going to be transferred to the healthy network. In this methodology the daily load curve is divided into 24 time intervals. The optimal service restoration network configurations is considered to satisfy the security constraints, considering the load of each time interval during the fault restoration period. This kind of DSR plan reflects the temporal characteristic of load variation on one hand, as well as the spatial characteristic of changing network configuration on the other hand.

The problem is formulated mathematically by defining the objective functions as Minimum total loss of load and Minimum total number of switching operations over the restoration period. The optimization problem should contain the branch current, and node voltage limitations. The distribution system radial configuration limit constraints are implemented as well [28]. The multi-objective mathematical model for the DSR plan is established as following:

$$\min \quad f_1(\boldsymbol{X}) = \sum_{t \in T_r} \Big(\sum_{n \in \Omega_N} P_{t,n} - \sum_{k \in \Omega_K} P_{t,k} \Big) \tag{1}$$

$$\min \quad f_2(\boldsymbol{X}) = \sum_{t \in T_r} (\sum_{m \in M} \left| S_{t,m} - S_{t-1,m} \right|) \tag{2}$$

$$s.t. \qquad I_{t,b} \le I_{b.\max} \quad (t \in T_r) \tag{3}$$

$$U_{\min} \le U_{t,k} \le U_{\max} \quad (t \in T_r) \tag{4}$$

$$g_t \in G \quad (t \in T_r) \tag{5}$$

Where, f_1 and f_2 are the total loss of load and total number of switching operations over the fault restoration period respectively; t is the number of the time intervals; T_r is the set of time intervals over the fault restoration period, e.g. if the fault occurred at 20th time interval and is cleared at 24th time interval, T_r={20, 21, 22, 23}; $\boldsymbol{X}$ is the matrix of the status of the branch switches. The status contains the time interval over the fault restoration period, $\boldsymbol{X}=[S_{t,m}]$, where t$\in T_r$, $m=1\cdots M$, and M is the total number of the branches in distribution systems. $S_{t,m}$ is the status of the branch number m at the time interval t, If no switch is installed or the switch is closed, $S_{t,m}=1$. The open state is $S_{t,m}=0$; while $\boldsymbol{\Omega}_N$ is the set of nodes of the distribution systems and $P_{t,n}$ is the active load power of node n at the t time interval before the service restoration respectively; $\boldsymbol{\Omega}_K$ and $P_{t,k}$ are similar to parameters stated above for after the restoration. In other words, N and K are the total number of nodes of the distribution system before and after the service restoration; $I_{t,b}$, $U_{t,k}$ and g_t are the current of branch b, the voltage at node k and the network configuration of the distribution system used for service restoration at the t time interval respectively. $I_{b.max}$ is the ampacity of the branch b; U_{max} and U_{min} are the maximum and minimum acceptable node voltages; and $\boldsymbol{G}$ is the set of all radial configurations.

2.3. Restoration Methodology

The DSR methodology, established in this section will be applied to solve a service restoration problem for distribution systems containing *w* branches. In a case that the fault restoration period includes *d* time intervals, the solution space of this problem will be $2^{d \times w}$. It shows that, the solution space of this model will increase exponentially with the increase in outage duration.

In practical service restoration process, the customer's satisfaction to the utility is mostly affected by the availability of supply, so the objective of minimum total loss of load is more important than the objective of minimum number of switching operations [28]. Therefore, in order to reduce the complexity of optimization computation and enhance the calculating speed, the objective of minimum loss of load and the objective of minimum number of switching operations are separated into two stages to solve as the priority. The two stages include finding the network configurations for each time interval over the fault restoration period with the minimum loss of load and identifying the optimal DSR plan with minimum total number of switching operations over the fault restoration period. Stage 1 optimally searches for the network configurations, which satisfy the security constraints, for each time interval with minimum loss of load successively and thereby the set of candidate network configurations is obtained for the whole fault restoration period. In stage 2, the enumerating combination method is adopted to obtain the final plan with minimum number of switching operations by selecting configurations from the set of candidate network configurations.

Therefore the multi-objective mathematical model for DSR plan can be simplified into single objective mathematical models for each time interval in stage 1. The details are as follows:

$$\min \quad P_{t,c}(\boldsymbol{X_{t,r}}) = \sum_{n\in\Omega_N} P_{t,n} - \sum_{k\in\Omega_K} P_{t,k} \tag{6}$$

$$s.t. \qquad I_{t,b} \le I_{b.\max} \tag{7}$$

$$U_{\min} \le U_{t,k} \le U_{\max} \tag{8}$$

$$g_t \in G \tag{9}$$

Where, $P_{t,c}$ is the loss of load at the tth time interval; $\boldsymbol{X}_{t,r}$ is the vector of status of switch on each branch of the distribution systems used for service restoration at the tth time interval, $\boldsymbol{X}_{t,r}$=[$S_{t,r1}$, ⋯, $S_{t,rm}$, ⋯$S_{t,rM}$].

The solution space of the models (6)~(9) is 2^w. It shows that, using the two-stage method to solve the multi-objective mathematical model of the DSR can reduce the solution space, and furthermore reduce the complexity in optimization.

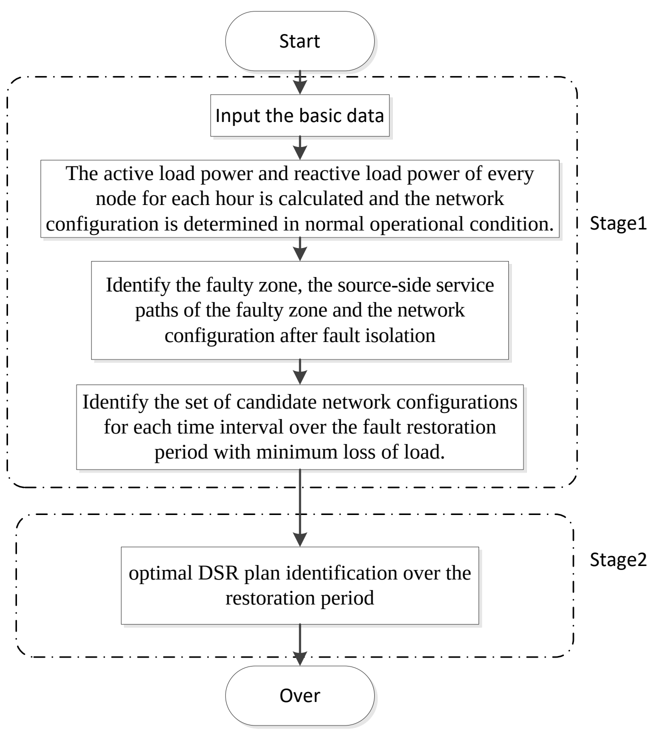


Figure 1 Flowchart of DSR method

The flowchart in Fig. 1 shows the computation processes of the two-stage method, and, the detail processes are described as follow.

2.4. Stage 1 of DSR Method

The process contains various steps. The first step is to enter the required basic data. Next the active load power and reactive load power of every node will be calculated for each time interval based on the chosen load curves and the network configuration is determined in normal operational condition; thirdly, identify the faulty zone, the source-side service paths of the faulty zone and the network configuration after fault isolation; at last, perform the conventional genetic algorithm (GA) [29] to identify the set of candidate network configurations with minimum loss of load for each time interval over the fault restoration period. The details of each step are described as following.

1) Step 1

Input the basic data. The basic data are divided into two categories: the data about the distribution system and the data used in the genetic algorithm. The data about distribution systems include: total number of the branches, branch number, sending and receiving end node number of each branch, resistance and reactance of each branch, ampacity of each branch, the type of switch installed on each branch (considering options such as without any switches, with sectionalizing switch in, and with tie switch), feeder number that each branch belongs to; total number of the nodes in distribution systems, total number of the power sources, power source number, active load power and reactive load power of each node, type of customers for each node, load curves for each type of customers, maximum and minimum acceptable node voltage; faulty branch number, fault occurrence and clearance time; and finally the system base values for voltage and MVA. The basic data used in the genetic algorithm includes: size of the population, maximum evolution generation, generation gap, cross-over rate and mutation probability.

2) Step 2

The active load power and reactive load power of every node for each hour is calculated and the network configuration is determined in normal operational condition. Based on the data about active load power and reactive load power of each node and the different types of load curves inputted in step 1, calculate the hourly active load power and reactive load power of every node based on the principle of keeping the power factor unchanged. Then according to the location of each installed tie switch in distribution systems, determine the network configuration in normal operational situation.

3) Step 3

This step identifies the faulty zone, the source-side service paths of the faulty zone and the network configuration after fault isolation. For the convenience of optimization computation and reduction of computing time, the source-side service paths of the faulty zone are defined by a set of branches between the power source and the faulty zone. The conventional depth-first search algorithm[30] is performed to identify the faulty zone according to whether a switch installed at the head of the faulty branch and the source-side service paths of the faulty zone starting from the power source of the feeder which the faulty branch belongs to. At last, based on the network configuration in normal operational situation identified in step 2, boundary switches of the faulty zone is utilized to isolate the fault, and identify the network configuration after fault isolation.

4) Step 4

Conventional genetic algorithm (GA) is adopted to identify the set of candidate network configurations for each time interval over the fault restoration period with minimum loss of load. In the network configuration obtained in step 3 after fault isolation, use the loads, which are obtained according to the load curves, of each time interval over the fault restoration period to solve the corresponding optimization mathematical model for the service restoration of distribution systems. This is done in order to obtain the network configuration with minimum loss of load for each time interval over the fault restoration period after fault isolation, for the convenience of the identification of the set of candidate network configurations of the DSR plan. Identifying network configurations for each time interval over the fault restoration period with minimum loss of load by adopting the conventional genetic algorithm can be divided into 4 sub-steps which are described as following:

Step 4.1 - Generates the initialized population. Based on the size of the population inputted in step 1, the binary coding system {0, 1} is used to randomly encode the strings to form the initialized population. The number of the strings is the size of the population. The length of each string in initialized population is the total number of the branches, and every bit of the string represents the status of the switch installed at the head of the corresponding branch. If the bit of the string is the binary digit 0, the status of the switch installed on the corresponding branch is open; if the bit of the string is the binary digit 1, the status of the switch installed on the corresponding branch is closed.

Step 4.2 - Calculates the value of objective function of each string in population. In order to evaluate the fitness of each string obtained in step 4.1, in initialized population, the value of objective function of each string is calculated. The smaller value of objective function is, the better fitness the string has. The details about how to calculate the value of objective function of each string are described as below:

Step 4.2.1 - Revises the string. The bits representing the statuses of switches installed on the source-side of the healthy branches are set to binary digit 1; and bits representing the statuses of switches, which are installed on the boundary branches of faulty zone, are revised as binary digit 0 to realize the fault isolation.

Step 4.2.2 - Decodes the string. Based on the revised string and the inputted data for the branches, identify the data about the corresponding branches with binary digit 1.

Step 4.2.3 – Forms radial distribution systems connected with different power sources. In order to form the radial network configuration connected to each power source, the depth-first search algorithm is adopted using branch data after decoding in step 4.2.2. First, set the different power sources as initial points, and set the branches which tie switches installed on them as the boundaries, then, search to form the initial radical configurations, which is started from different initial points. Second, in the different new configurations, search sending and receiving nodes of the branches which tie switches installed on them respectively. If both side nodes of a tie line have been searched, open the tie switch to satisfy the requirement of radial configuration constraint in formula (9).Otherwise, search the initial radial configuration, which connects with the sending node or the receiving node of the tie line, and the decoded data about the branches which are not searched before, to form the final radial network configuration of the string at last.

Step 4.2.4 - Load flow calculation is used for different radial network configurations connected with different power sources. First, according to the set of the branches of the radial network configurations obtained in step 4.2.3, based on the inputted basic data about the distribution systems and the calculated active load power and reactive load power of every node over the fault restoration period, identify the resistance and reactance of every branch and the active load power and reactive load power of every node of the radial network configurations connected with different power sources at this time interval. Secondly, conventional backward/forward sweep algorithm is used to calculate the node voltages and branch currents of each network configuration connected with different power sources. If load flow is not converged for the network configuration connected by any power source during the calculation, stop the entire load flow process.

Step 4.2.5 - Calculate the value of the objective function of the string. If load flow is not converged for any network configuration connected with different power sources in step 4.2.4, assign a large number (e.g. 10^9) as the value of objective function of the string. When the load flow is converged for all of network configurations connected with different power sources, calculate the total value of violation of the string, the formula is showing below:

$$F_{t,pen} = \sum_{i-1}^{K_S} \left(\sum_{k \in \alpha_{t,i}} \frac{U_{\min} - U_{t,k}}{U_B} + \sum_{k \in \beta_{t,i}} \frac{U_{t,k} - U_{\max}}{U_B} + \sum_{b \in \gamma_{t,i}} \frac{I_{t,b}}{I_{b.\max}} \right) \tag{10}$$

where, $F_{t,pen}$ is the value of violation of the service restoration distribution systems at the tth time interval; K_S is the total number of the power sources; $\boldsymbol{\alpha}_{t,i}$、$\boldsymbol{\beta}_{t,i}$ and $\boldsymbol{\gamma}_{t,i}$ are the set of nodes whose voltage violate the minimum acceptable limit, set of nodes whose voltage violates the maximum acceptable limit and the set of branches whose currents violate the ampacity respectively in network connected with the ith power source at the tth time interval. If the value of violation of the string is not zero, assign a large number (e.g. 10^9) as the value of objective function of the string. When the value of violation is zero, calculate the value of objective function of the string according to formula (6).

Step 4.3 - Conduct evolutionary computation of the population by adopting conventional genetic algorithm. First, define the current population as the parent population, and calculate the fitness value of every string in parent population based on its value of objective function.

Secondly, selection, cross-over and mutation operators are conducted in parent population to produce the offspring population, and use the method in step 4.2 to calculate the value of objective function of every string in the offspring population. Thirdly, replace some strings in the parent population with some new strings in the offspring population. At last, judge whether the evolutionary computation of the population is over. If the generation does not reach the maximum evolution generation, add 1 to the evolution generation, take the new population as the current population, and repeat this step until the evolution generation reaches the maximum evolution generation. Otherwise, evolutionary computation of the population is finished.

Step 4.4 - Identify the set of network configurations with minimum loss of load for each time interval. Select the network configurations with the same minimum loss of load but different string from the results obtained in step 4.3.

2.5. Stage 2 of DSR Method

DSR plan is defined by a set of hourly service restoration plans, with one plan per hour, over the fault restoration period. The set of candidate network configurations for the DSR is formed by sets of network configurations obtained in the stage 1 with minimum loss of load at each time interval. Based on the number of the candidate service restoration network configurations of each hour over the fault restoration period and the fault duration hours, the combinations of the dynamic restoration plans will be constructed. Then the number of switching operations for all DSR plans will be calculated. The first combination with minimum number of switching operations is the optimal DSR plan based on (11).

$$\min \quad f_2(\boldsymbol{X}) = \sum_{t \in T_r} \left(\sum_{m \in M} \left| S_{t,m} - S_{t-1,m} \right| \right) \tag{11}$$

2.6. The Service Restoration Process of Distribution Systems

In this part of the paper the process mentioned previously is elaborated through a simple two-feeder distribution system shown in Fig. 2. It contains feeders F_1, F_2; tie line T; circuit breakers B_1, B_2; sectionalizing switches S_0, S_1 and tie switch S_T; loads L_0~L_3. In normal operational situation, circuit breakers B_1, B_2 and sectionalizing switches S_0, S_1 are all closed, while the tie switch S_T is open. The feeders F_1 and F_2 are divided into 4 segments Z_0~Z_3, which do not contain any switches, by the sectionalizing switches and the tie switch. Feeder F_1 provides service to load L_0 and L_1, while the service to load L_2 and L_3 is provided by Feeder F_2.

Faulty zone is defined by a set of branches which takes the point of the fault as the center, and takes the switches closest to the point of the fault as the boundary.

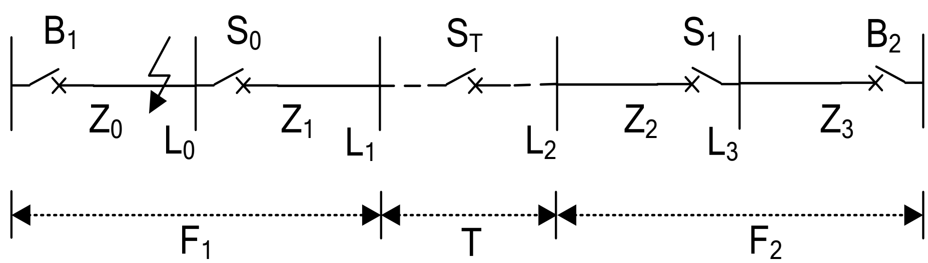


Figure 2 A simple two-feeder distribution system

When a permanent fault occurs in segment Z_0 in Fig. 2, the circuit breaker B_1 is tripped, the segment Z_0 is identified as the faulty zone by fault location technologies and the sectionalizing switch S_0 is opened to provide fault isolation. Meanwhile, the service to the loads L_0 and L_1 is interrupted. The service to the load L_1 can be restored by closing the tie switch S_T. However, the success to restore the service to load L_1 by feeder F_2 depends on whether the security constraints can be satisfied after closing the tie switch S_T.

In our study a day is divided into 24 hours, and each hour is a time interval. During 24 time intervals of a day, the available ampacity of feeder F_2 and load current of load L_1 are shown in Fig. 3 in per unit.

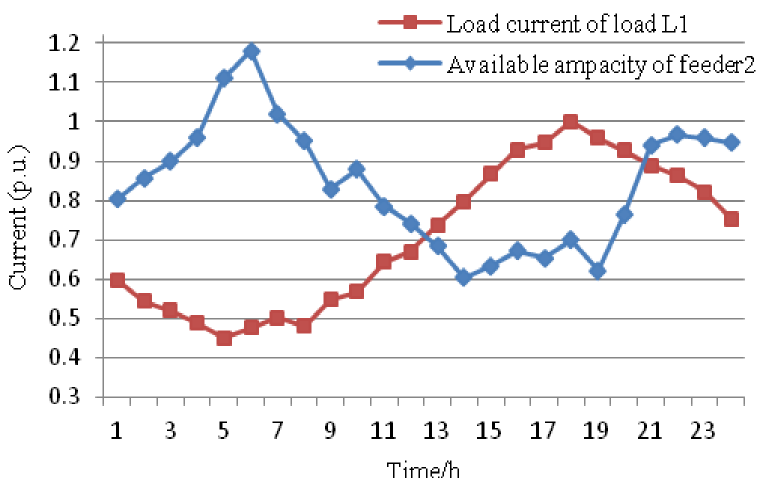


Figure 3 Load current of L_1 and available ampacity of feeder F_2 in each time interval

If the maximum load is used as a constant load model in service restoration plan, service to some unaffected outage loads may be hindered due to limited ampacity of the supporting feeder. On the other hand, considering a realistic variable load profile, if the available ampacity of the supporting feeder exceeds the load current, during the fault restoration period, the tie switch can be closed to restore the service, otherwise the tie switch cannot operate. Following explains several cases illustrated studying the feeder shown in figure1.

Case1: A permanent fault occurs in segment Z_0 at the 20th time interval, repairing the fault needs 4 time intervals, and the fault is cleared at the 24th time interval. As shown in Fig. 3, the available ampacity of feeder F_2 is less than the load current of load L_1 at the 20th time interval, thus the tie switch S_T cannot close over the whole fault restoration period when using the method proposed. But the available ampacity of feeder F_2 exceeds the load current of load L_1 during 3 time intervals from the 21th time interval to the 23th time interval. If the tie switch S_T is closed to restore the service to load L_1 at the 21th time interval, no branches will be overloading and the service to the unaffected outage area is restored in time, and the outage duration of customers in load L_1 will be shortened from 4 hours to 1 hour in this way.

Case 2: it is assumed that a permanent fault occurs in segment Z_0 at the 8th time interval, and repairing the fault needs 6 time intervals. Therefore, fault will be cleared at the 14th time interval. As shown in Fig. 3, the available ampacity of the feeder F_2 is less than the load current of load L_1 at the 13th time interval failing to satisfy the requirement that available ampacity of feeder F_2 always exceeds the load current of load L_1 over the fault restoration period, and thus the tie switch S_T is cannot close to restore the service over the fault restoration period. However, available ampacity of feeder F_2 exceeds the load current of load L_1 from the 8th time interval to the 12th time interval. Therefore, if the tie switch S_T is closed at the 8th time interval and the tie switch S_T is opened at the 13th time interval, service to the load L_1 can be restored in time, and the outage duration is shortened from 6 hours to 1 hour. Meanwhile, after utilities use the tech. they can tell the customers because a new tech. is applied, power can be restored periods before systems are fixed thoroughly and the power may be cut again before the planning restored time, so that the utility can inform the customers of the outage information in advance, reducing the cost of some the customers brought by the sudden black out thereby.

To enhance the restoration methodology the proposed DSR will operate based on load curves.

CHAPTER 3

CASE STUDIES

3.1. Introduction to Chapter 3

An 11-kV distribution system [25] shown in Fig. 4 is studied. This distribution system contains 2 substation buses, 4 feeders, 70 nodes and 72 branches. The ampacity of each branch is calculated in [31]. Resistance and reactance data that are used in this case are reported in Appendix Table VI. Residential, commercial and industrial load curves are shown in Fig. 5. Data of the load curves are given in Appendix Table VII in details. Data for genetic algorithm is: size of the population is 100; maximum evolution generation is 300; generation gap is 0.95; rate of cross-over is 0.9 and mutation probability is 0.01.

Assumptions in the computation are listed below:

- All sectionalizing switches are closed and all tie switches are open in normal operational situation.
- Regardless of the level of load.
- Malfunction and rejecting operation of switches are not taken into consideration.
- Only a single fault is considered in the distribution system.
- U_{max}=1.1*p.u.* and U_{min}=0.9*p.u.*

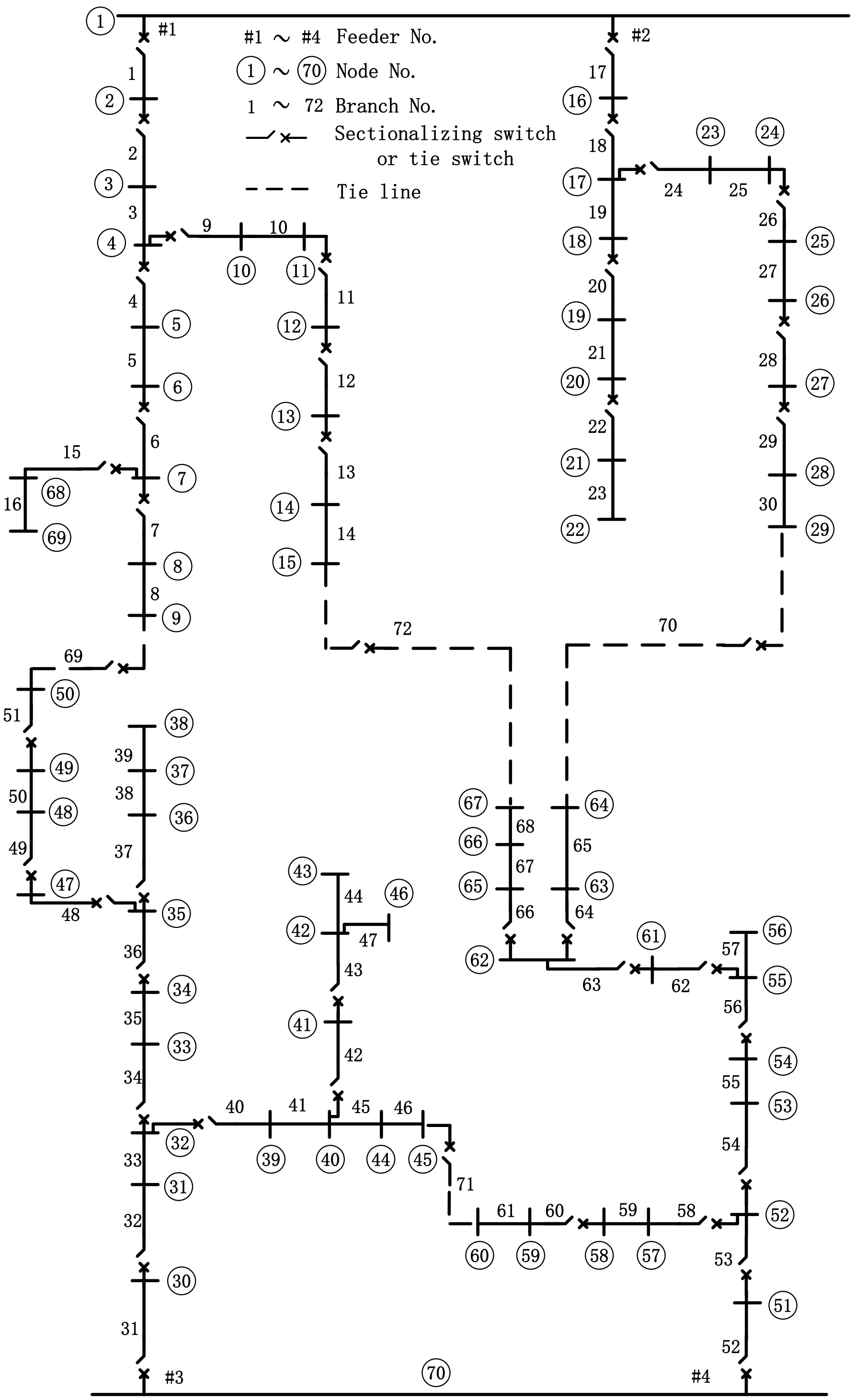


Figure 4 70-node distribution system

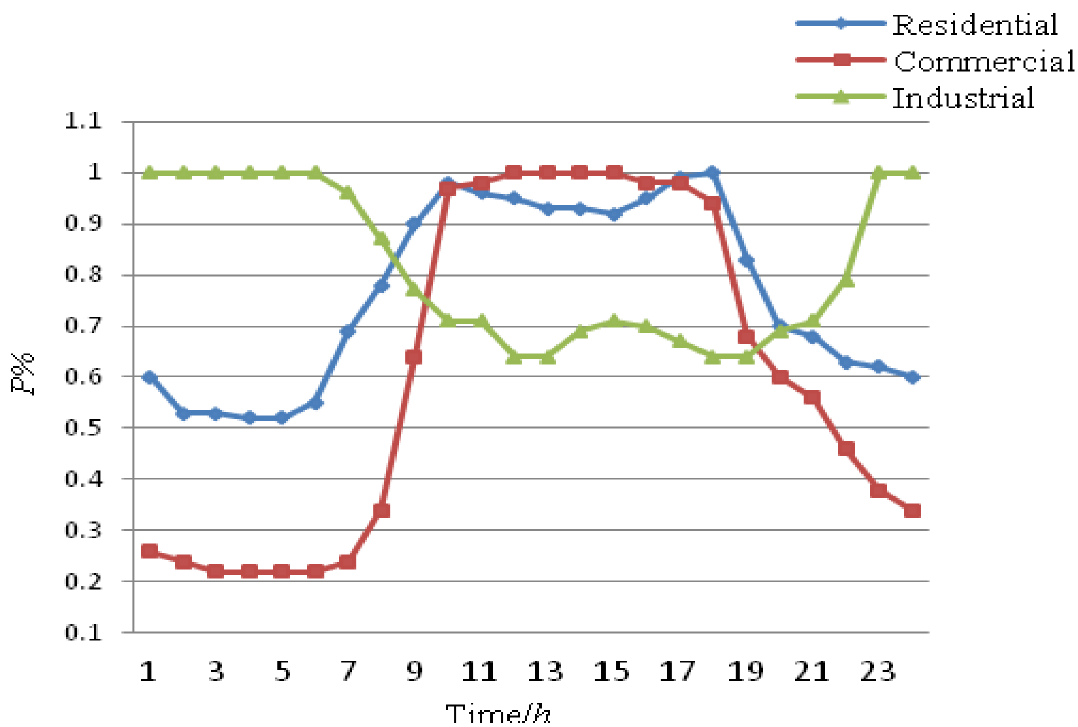


Figure 5 Residential, commercial, industrial hourly load curves

3.2. The Fault Occurs on the Branch 55

1) Case 1

The occurrence of the fault on branch 55 will cause outages for load points 53~56 and 61~67. Among them, the service to the load points 53 and 54 will not be restored until the fault has been cleared, and the service to the rest of the unaffected outage load points can be restored by feeder 1 and feeder 2 over the fault restoration period.

As for the case 1, 9 times of switching operations are needed totally in the optimal DSR plan obtained by using the proposed method. During the 18th~21th time intervals, all statuses of switches are the same in each time interval except for the sectionalizing switches on the branches 62~64 changing their statuses with the time. Different from the normal operational situation, the sectionalizing switches on branches 54, 56, 66 are changed to be closed and the tie switches installed on branches 70, 72 are changed to be open. As shown in Fig. 4, open the sectionalizing switches on branches 54 and 56 to isolate the fault. Open the sectionalizing switch on branch 66 so as to avoid the loop during the service restoration. Close tie switch on branch 72 to restore the service to load points 65~67 by feeder 1. Close the tie switch on branch70 to restore the service to the load points 55~56 and 61~64 by feeder 2. But whether feeder 2 has the ability to restore the service to these load points depends on the influence of load variation on the statuses of switches installed on branches 62~64.

Table 1

Status of switches on branch 62~64 and supplied load points in outage area of optimal DSR plan on case 1

Plan implementation time	18th time interval	19th time interval	20th time interval	21th time interval
Statuses of switches on branch 62~64	{1， 1， 0}	{1， 0， 1}	{0， 1， 1}	{1， 1， 1}
Branches of switches to be opened	56,64,66	56,63,66	56,62,66	56,66
Branches of switches to be closed	62,63,70, 72	62,64,70, 72	63,64,70, 72	62,63,64, 70,72
Supplied load points in outage area	63,64,65, 66,67	62,63,64, 65,66,67	61,62,63, 64,65,66, 67	55,56,61, 62,63,64, 65,66,67

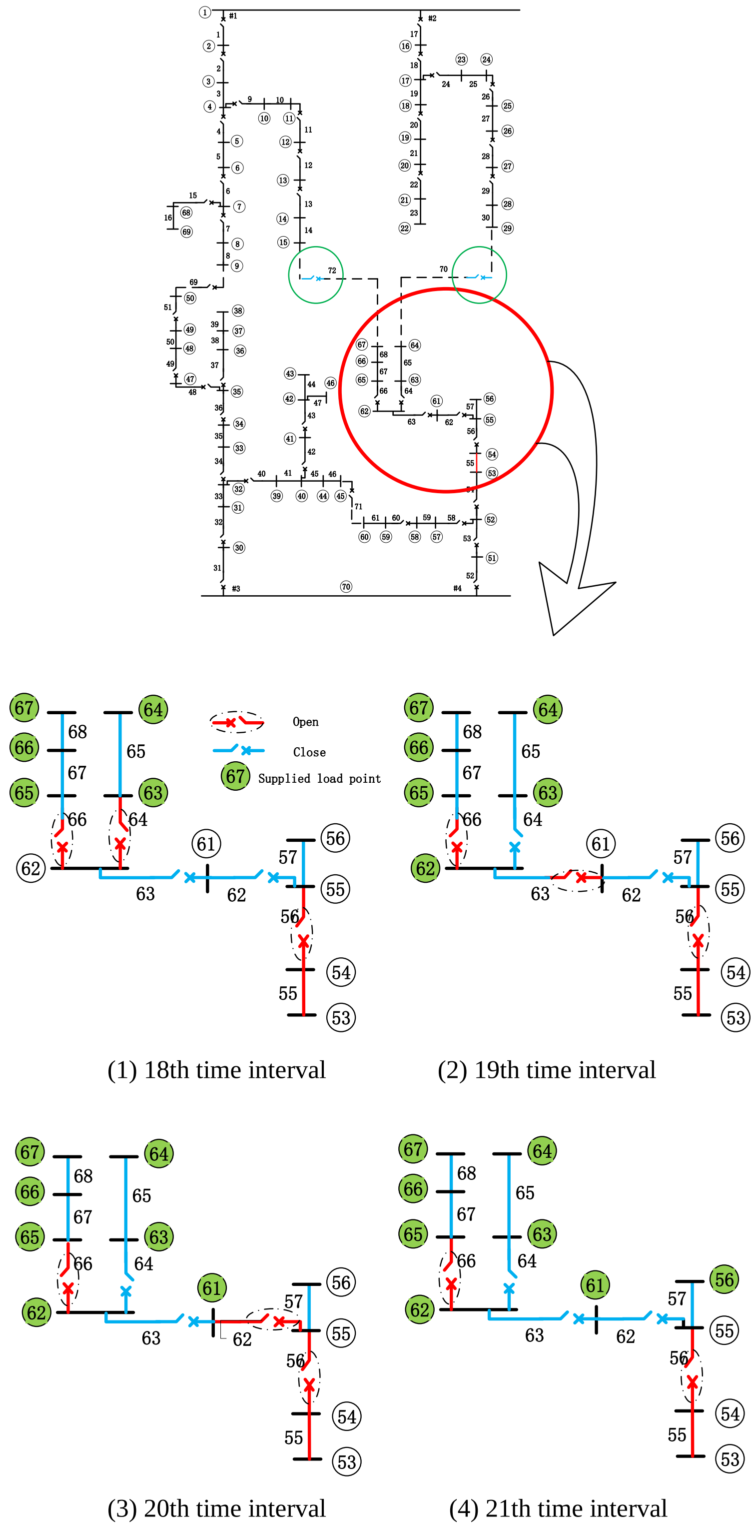


Figure 6 Status of switches on case 1

Table I and Fig. 6 give changing process of statuses of sectionalizing switches on branches 62~64 and the supplied load points in outage area of the optimal DSR plan in case 1. As shown in Fig. 4, service to the outage load points 55~56 and 61~64 may be restored by feeder 2 through closing the tie switch on branch 70 over the fault restoration period. As shown in Table I, feeder 2 has the ability to restore the service to the load points 63 and 64 by opening the sectionalizing switch on branch 64 at 18th time interval. Service to the load point 62 can be further restored by closing the sectionalizing switch on branch 64 and opening the sectionalizing switch on branch 63 at 19th time interval. Service to the outage load point 61 can be restored in the next step by closing sectionalizing switches on branches 63 and 64 and opening the sectionalizing switch on branch 62 at 20th time interval. Closing the sectionalizing switches on branches 62~64 at 21th time interval, the service to the load points 55 and 56 can also be restored.

It can be seen that, the service to the load points 62, 61, 55 and 56 can be restored progressively step by step through tie line 70 by adopting the DSR plan. This is because during the fault restoration period, residential and commercial loads are quite heavy at the 18th time interval as illustrated in Fig. 5, and they are decreasing with time passing by. This may cause the increase in the available ampacity of feeder 2, while the demanding for the feeder 2 by load points 62, 61, 55, 56 is also decreasing. With the loads decreasing, feeder 2 can restore the entire outage loads step by step though it cannot restore the service to all of these outage loads at 18th time interval.

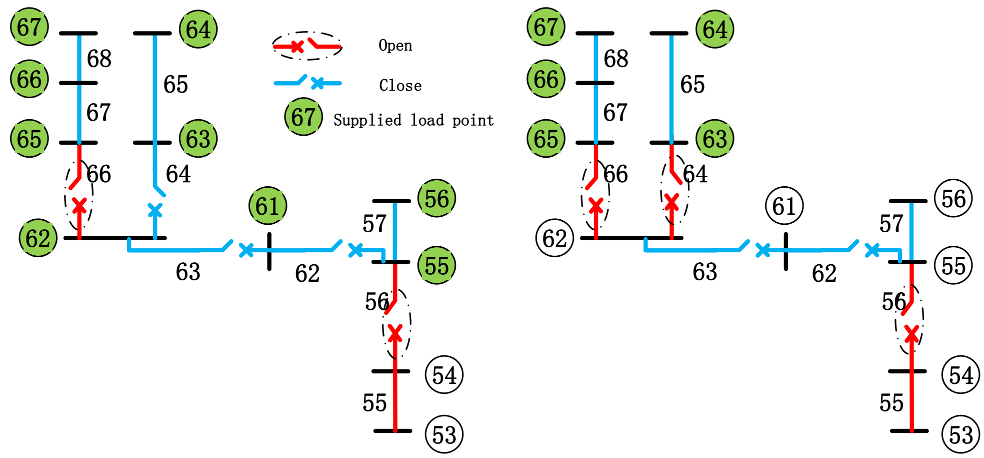
2) Case 2

As for Case 2, 4 times of switching operations are needed totally in the optimal DSR plan obtained by using the proposed method in this paper. The statuses of all sectionalizing switches and tie switches are the same with case 1 except for the switches on branches 62~64. During the fault restoration period of case 2, the sectionalizing switches on branches 62 and 63 are always closed, and the network configuration at the 7th time interval is the same with the configuration at the 8th time interval, and sectionalizing switch on branch 64 is closed. The network configuration at the 9th time interval is the same with the configuration at the 10th time interval, and the sectionalizing switch on branch 64 is open. The changing process of the status of the switch on branch 64 and the supplied load points in outage area in the optimal DSR plan are given in Table II and Fig.6 of case 2.

Table 2

Status of switch on branch 64 and supplied load points in outage area of optimal DSR plan on case 2

Plan implementation time	7th and 8th time interval	9th and 10th time interval
Branches of switches to be opened	56,66	56,64,66
Branches of switches to be closed	64,70,72	70,72
Supplied load points in outage area	55,56,61,62, 63,64,65,66, 67	63,64,65, 66,67



(1) 7~8th time interval (2) 9~10th time interval

Figure 7 Status of switches on case 2

As shown in Fig. 5, residential and commercial loads are quite light at the 7th time interval and they are increasing with the time afterwards. As shown in Fig. 4, after the occurrence of fault on branch 55 at 7th time interval, feeder 1 can restore the service to the load points 65~67 by closing the tie switch on branch 72 and open the sectionalizing switch on branch 66. Feeder 2 with a larger available ampacity at the 7th and 8th time intervals can restore the service to the load points 55~56 and 61~64, so the service to these load points is restored by the feeder 2 in Table II. With the time passing by, the residential and the commercial loads are increasing gradually, which makes the available ampacity of feeder 2 decrease gradually, resulting in that only loads points 63 and 64 can be restored by feeder 2 at the 9th and 10th time interval. In order to avoid overloading in feeder 2, the sectionalizing switch on branch 64 must be opened to interrupt the service to load points 55~56 and 61~62. Because the sectionalizing switch on branch 64 to be opened at the 9th time interval can be forecasted based on the load curves, which will result in the service interruption of load points 55~56 and 61~62, the utility can inform these customers of the outage information so as to reduce the cost caused by the sudden black out.

When using the method in [24] to make the service restoration plan, the obtained service restoration network configuration can only restore the service to load points 63~67 over the whole fault restoration period to satisfy the requirement of avoiding overloading in any branches over the whole fault restoration period. Load points 55~56 and 61~62 will be in outage status from the 7th time interval to the 10th time interval.

It can be seen that, adoption of the DSR plan not only restore the service to the unaffected outage customers as much as possible, but also inform the customers of the information about any upcoming outages in time before overloading occurs. Therefore, any unnecessary cost associated with sudden loss of electricity will be eliminated.

Table III and Table IV give the comparison between the proposed method and method in [24] about the outage duration and restored electrical quantity over the fault restoration period respectively. As illustrated in Table III, outage duration of load

Table 3

Outage duration of unaffected loads in two cases (h)

Node number	Case1		Case2	
	Proposed method	Method In [24]	Proposed method	Method in [24]
62	1	4	2	4
61	2	4	2	4
55	3	4	2	4
56	3	4	2	4

Table 4

Restored electrical quantities over the fault restoration period by two methods (kw·h)

Case 1		Case 2	
Proposed method	Method in [24]	Proposed method	Method in [24]
2137.8	1234.3	1378.9	972.4

points 62,61, 55 and 56 can be shortened from 4 hours to 1hour, 2hours, and 3 hours respectively in case 1. In case 2, outage duration of load points 55~56 and 61~62 are all shortened from 4 hours to 2 hours. As illustrated in Table IV, more electrical quantity can be restored by the proposed method compared with the method in [24] in both cases, representing that the loss of electrical quantity of the customers is reduced while increasing the energy sales of the utility by the proposed method in this paper.

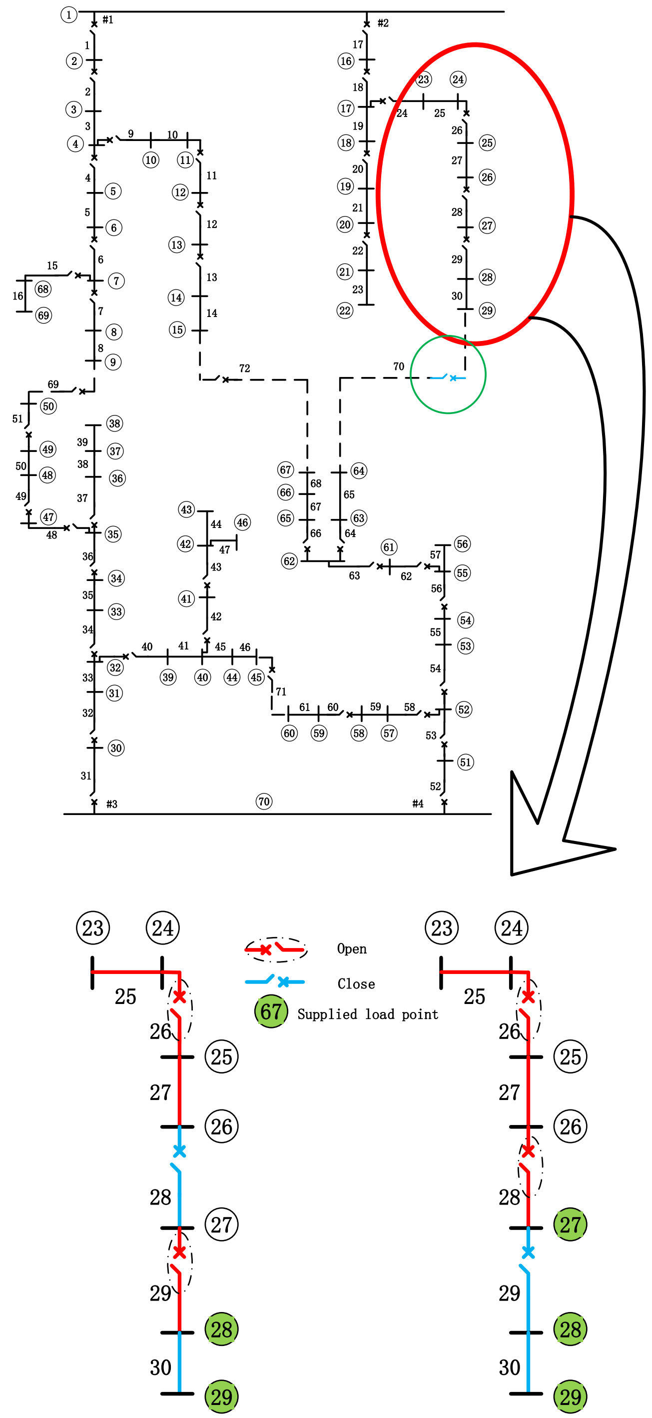
3.3. The Fault Occurs on Branch 25

The methodology in this paper considers the feeder voltage constraints during service restoration plan, while using a predictive load flow to judge whether the final service restoration plan can satisfy the requirement of the voltage after obtaining the final service restoration plan. The mentioned considerations have not been addressed in similar literature. If a fault occurs on branch 25 at the 18th time interval and is cleared at the 21th time interval. As shown in Fig. 8, service to load points 25~29 will be interrupted. If using a constant load a final plan of closing the tie switch on branch 70 to restore the load points 25~29 by feeder 4 is obtained because the load currents of points 25~29 will not cause any overloading in feeder 4. But using the load flow to validate the obtained plan and test the system security requirements, voltage at node 25 will be calculated below the minimum acceptable voltage at the 18th time interval, therefore, this plan is an ineffective plan, and load points 25~29 will be in outage for 3 hours. On the other hand utilizing the optimal DSR plan by adopting method proposed in this paper is showing satisfactory results. These results are tabulated in Table V. As shown in Table V, the service to load points 28 and 29 can be restored by closing the tie switch on branch 70 and opening the sectionalizing switch on branch 29 at 18th time interval. At the 19th and 20th time intervals, service to load point 27 will be restored further by closing tie switch on branch 70 and the sectionalizing switch on branch 29 and opening the sectionalizing switch on branch 28.

Table 5

Optimal DSR plan when the fault occurs on branch 25

Plan implementation time	18th time interval	19th and 20th time interval
Branches of switches to be opened	29	28
Branches of switches to be closed	70	70, 29
Supplied load points in outage area	29, 28	29, 28, 27



(1)18th time interval (2) 19th&20th time interval

Figure 8 Status of switches when the fault occurs on branch 25

The obtained final optimal DSR plan will be an effective plan due to not violating any operational and security conditions.

CHAPTER 4

CONCLUSIONS

The project addresses some of the shortcomings of the existing load models used in service restoration of the distribution systems. A DSR of distribution system method, which is based on the load curves, is proposed in this paper. Taking the load variation into consideration, the proposed method can identify the optimal service restoration network configurations based on the load of each hour over the fault restoration period. The obtained optimal DSR plan can take full advantage of the load curves to timely change the configuration to satisfy the need of the load variation, restoring the service to the outage loads. The case studies indicate that, compared to the existing methodologies, the temporal and spatial proposed method not only gives a secure plan to restore more loads, but also further shorten the outage duration of several customers and avoid the unnecessary cost due to sudden blackouts.

Appendix

Data, which are used in case studies, about the branches and loads of the distribution system is given in Table VI. In the column “type of customers”, “R” represents residential, “C” represents commercial while “I” represents industrial. Data about residential, commercial and industrial hourly load curves are given in Table VII.

Table 6
Data about branches and loads used in the distribution system in case studies

branch number (i)	sending node IS (i)	receiving node IR (i)	Resistance of branch (Ω)	Reactance of branch (Ω)	Active power load (IR) (kW)	Reactive power load (IR) (kVar)	Type of customers
1	1	2	0.4388	0.4296	423	332	R
2	2	3	0.4388	0.4296	310	168	R
3	3	4	0.5852	0.5728	658	300	R
4	4	5	0.2924	0.2864	318	184	R
5	5	6	0.1464	0.1432	64	33	R
6	6	7	0.7312	0.7160	375	152	R
7	7	8	0.4388	0.4296	55	37	R
8	8	9	0.2924	0.2864	68	41	R
9	4	10	0.2924	0.2864	85	37	R
10	10	11	0.4320	0.2936	68	33	R
11	11	12	0.6480	0.4404	212	148	R
12	12	13	0.4320	0.2936	215	102	R
13	13	14	0.5400	0.3668	106	55	R
14	14	15	0.3240	0.2200	169	92	R
15	7	68	0.7776	0.5284	423	221	R
16	68	69	0.4320	0.2936	169	111	R
17	1	16	0.6480	0.4404	300	200	R
18	16	17	0.4388	0.4296	392	190	R
19	17	18	0.1464	0.1432	56	35	R
20	18	19	0.5852	0.5728	48	28	R
21	19	20	0.3656	0.3580	200	80	R
22	20	21	0.3216	0.3148	334	197	R
23	21	22	0.4532	0.4440	186	118	R
24	17	23	0.1900	0.1860	190	127	R
25	23	24	0.8856	0.6020	275	220	R
26	24	25	0.6480	0.4440	267	226	R
27	25	26	0.4320	0.2936	372	236	R
28	26	27	0.2160	0.1468	372	216	R
29	27	28	0.2160	0.1468	446	276	R
30	28	29	0.4320	0.2936	180	80	R
31	70	30	0.4320	0.2936	187	123	I
32	30	31	0.1464	0.1432	140	99	I
33	31	32	0.2924	0.2864	30	20	I

34	32	33	0.2924	0.2864	37	22	I
35	33	34	0.3216	0.3148	117	74	I
36	34	35	0.4680	0.4580	94	69	I
37	35	36	0.3072	0.3008	140	99	I
38	36	37	0.2924	0.2864	94	74	I
39	37	38	0.4388	0.4296	70	62	I
40	32	39	0.5852	0.5728	351	246	I
41	39	40	0.4320	0.2936	140	86	I
42	40	41	0.2160	0.1468	281	172	I
43	41	42	0.4320	0.2936	211	148	I
44	42	43	0.7344	0.4992	42	25	I
45	40	44	0.5184	0.3524	37	25	I
46	44	45	0.4752	0.3228	234	123	I
47	42	46	0.2160	0.1468	140	99	I
48	35	47	0.4320	0.2936	211	172	I
49	47	48	0.2160	0.1468	199	135	I
50	48	49	0.4320	0.2936	234	172	I
51	49	50	0.4320	0.2936	328	222	I
52	70	51	0.4320	0.2936	155	94	C
53	51	52	0.1464	0.1432	52	26	C
54	52	53	0.5852	0.5728	103	70	C
55	53	54	0.5852	0.5728	93	56	C
56	54	55	0.3656	0.3580	177	147	C
57	55	56	0.4388	0.4296	111	70	C
58	52	57	0.4388	0.4296	206	117	C
59	57	58	0.1080	0.0732	619	282	C
60	58	59	0.1080	0.0732	323	258	C
61	59	60	0.3240	0.2200	65	23	C
62	55	61	0.5184	0.3524	26	12	C
63	61	62	0.4752	0.3228	387	305	C
64	62	63	0.4752	0.3228	129	70	C
65	63	64	0.3240	0.2200	50	20	C
66	62	65	0.6480	0.4404	80	60	C
67	65	66	0.4320	0.2936	120	80	C
68	66	67	0.2160	0.1468	65	35	C
69	9	50	0.4320	0.2936	-	-	-
70	29	64	0.3632	0.2904	-	-	-
71	45	60	0.1016	0.0812	-	-	-
72	67	15	0.1816	0.1452	-	-	-

Table 7
Residential, commercial, industrial load curves data

Time interval	P/P_{max}(%)		
	Residential	Commercial	Industrial
1	0.6	0.26	1
2	0.53	0.24	1
3	0.53	0.22	1
4	0.52	0.22	1
5	0.52	0.22	1
6	0.55	0.22	1
7	0.69	0.24	0.96
8	0.78	0.34	0.87
9	0.9	0.64	0.77
10	0.98	0.97	0.71
11	0.96	0.98	0.71
12	0.95	1	0.64
13	0.93	1	0.64
14	0.93	1	0.69
15	0.92	1	0.71
16	0.95	0.98	0.7
17	0.99	0.98	0.67
18	1	0.94	0.64
19	0.83	0.68	0.64
20	0.7	0.6	0.69
21	0.68	0.56	0.71
22	0.63	0.46	0.79
23	0.62	0.38	1
24	0.6	0.34	1

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