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Preference Ranking for Restoration Plans in Distribution System via Grey Relational Analysis

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Abstract – The blackout in a power system could cause huge direct and indirect financial losses. How to plan an optimal restoration plan when a fault occurs on a power system is an import issue in modern power system operations. In this paper, the grey relational analysis approach is proposed to develop a decision-making system for choosing a restoration plan to power distribution systems. To demonstrate the effectiveness of the proposed method, a typical Taiwan Power Company's (Taipower) distribution system is examined. The tested results show that the approach can provide valuable information to operators for planning a restoration procedure.

Keywords: Power distribution system, Grey relational analysis, Service restoration

Introduction

When a fault occurs on a distribution system, the system operators need to isolate the faulted area and to restore the load in the out-of-service area through network reconfiguration without violating operation constraints. This problem is referred to as the distribution system service restoration. To restore the electricity service, the operators tend to use their past experience and heuristic rules to reach a restoration plan. In general, the practical guidelines for a restoration plan including minimal number of switching operations, minimal loads in out-of-service areas, no overloaded elements, etc. When power systems become larger and complicated, finding a suitable restoration plan becomes more and more difficult, particularly for new operators. Therefore, the development of an effective and fast method to assist operators in getting a satisfied restoration plan is needed.

In past years, a lot of researchers were devoted to the service restoration problem of power distribution systems [1-6]. In the light of previous developments, the methods to restoration problems can be roughly classified into several types: heuristic algorithms, mathematical programming, knowledge-based systems, and soft computing. However, all of these methods merely provide a solution, rather than make further quantitative analysis in the preference ranking of each restoration plan.

The grey relational analysis is an important approach of grey system theory in the application of evaluating a set of alternatives in terms of decision criteria and is successfully applied to many fields [7-9]. Most of the researchers know that the choice of restoration plans is a type of multi-criteria decision-making problem. Nevertheless, we can not find the grey relational analysis is used to solve the restoration problem in the published literature. The primary goal of this paper is trying to construct a measurement model, via the grey relational analysis, to provide useful information and help system operators to make a right decision on the problem of service restoration. In this paper, the feasibility of the developed algorithm for service restoration is demonstrated on a typical distribution network with promising results.

Problem Description

A practical example is used in this section to demonstrate the nature of the service restoration problem. Fig.1 shows a typical distribution system of Taiwan Power Company (TPC) [3]. From Fig.1, the feeder YD28 supplies power to nine laterals LAT1, LAT2, LAT3, LAT4, LAT5, LAT6, LAT7, LAT8, and LAT9. Each lateral has its supporting lateral (LAT10, LAT11, LAT12, LAT13, LAT14, LAT15, LAT16, and LAT17) from other feeders. For example, lateral LAT1 is connected with lateral LAT10 via a normally-opened switch SW1. It is also noted that feeder YD28 is connected with its supporting feeder YE29 through a normally-opened tie switch SW9.

When a fault occurs at point A of feeder YD28, as shown in Fig.1, the corresponding circuit breaker will trip and the switch SW10 will open to isolate the fault. Hence, the nine laterals, LAT1~LAT9, are out-of-service. Assume that the fault has been identified and isolated by opening the switch SW10. Under the circumstances, all laterals connected to YD28 are out-of-service. How to restore the electricity power of the out-of-service region outside the faulted zone by switching the supporting feeders and/or laterals is the major concern and is a real challenge in the restoration process.

In general, the solution for restoration planning is possibly not unique. There are numerous solutions to the restoration problem in most situations. It is the major concern in our works to pick out and to rank each feasible restoration plan that meets operation constraints. At Taiwan Power Company, the restoration plan must satisfy the following criteria.

1) To reach the restoration plan in a short time to avoid customers' inconvenience and enhance service reliability.
2) The out-of-service load within the unfaulted area should be restored as much as possible.
3) Fewer number of switching operations in the restoration plan is expected.
4) It is expected that the configuration of the distribution system after restoration is close to the original system.
5) Radial type of distribution systems need to be retained.
6) The equipment overload is not allowed.

Obviously, some of these criteria conflict each other, thus, tradeoff will be considered. Therefore, the work of the restoration problem can be regarded as a multiple criteria decision-making problem subject to operation constraints. Among various restoration plans, we try to develop a quantitative approach to evaluate these plans by using the proposed grey relational approach based on the following conditions.

A. Objectives

1) Minimize the number of switching operations, $f_1(X)$

$$f_1(X) = \sum_{i=1}^{N_{sw}} x_i \tag{1}$$

where $f_1(X)$ denotes the number of switching operations under the switch state vector X, $X = [x_1, x_2, \ldots, x_{N\text{sw}}]$, and N_{sw} represents the total number of switches in the considered system and x_i is the status of switch i, which can be described as follows.

$$x_i = \begin{cases} 1, & \text{if the status of the switch } (\text{SW}i) \text{ is changed} \\ 0, & \text{otherwise.} \end{cases}$$

It is desirable that the number of switching operations is minimized so that the chance of a switching surge and the operation cost can be reduced.

2) Minimize the loading of supported feeders, $f_2(X)$

$$f_2(X) = \underset{i}{\mathrm{Max}}\ \{\mathrm{I}_{FDi}\},\quad i = 1,2,\ldots, N_{FD} \tag{2}$$

where $f_2(X)$ is the maximum loading among supported feeders and I_{FDi} denotes the load current of the supported feeder ***FDi*** after switching. N_{FD} represents the total number of supported feeders. Hence the minimization of $f_2(X)$ is desirable.

3) Minimize the loading of supported laterals, $f_3(X)$

$$f_3(X) = \underset{i}{\mathrm{Max}}\ \{\mathrm{I}_{LATi}\},\quad i = 1,2,\ldots, N_{LAT} \tag{3}$$

where $f_3(X)$ is the maximum loading among supported laterals and I_{LATi} denotes the load current of the supported lateral ***LATi*** after switching. N_{LAT} represents the total number of supported laterals. The minimization of $f_3(X)$ is desirable.

B. Constraints

1) No components are overloaded
2) Radial system structure is kept

Prior to considering the fault, we assume that the rated capacities for each feeder and each lateral are 450A and 100A, respectively.

Table 1 gives the pre-fault load currents of laterals LAT1 to LAT17. Table 2 lists the related pre-fault feeder currents. All units in the tables are Ampere. Figure 1 illustrate a typical distribution system of TPC.

Table 1. The pre-fault lateral currents

LAT1	LAT2	LAT3	LAT4	LAT5	LAT6	LAT7	LAT8	LAT9
25	45	62	47	65	67	60	55	20
LAT10	LAT11	LAT12	LAT13	LAT14	LAT15	LAT16	LAT17	
51	39	24	37	34	31	60	80	

Table 2. The pre-fault feeder currents

YD28	YD25	YC22	YC27	YE26	YE29
446	240	220	260	256	127

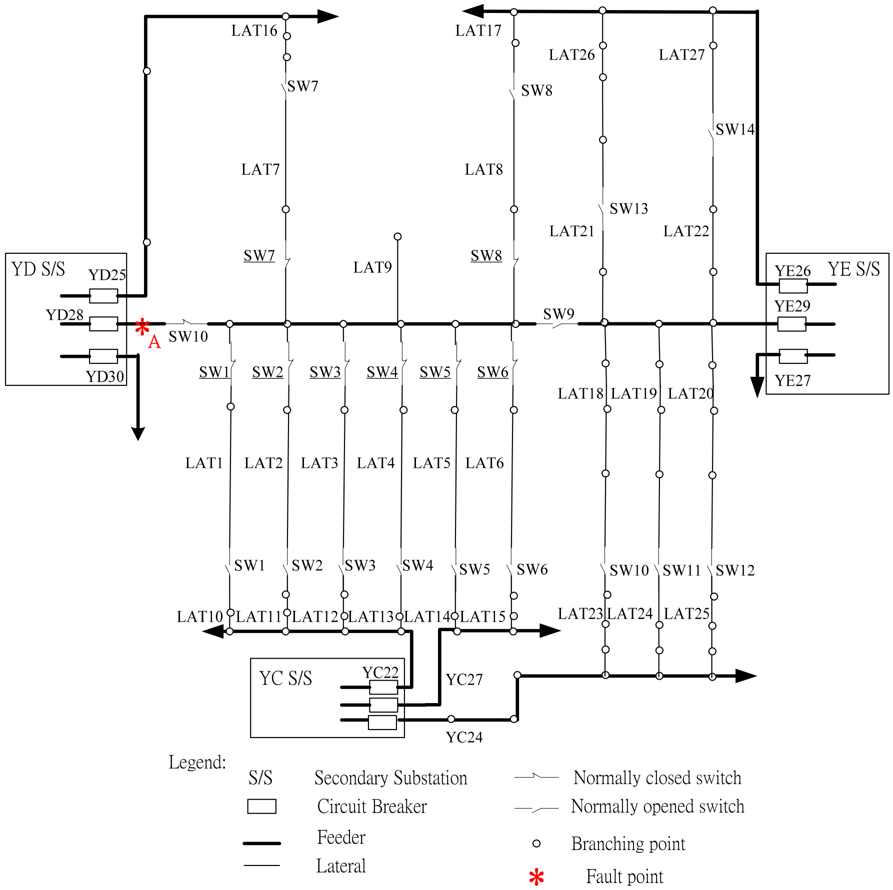

Fig.1. A typical distribution system of TPC

The Grey Relational Analysis Approach

The grey system theory was first proposed by Professor J.L. Deng in 1982 [10-11]. It provides a method that can come to a decision or to solve a predictive problem with a few data. Up to now, the method has been used successfully in many fields, and attracts many researchers to go on studying. The grey relational analysis is an important approach of grey system theory in the application of decision-making. The major power of grey relational analysis is to calculate the correlative degrees of two discrete sequences with a straightforward and simple measurement model. The algorithm of the grey relational analysis is illustrated below:

A sequence is comparable if it satisfies the following three conditions:

1). Dimensionless: Since the quantity of the elements in a sequence with different units cannot be compared, the sequence needs to be normalized and transferred into dimensionless type, if necessary.

2). Scaling: The elements of a sequence should be kept in the same scaling or order for comparison.

3). Polarization: The state of a factor within sequences should be kept in the same direction.

1). To calculate the grey relational grade, the grey relational coefficient, $g(x_i(k), x_j(k))$, at point k between two discrete sequences x_i and x_j will be introduced.

Let

$$\Delta_{\min} = \min_{\forall i, \forall j} \min_{\forall k} \left| x_i(k) - x_j(k) \right| \tag{4}$$

$$\Delta_{\max} = \max_{\forall i, \forall j} \max_{\forall k} \left| x_i(k) - x_j(k) \right| \tag{5}$$

The grey relational coefficient can be defined as follows:

$$g(x_i(k), x_j(k)) = \frac{\Delta_{\min} + x\Delta_{\max}}{\Delta_{ij}(k) + x\Delta_{\max}} \tag{6}$$

where x is the so-called distinguishing coefficient, and the grey relational grade, Γ_{ij}, can be derived from

$$\Gamma_{ij} = \sum_{k=1}^{m} b_k g(x_i(k), x_j(k)) \tag{7}$$

The weighting factor b_k must satisfy $\sum_{k=1}^{m} b_k = 1$.

In general, we usually calculate the grey relational grade in equal weighting fashion, that is,

$$b_k = \frac{1}{m}, \quad k = 1,2,3,\mathbf{L}, m. \tag{8}$$

Note that the determination of the distinguishing coefficient x will directly affect the value of the grey relational coefficient g.

The grey relational grade can be derived from

$$\Gamma_{ij} = \frac{\Delta_{\max} + \Delta_{\min}}{\Delta'_{ij} + \Delta_{\max}} \tag{9}$$

where Δ'_{ij} is the difference information in difference space.

If we describe each restoration plan with their objective functions and regard them as the comparative sequences, we can use the grey relational measure to find the similarity between each comparative sequence and the reference sequence formed by the selected ideal objective function. Therefore, the value of grey relational grade represents the preference degree for each restoration plan.

Case Study

The example described in previous section will be used to demonstrate the feasibility of using grey relational analysis. Since the rated capacities for a lateral is 100A, LAT7, and LAT8 cannot connect to the supporting laterals (LAT16 and LAT17) in this fault case. Table 3 shows the switching operations and the corresponding lateral and feeder currents. The cells in Table 3 with " * " mean that the corresponding line currents remain unchanged. To keep radial system structure for fitting the constraint, the normally-closed switch SW***i*** (*i*=1,2,…,8) at the head of lateral LAT*i* must be opened when the corresponding normally-opened lateral tie switch SW*i* is closed to restore the power at lateral LAT*i* by its supporting lateral. For example, in restoration plan 4, the switches for operation are SW9, (SW1, SW1), (SW2, SW2), and (SW3, SW3), denoted by "9,1,2,3" for short, and the number of switch operations is 7.

In Table 3, owing to the limitation of a feeder capacity is 450 A, the feeder YE29 is overloaded in restoration plan 1 to restoration plan 3. Therefore, restoration plan 4 to restoration plan 10 are chosen to be candidate restoration plans. We rearrange and list these data in Table 4. Obviously, from Table 4, the minimal number of switching operations is 5, and the minimum of the line currents for LAT10 to LAT15, YE29, YC22, and YC27 would be 51, 39, 24, 37, 34, 31, 419, 220, and 260, respectively. Therefore, the ideal sequence or reference sequence, x_0, (in this case, the minimum is better) is chosen as

$$x_0 = (5, 51, 39, 24, 37, 34, 31, 419, 220, 260)$$

Hence, we can derive the grey relational grade from Equ. (9).

To generate the comparable sequences that possess the properties of dimensionless, scaling, and polarization, the data pre-processing is needed. After building up the grey relational analysis steps, we can calculate the values of Δ_{max}, and Δ_{min} are equal to 1 and 0, respectively. Table 5 shows the results of the grey relational grades after finishing the analysis. From Table 5, it is shown that the third candidate plan (the largest value in Γ_{0j}) gives the best choice of the study. That is, the plan by switching SW9, (SW3, SW3), (SW6, SW6) is selected.

Table 3. Load currents on supporting lines after restoration

Restoration plan	Switches	LAT 10	LAT 11	LAT 12	LAT 13	LAT 14	LAT 15	YE 29	YC 22	YC 27
1	9	*	*	*	*	*	*	573	*	*
2	9,1	76	*	*	*	*	*	548	245	*
3	9,1,2	76	84	*	*	*	*	503	290	*
4	9,1,2,3	76	84	86	*	*	*	441	352	*
5	9,5,6	*	*	*	*	99	98	441	*	392
6	9,3,6	*	*	86	*	*	98	444	282	327
7	9,1,2,5	76	84	*	*	99	*	438	290	325
8	9,1,2,6	76	84	*	*	*	98	436	290	327
9	9,2,3,4	*	84	86	84	*	*	419	374	*
10	9,1,3,4	76	*	86	84	*	*	439	354	*

Table 4. The candidate service restoration plans

Candidate Plan	Number of switch	LAT 10	LAT 11	LAT 12	LAT 13	LAT 14	LAT 15	YE 29	YC 22	YC 27
1	7	76	84	86	37	34	31	441	352	260
2	5	51	39	24	37	99	98	441	220	392
3	5	51	39	86	37	34	98	444	282	327
4	7	76	84	24	37	99	31	438	290	325
5	7	76	84	24	37	34	98	436	290	327
6	7	51	84	86	84	34	31	419	374	260
7	7	76	39	86	84	34	31	439	354	260

Table 5. Grey relational grades

Candidate Plan	Δ'_{0j}	Γ_{0j}
1	0.234715	0.8099038
2	0.194278	0.8373259
3	**0.184925**	**0.8439354**
4	0.224203	0.8168581
5	0.22196	0.8183571
6	0.223607	0.817256
7	0.232317	0.8114794

In this work, the algorithm has been implemented in C++ language on the Pentium-Ⅲ 1GHz PC. Since the computation procedure of the proposed system is simple and easy to implement, it took less than one second to analyze and get the preference ranking of feasible restoration plans.

Conclusions

In this paper, the grey relational analysis to obtain the most preferable restoration plan for distribution system service restoration is proposed. Using the proposed method, the system operators can easily make a right decision. Since it is easy to evaluate the alternatives by some simple numerical operations, the proposed method is feasible and is observed promising.

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