Fault Line Selection Method for Distribution Network Based on Angle Similarity

Guang Feng¹, Ming Chen¹, Guojie Xiang², Kun Yu²* and Xiangjun Zeng²

¹State Grid Henan Electric Power Company Electric Power Research Institute, Henan, China
²Changsha University of Science and Technology, Hunan, China

*kunyu0707@163.com

Abstract. Aiming at the problem that the current distribution network protection technology has a low accuracy of line selection, the method of fault line selection based on angle similarity is proposed. A plurality of fault feature quantities of each feeder in different operating states are collected to form a historical database. The clustering centers of fault classes and non-fault classes are obtained by fuzzy clustering analysis. Similarly, the real-time data of each feeder is collected to form a sample of the feature to be tested. The degree of similarity between the feature samples to be tested and the historical feature samples is analyzed by angle similarity. The sample to be tested is classified into a fault class or a non-fault class, and finally the fault feeder is accurately selected.

1. Introduction

Current small current grounding methods are commonly used in distribution networks at home and abroad[1]. When the single-phase ground fault occurs on the line, the ground fault current value is small[2], which makes it difficult to accurately detect the fault characteristic parameters. In addition, due to the influence of harmonic interference of the load, external environmental interference on the site, and defects in the fault line selection scheme, the existing fault line selection scheme is not ideal in actual operation. Therefore, the problem of single-phase ground fault line selection in small current grounding systems has always been a key issue in the power industry research[3].

The current distribution network selection scheme can be divided into three categories. The first type is a protection scheme based on the steady-state fault feature quantity. After the single-phase ground fault occurs, the fault line is selected according to the difference between the steady-state zero-sequence current of the faulty feeder and the steady-state zero-sequence current of the non-faulty feeder. The main methods include residual flow increment method[4], negative sequence current method and so on[5]. The second category is based on the transient fault feature quantity protection scheme[6-8]. Compared with the protection method based on the steady-state fault feature quantity, this method has more obvious fault information in the effective frequency band, which can effectively improve the correct rate of fault judgment[9]. However, since such methods generally require mathematical methods such as wavelet packet decomposition[10] to extract fault feature information in a specific frequency band, fault feature information is easily lost in this process. The third type is a ground fault line selection method based on injected signals. A characteristic signal is input into the
distribution network, and the flow of the input signal in the line is detected in real time to realize fault line selection.

The above traditional fault protection methods are mostly based on a single fault feature quantity, which greatly reduces the accuracy of fault line selection. In order to improve the accuracy of fault detection, the paper uses fuzzy clustering algorithm to comprehensively process fault feature quantities. A variety of protection schemes are effectively integrated, and complementary advantages between the schemes are realized. After the fault occurs, the fault state of each feeder is judged by the angle similarity. Finally, the fault is accurately selected.

2. Principle of fault line selection for distribution network based on angle similarity

Aiming at the fact that the current line selection technology only makes a judgment based on a single fault quantity, resulting in a lower accuracy of line selection, a fault line selection method based on angle similarity is proposed.

First, data collection and processing is required. The s kinds of fault feature quantities of the protected feeders in n operating states are collected by the existing line measuring equipment. They are defined as n historical feature samples. The kth sample is:

\[ x_k = (x_{k1}, x_{k2}, \ldots, x_{ks})^T \] (1)

In the formula: \( k \) is an integer, the value interval is \([1, n]\), \( x_{k1}, \ldots, x_{ks} \) are the specific values of the \( s \) fault feature quantities extracted under the \( k \)th operating condition.

Standardization of each fault sample can be obtained:

\[ x_{kj} = \frac{x_{kj} - \frac{1}{n} \sum_{k=1}^{n} x_{kj}}{\sqrt{\frac{1}{n-1} \sum_{k=1}^{n} (x_{kj} - \frac{1}{n} \sum_{k=1}^{n} x_{kj})^2}} \] (2)

The value interval of \( j \) is \([1, s]\). After standardization, the \( k \)th sample \( x_k = (x_{k1}, x_{k2}, \ldots, x_{ks})^T \). In the same way, the real-time feature sample \( x_g = (x_{g1}, \ldots, x_{gs})^T \) of the protected feeder in the real-time operating state of the distribution network can be obtained. \( x_{g1}, \ldots, x_{gs} \) are specific values of \( s \) fault feature quantities extracted in real time by the protected feeder.

Fuzzy clustering analysis was performed on the standardized samples \( x_1, \ldots, x_n \). The samples are divided into fault classes and non-fault classes to find faulty and non-fault cluster centers. Let the objective function be:

\[ J = \sum_{i=1}^{n} \sum_{j=1}^{2} (\mu_{ik})^2 \|x_k - c_i\|^2 \] (3)

In the formula: the value of \( i \) is 1 or 2. \( c_1 \) is the fault clustering center. \( c_2 \) is a non-fault clustering center. \( \mu_{ik} \) indicates that the cluster sample \( x_k \) is subordinate to the membership degree of the \( i \)th cluster type, and satisfies the condition \( \sum_{k=1}^{n} \mu_{ik} = 1 \).

The cluster center and membership degree can be obtained by extremum:

\[ c_i = \frac{\sum_{k=1}^{n} (\mu_{ik})^2 \cdot x_k}{\sum_{k=1}^{n} (\mu_{ik})^2} \] (4)

\[ \mu_{ik} = \frac{1}{\sum_{j=1}^{2} (1/\|x_k - p_j\|^2)} \] (5)
The initial value of the cluster center \( c_i \) can be assumed. Through the mutual iteration of \( \mu_{ik} \) and \( c_i \), the fault and non-fault clustering centers can be obtained when the membership degree is less than an iteration stop threshold.

When the electrical parameters of the power distribution system change, in order to judge whether the protected feeder is faulty, it is necessary to calculate the similarity between the sample \( x_g \) to be tested and each cluster center. The angle similarity measure criterion was proposed by the paper. This criterion is to judge the fault state based on the cosine of the angle between the two sample phasors.

The cosine of the angle between the sample \( x_g \) to be tested and the \( i \)th cluster center \( c_i \) is:

\[
\cos \theta_{g1} = \frac{\sum_{b=1}^{n} x_{gb} c_{ib}}{\sqrt{\sum_{b=1}^{n} x_{gb}^2 \sum_{b=1}^{n} c_{ib}^2}}
\]

In the formula: \( \cos \theta_{g1} \) represents the angle cosine of the sample \( x_g \) to be tested and the center of the fault class. \( \cos \theta_{g2} \) represents the angle cosine of the sample \( x_g \) to be tested and the center of the non-faulty class.

Define the fault measure as:

\[
\delta_{g1} = \frac{\cos \theta_{g1} + 1}{\cos \theta_{g1} + \cos \theta_{g2} + 2}
\]

The non-fault measure is:

\[
\delta_{g2} = \frac{\cos \theta_{g2} + 1}{\cos \theta_{g1} + \cos \theta_{g2} + 2}
\]

If \( \delta_{g1} < \delta_{g2} \), it means that the real-time feature sample data belongs to the non-faulty class, and the protected feeder does not fail. If \( \delta_{g1} > \delta_{g2} \), the protected feeder fails. When the distribution network fails, the sample to be tested extracted from each line can calculate the angle similarity with each cluster center. By synthesizing the fault information of each feeder, the accurate line selection of the distribution network fault can be realized, and the reliability of the system power supply can be improved.

3. Distribution network fault line selection scheme

Based on the above principle, the implementation scheme of the fault line selection protection method for distribution network is proposed as shown in figure 1. The fault feeder determination steps are as follows:

1) Extracting historical feature samples \( X_k^f \) in various operating states. \( X_k^f \) is standardized to obtain the \( x_k \).

2) Classification of historical samples by fuzzy clustering algorithm to obtain cluster center \( c_i \).

3) The zero sequence voltage value of the distribution network is monitored in real time. Once the system zero sequence voltage exceeds the preset threshold \( U_{set}=10\%E_\phi \), the line selection scheme is initiated immediately. \( E_\phi \) is the system phase voltage value.

4) The real-time data in the protected feeder is collected, and the \( s \) fault feature quantities are extracted to form a real-time feature sample \( X_g^f \).

5) The sample \( X_g^f \) to be tested is standardized to obtain \( x_g \). The angle similarity between the sample to be tested and the fault clustering center and the non-fault clustering center is calculated separately. And find \( \delta_{g1}, \delta_{g2} \).

6) If \( \delta_{g1} > \delta_{g2} \), the protected feeder fails. The real-time feature samples are grouped into the historical sample set and returned to Step 3. If \( \delta_{g1} < \delta_{g2} \), the protected feeder does not malfunction. The real-time feature samples are grouped into the historical sample set and returned to step 3.
If the above judgment is made for each feeder, the faulty feeder can be selected to complete the feeder protection scheme.

4. Simulation
The 35kV distribution network model was built in the PSCAD simulation environment. The system consists of three overhead lines and one cable line. The specific parameters of the line are listed in table 1. The fault state is analyzed by taking the feeder 4 as an example. A measuring element is placed at the beginning of the line. The fault feature quantity is extracted from the collected fault information. The fault characteristic quantity is sequentially the phase difference $x_{k1}$ measured by the zero sequence admittance grounding relay, the negative sequence current $x_{k2}$, the zero sequence current $x_{k3}$ and the ground fault resistance $x_{k4}$.

| Feeder | Length/km | Per relative capacitance/μF | Phase capacitance/μF | Damping rate | Load/KVA | Power factor |
|--------|-----------|-----------------------------|----------------------|--------------|----------|-------------|
| 1      | 30        | 0.15                        | 0.038                | 4%           | 2000     | 0.8         |
| 2      | 100       | 0.50                        | 0.125                | 4%           | 10000    | 0.8         |
| 3      | 30        | 1.80                        | 0.720                | 3%           | 2000     | 0.8         |
| 4      | 20        | 0.10                        | 0.025                | 4%           | 1000     | 0.8         |

Sixteen system fault states were simulated based on the above-mentioned distribution network parameter settings. Eight of them are data when the feeder 4 fails. The remaining 8 groups are the data for other feeder failures. The fault feature quantities are extracted separately, and the data is listed in table 2. The fault clustering center and the non-fault clustering center can be calculated according to formula (4), and the calculation results are shown in table 3.
Table 2. System history feature sample set.

| Fault type | Historical feature sample | Fault feature quantity |
|------------|---------------------------|------------------------|
|            | $x'_1$/(°)                | $x'_{k2}$/A             | $x'_{k3}$/A             | $x'_{k4}$/Ω             |
| External fault |                             |                        |                        |                        |
| $x'_1$     | 65                        | 0.878                  | 0.682                  | 69173                  |
| $x'_2$     | 66                        | 0.601                  | 0.735                  | 74327                  |
| $x'_3$     | 66                        | 0.583                  | 0.637                  | 74524                  |
| $x'_4$     | 68                        | 0.448                  | 0.694                  | 92530                  |
| $x'_5$     | 68                        | 0.442                  | 0.611                  | 93103                  |
| $x'_6$     | 68                        | 0.276                  | 0.474                  | 33167                  |
| $x'_7$     | 68                        | 0.285                  | 0.420                  | 33752                  |
| $x'_8$     | 70                        | 0.147                  | 0.327                  | 40697                  |
| Internal fault |                             |                        |                        |                        |
| $x'_9$     | 165                       | 15.77                  | 14.54                  | 4.3                    |
| $x'_{10}$  | 163                       | 11.25                  | 10.69                  | 98.4                   |
| $x'_{11}$  | 163                       | 10.55                  | 9.67                   | 113.1                  |
| $x'_{12}$  | 161                       | 8.87                   | 6.35                   | 976.3                  |
| $x'_{13}$  | 160                       | 8.34                   | 8.01                   | 1034.2                 |
| $x'_{14}$  | 159                       | 4.76                   | 4.52                   | 4982.6                 |
| $x'_{15}$  | 158                       | 4.72                   | 3.96                   | 5212.4                 |
| $x'_{16}$  | 157                       | 2.93                   | 2.43                   | 9854.6                 |

Table 3. Cluster center coordinates of historical data.

| Cluster center | Coordinate value |
|---------------|------------------|
| $c_1$         | -0.879           |
|               | -0.796           |
|               | -0.758           |
|               | 0.804            |
| $c_2$         | 0.966            |
|               | 0.917            |
|               | 0.903            |
|               | -0.870           |

Table 4. Fault data of real-time feature samples.

| Fault type | Sample | Fault feature quantity |
|------------|--------|------------------------|
|            | $x'_{k1}$/(°) | $x'_{k2}$/A | $x'_{k3}$/A | $x'_{k4}$/Ω |
| External fault |                   |            |            |            |
| $Y_1$      | 58                  | 0.992      | 1.735      | 44858      |
| $Y_2$      | 77                  | 0.433      | 0.835      | 51356      |
| Internal fault |                   |            |            |            |
| $Y_3$      | 288                 | 4.31       | 3.78       | 4863       |
| $Y_4$      | 276                 | 0.94       | 1.45       | 13057      |

Table 5. Feeder 4 fault judgment.

| Sample | $\delta_{g1}$ | $\delta_{g2}$ | Protection judgment result |
|--------|---------------|---------------|---------------------------|
| $Y_1$  | 0.398         | 0.602         | $\delta_{g1} < \delta_{g2}$ | No failure |
| $Y_2$  | 0.430         | 0.570         | $\delta_{g1} < \delta_{g2}$ | No failure |
| $Y_3$  | 0.701         | 0.299         | $\delta_{g1} > \delta_{g2}$ | Failure    |
| $Y_4$  | 0.598         | 0.402         | $\delta_{g1} > \delta_{g2}$ | Failure    |

Four kinds of system fault states are simulated, and the fault feature quantities are listed in table 4. The fault measure is calculated according to the angle similarity formula, and the protection judgment result of the feeder 4 is shown in table 5. It can be seen that when the feeder 4 fails, the fault measure is greater than the non-fault measure, and the feeder 4 can be accurately judged to be faulty. When other feeders fail, the fault measure is less than the non-fault measure, then it is judged that the feeder 4 has not failed. The results in table 5 are consistent with the failure hypotheses in table 4, which verifies the feasibility of the proposed line protection method. Other feeders can still be judged.
According to this method, and finally the faulty feeder can be accurately judged, providing necessary reference for subsequent correct fault handling.

5 Conclusion
A fault line selection method for small current grounding systems was proposed. The degree of similarity between the feature samples to be tested and the historical feature samples are analyzed by the angle similarity, and the samples to be tested are classified into fault classes or non-fault classes. The PSCAD simulation proves that the line selection method can accurately identify the fault samples and realize fault line selection. And draw the following conclusions:
1) This method breaks through the bottleneck of the traditional protection method that needs to compare the electrical parameters with the protection setting values to judge the operating state of the system. It is not necessary to set the protection setting value.
2) The fault feature quantities in the various fault line selection methods are combined and used as protection evaluation indicators. In the case that the line selection process is disturbed, the solution can still accurately perform line selection protection.

Acknowledgement
This work was supported in part by National Natural Science Foundation of China 51737002 and China Electric Power Research Institute of State Grid Henan Electric Power Company Science and Technology Project SGHADK00PJJS1800394 "Research on fault diagnosis and self-organizing control of high permeability distributed generation distribution networks".

References
[1] Xue Yongduan, Li Juan and Xu Bingyin. Transient equivalent circuit and transient analysis of single-phase earth fault in arc suppression coil grounded system[J]. Proceedings of the CSEE, 2015, 35(22): 5703-14.
[2] Xue Yongduan, Guo Liwei and Zhang Linli. Selection problems of neutral grounding mode in active distribution networks[J]. Automation of Electric Power Systems, 2015,39(13): 129-136.
[3] Xue Yongduan, Li Juan and Chen Xiaoru. Faulty feeder selection and transition resistance identification of high impedance fault in a resonant grounding system using transient signals[J]. Proceedings of the CSEE, 2017,37(17): 5037-48, 5223.
[4] Zeng Xiangjun, Wang Yuanyuann and Li Jian. Novel principle of faults are extinguishing & feeder protection based on flexible grounding control for distribution networks[J]. Proceedings of the CSEE, 2012, 32(16): 137-143.
[5] Zhao Jianwen, Li Ke and Sui Xiaona. New fault line selection method of multilevel fuzzy data fusion[J]. Proceedings of the CSU-EPSA, 2016, 28(2): 56-60.
[6] DENG Feng, ZENG Xiangjun and Pan Lanlan. Research on multi-terminal traveling wave fault location method in complicated networks based on cloud computing platform[J]. Protection and Control of Modern Power Systems, 2017, 2(2): 199-210.
[7] Xu Yan, Liu Jingyan and Fu Yuan. Fault-line selection and fault-type recognition in DC systems based on graph theory[J]. Protection and Control of Modern Power Systems, 2018, 3(3): 267-276.
[8] Pan Benren, Song Huamao and Zhang Qiuqiang. Reactive power analysis and novel faulty selection method in resonant grounding system[J]. Power System Protection and Control, 2017, 45(14): 51-56.
[9] Qiu Jin, Tian Ye and Li Guanhua. Study on transient line selection of small current grounding fault based on field recorded waveform[J]. Power System Protection and Control, 2019, 47(6): 180-187.
[10] Zhang Shuqing, Ma Yue and Li Pan. Application of improved generalized harmonic wavelet packet decomposition and chaos oscillator to fault line detection in small current grounding system[J]. Transactions of China Electrotechnical Society, 2015, 30(3): 13-20, 43.