A new discrimination of stator single-phase grounding fault based on multi-dimensional fusion for Powerformer

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Abstract. Some existing fusion discriminations are used to identify whether a stator single-phase grounding fault occurs in parallel Powerformers. However, such methods are complicated to operate and require a large amount of training data as support. Therefore, a new discrimination of stator single-phase grounding fault based on multi-dimensional fusion for Powerformer is proposed. Firstly, the faulty Manhattan distance and the sound Manhattan distance about each Powerformer are calculated by the fusion formula of Manhattan distance base on the four features extracted in Powerformer. Then, the sizes of the faulty and sound Manhattan distances about each Powerformer are compared. If the faulty Manhattan distance of the Powerformer is less than the sound Manhattan distance, the Powerformer can be judged as the fault, otherwise, it can be judged as the sound Powerformer. The simulation experiment show that this method does not need a large number of data as support, nor does need to set the threshold value artificially, so it improves the practicability and applicability of the method.

1. Introduction
Powerformer which uses high voltage cable to wind the stator winding can obtain high voltage output without matching with the booster transformer, and has been applied in many fields. The stator single-phase grounding fault is the most common fault in the Powerformer. In order to strengthen the protection of the Powerformer, many scholars have developed the detection method of stator single-phase grounding fault for Powerformer. However, some of them focus on discrimination of single Powerformer, so its can’t be applied to judge the faulty Powerformer in parallel Powerformers. For example, when the stator single phase-to-grounding fault occurs in parallel Powerformers, the methods based on third-harmonic voltage [1-2] and zero sequence voltage [3-4] cannot judge the faulty Powerformer because third-harmonic voltage and zero sequence voltage about each Powerformer are the same. The method based on zero-sequence current [5] can judge the faulty Powerformer in parallel Powerformers, but it is greatly disturbed by noise. In the other part, the methods based on intelligent fusion algorithm [6-7] to integrated leakage current with zero-sequence current for parallel Powerformers are complicated to operate and require a large amount of training data as support.

Aiming at the above deficiencies, a new discrimination of stator single-phase grounding fault based on multi-dimensional fusion for Powerformer is proposed in the paper. This discrimination integrates four fault characteristics, which include the amplitude and phase angle of fundamental leakage current, the amplitude and phase angle of fundamental zero-sequence current in Powerformer terminal. In the
discrimination process, there cannot need to collect a large amount of data as support, and there is no need to set a threshold value, which improves the practicability of the discrimination.

2. Feature selection and data processing

It is known through Literature [8] that the amplitudes and phase angles of fundamental leakage current for sound Powerformers are the same when the stator single phase-to-grounding fault occurs in parallel Powerformers, but the phase difference between the fundamental leakage current of the faulty Powerformer and any sound Powerformer is 180 degrees, what’s more, the amplitude of fundamental leakage current for the faulty Powerformer is greater than the sum of all sound Powerformers. The characteristic of fundamental zero-sequence current in Powerformer terminal is consistent with the leakage current. Therefore, this paper will extract the information of four fault feature which include the amplitude and phase angle of fundamental leakage current, the amplitude and phase angle of fundamental zero-sequence current in Powerformer terminal by FFT algorithm, which will be used as the original fault feature quantities of this discrimination.

In order to make the faulty boundaries about the four feature quantities more datable, the four feature quantities need to be processed with data. The amplitude coefficient and phase angle coefficient of fundamental leakage current, the amplitude coefficient and phase angle coefficient of fundamental zero-sequence current in Powerformer terminal are obtained by data processing, and the specific formulas are as follows:

$$XP_i = \frac{I_{0pl} - \min\{I_{0pl}, \cdots, I_{0pl}\}}{\max\{I_{0pl}, \cdots, I_{0pl}\} - \min\{I_{0pl}, \cdots, I_{0pl}\}}$$  \hspace{1cm} (1)$$

$$LP_i = \frac{I_{p1} - \min\{I_{p1}, \cdots, I_{p1}\}}{\max\{I_{p1}, \cdots, I_{p1}\} - \min\{I_{p1}, \cdots, I_{p1}\}}$$  \hspace{1cm} (2)$$

$$X\theta_i = \frac{\sum_{j=1}^{l} (I_{0j} - I_{0g})}{\pi(l-1)}$$  \hspace{1cm} (3)$$

$$L\theta_i = \frac{\sum_{j=1}^{l} (I_{j} - I_{g})}{\pi(l-1)}$$  \hspace{1cm} (4)$$

Where, $XP_i$ is the amplitude coefficient of fundamental leakage current about Powerformer $i$, $LP_i$ is the amplitude coefficient of fundamental zero-sequence current in Powerformer $i$ terminal, $X\theta_i$ is the phase angle coefficient of fundamental leakage current about Powerformer $i$, and $L\theta_i$ is the phase angle coefficient of fundamental zero-sequence current in Powerformer $i$ terminal. $I_{0pl}$ is the amplitude of fundamental leakage current about Powerformer $i$, $I_{p1}$ is the amplitude of fundamental zero-sequence current in Powerformer $i$ terminal, $I_{0j}$ is the phase angle of fundamental leakage current about Powerformer $i$, $I_{j}$ is the phase angle of fundamental zero-sequence current in Powerformer $i$ terminal, and $l$ is the total number of Powerformers in the system.

According to the formulas, it is known that the amplitude coefficients of fundamental leakage current and zero-sequence current in Powerformer terminal range from 0 to 1, where the amplitude coefficient of the faulty Powerformer is close to 1, and the amplitude coefficients of the sound Powerformer are close to 0. It is also known that the phase angle coefficients of fundamental leakage current and zero-sequence current in Powerformer terminal range from -1 to $\frac{1}{l-1}$, where the phase angle coefficient of the faulty Powerformer is close to -1, and the phase angle coefficients of the sound Powerformer are close to $\frac{1}{l-1}$. 


3. Principle of criterion

The above four feature quantities after data processing can be used as four-dimensional coordinates, where the amplitude coefficients of fundamental leakage current and zero-sequence current in Powerformer terminal are the x, y, z, and w coordinates respectively. So it can be known that the coordinate point of the faulty Powerformer is close to \((1, 1, -1, -1)\), and the coordinate point of the any sound Powerformer is close to \((0, 0, 1, -1, 1)\). If the coordinate point \((1, 1, -1, -1)\) and the coordinate point \((0, 0, 1, -1, 1)\) can be as the faulty class center and the sound class center respectively, so the distance between the coordinate point of the faulty Powerformer and the faulty class center is far less than the distance between the former and the sound class center, then the distance between the coordinate point of the any sound Powerformer and the sound class center is far less than the distance between the former and the faulty class center. In this case, the distance between the coordinate point and each center point can be described through the Manhattan distance [9-10], and the specific formulas are as follows:

\[
D_{if} = |XP_i - 1| + |LP_i - 1| + |X\theta_i + 1| + |L\theta_i + 1| \quad (5)
\]

\[
D_{is} = |XP_i| + |LP_i| + |X\theta_i - \frac{1}{l-1}| + |L\theta_i - \frac{1}{l-1}| \quad (6)
\]

Where, \(D_{if}\) is the Manhattan distance between the coordinate point of the Powerformer \(i\) and the faulty class center, referred to as the faulty Manhattan distance for the Powerformer \(i\). \(D_{is}\) is the Manhattan distance between the coordinate point of the Powerformer \(i\) and the sound class center, referred to as the sound Manhattan distance for the Powerformer \(i\).

![Figure 1. The specific process about discrimination.](image-url)
According to the above equations, the faulty Manhattan distances and the sound Manhattan distances for all Powerformers can be calculated when a stator single-phase grounding fault occurs in parallel Powerformers. Then it can be determined that the Powerformer $i$ is faulty if $D_{if} < D_{is}$, otherwise it is sound. The specific process about discrimination is shown in Figure 1.

4. Simulation experiment and analysis
In this paper, EMTP simulation software is used to build the simulation model about stator single-phase grounding fault with three parallel Powerformers, and it is shown in Figure 2 below, which the parameters of specific model in the system are shown in Table 1.

| The subsidiary about parameters | Powerformer 1 | Powerformer 2 | Powerformer 3 |
|---------------------------------|---------------|---------------|---------------|
| The rated frequency/Hz          | 50            | 50            | 50            |
| The rated capacity/MVA          | 75            | 75            | 75            |
| The rated output voltage/kV     | 150           | 150           | 150           |
| Winding capacitances to ground A phase/µF | 0.560 | 0.560 | 0.560 |
| Winding capacitances to ground B phase/µF | 0.577 | 0.577 | 0.577 |
| Winding capacitances to ground C phase/µF | 0.560 | 0.560 | 0.560 |

At present, it is simulated that a stator single-phase grounding fault occurs at 25% in phase C of Powerformer 3 when neutral is unearthed (fault resistance= 1000Ω). The leakage currents and zero-sequence currents in Powerformer terminal for all Powerformers can be extracted. In order to analyze the adaptability of this method to harsh environment, 20db white gaussian noise is added to analyze. The fundamental leakage currents and fundamental zero-sequence currents in Powerformer terminal can be extracted by FFT algorithm, and the fundamental leakage currents are only shown in Figure 3 because of Space limitation.
The fundamental leakage current when the fault occurs at 25% in phase C of Powerformer 3 with unearthed neutral considering 20db white gaussian noise (Fault resistance = 1000 Ω).

It is seen that the phase difference between the fundamental leakage current of the faulty Powerformer 3 and any sound Powerformers is 180 degrees by Figure 3, and the characteristic of fundamental zero-sequence current in Powerformer terminal is also consistent with the leakage current. Its faulty Manhattan distances for all powerformers are [0.84, 0.84, 4.83], and sound Manhattan distances are [4.92, 4.92, 0.17] by calculation respectively, so this method can judge that Powerformer 3 is faulty and it is less affected by noise.

To further validate its adaptability, simulation experiments of various failure conditions are implemented. Because the parameters of specific model in the system about each Powerformer are roughly the same, data from the sound Powerformer 1 is roughly the same as the sound Powerformer 2. In order to space limitation, the sound Powerformer 1 will be shown only in this paper. Then the faulty conditions and the four feature quantities extracted from Powerformer 1 and 3 are shown in Table 2 and Table 3, where α is the degree that the stator winding are shorted, HRG is the abbreviations about High-resistance grounding, and each experiment adds the 20db white gaussian noise.

Table 2. The original four feature quantities for the sound Powerformer 1.

| Connection mode | Fault resistance(Ω) | α | $I_{op1}$(A) | $I_{o1}$(A) | $I_{0p1}$($^\circ$) | $I_{01}$($^\circ$) |
|-----------------|---------------------|---|-------------|-------------|-------------------|-----------------|
| Ungrounded      | 5                   | 0.25 | 3.867     | 1.440       | 202.287           | 22.460         |
| Ungrounded      | 1000                | 0.50 | 2.765     | 0.846       | 257.580           | 77.971         |
| Ungrounded      | 5000                | 0.75 | 0.944     | 0.468       | 275.843           | 94.812         |
| HRG             | 5                   | 0.50 | 7.661     | 25.494      | 201.591           | 95.570         |
| HRG             | 1000                | 0.25 | 1.131     | 1.521       | 218.748           | 112.399        |
| HRG             | 5000                | 1.00 | 0.377     | 1.836       | 220.456           | 114.738        |

Table 3. The original four feature quantities for the faulty Powerformer 3.

| Connection mode | Fault resistance(Ω) | α | $I_{op3}$(A) | $I_{o3}$(A) | $I_{0p3}$($^\circ$) | $I_{03}$($^\circ$) |
|-----------------|---------------------|---|-------------|-------------|-------------------|-----------------|
| Ungrounded      | 5                   | 0.25 | 12.059    | 3.357       | 37.047            | -142.666        |
| Ungrounded      | 1000                | 0.50 | 9.602     | 2.503       | 92.830            | -88.694         |
| Ungrounded      | 5000                | 0.75 | 3.298     | 0.836       | 110.748           | -70.229         |
| HRG             | 5                   | 0.50 | 83.264    | 58.712      | 96.588            | -90.592         |
| HRG             | 1000                | 0.25 | 5.390     | 4.229       | 112.408           | -72.129         |
| HRG             | 5000                | 1.00 | 4.397     | 4.220       | 114.098           | -71.143         |

According to Table 2 and Table 3, the amplitude coefficient and phase angle coefficient of fundamental leakage current, the amplitude coefficient and phase angle coefficient of fundamental zero-sequence current in Powerformer terminal can be obtained by data processing, and the results is shown in Table 4 and Table 5.
Table 4. The four feature quantities after data processing for the sound Powerformer 1.

| Connection mode | Fault resistance(Ω) | α | $X_P$ | $L_P$ | $X_θ$ | $L_θ$ |
|-----------------|---------------------|---|-------|-------|-------|-------|
| Ungrounded      | 5                   | 0.25 | 0 | 0 | 0.459 | 0.459 |
| Ungrounded      | 1000                | 0.50 | 0 | 0 | 0.458 | 0.463 |
| Ungrounded      | 5000                | 0.75 | 0 | 0 | 0.459 | 0.458 |
| HRG             | 5                   | 0.50 | 0 | 0 | 0.292 | 0.517 |
| HRG             | 1000                | 0.25 | 0 | 0 | 0.295 | 0.513 |
| HRG             | 5000                | 1.00 | 0 | 0 | 0.295 | 0.516 |

Table 5. The four feature quantities after data processing for the faulty Powerformer 3.

| Connection mode | Fault resistance(Ω) | α | $X_P$ | $L_P$ | $X_θ$ | $L_θ$ |
|-----------------|---------------------|---|-------|-------|-------|-------|
| Ungrounded      | 5                   | 0.25 | 1 | 1 | -0.918 | -0.917 |
| Ungrounded      | 1000                | 0.50 | 1 | 1 | -0.915 | -0.926 |
| Ungrounded      | 5000                | 0.75 | 1 | 1 | -0.917 | -0.917 |
| HRG             | 5                   | 0.50 | 1 | 1 | -0.583 | -1.034 |
| HRG             | 1000                | 0.25 | 1 | 1 | -0.591 | -1.025 |
| HRG             | 5000                | 1.00 | 1 | 1 | -0.591 | -1.033 |

Based on discrimination flow chart about the stator single-phase grounding fault for Powerformer in Figure 1, the faulty and sound Manhattan distances for Powerformer 1 and Powerformer 3 can be calculated, and the results are shown in Table 6 as follows.

Table 6. The faulty and sound Manhattan distances for Powerformers.

| Connection mode | Fault resistance(Ω) | α | Powerformer 1 | Powerformer 3 |
|-----------------|---------------------|---|---------------|---------------|
|                 |                     |   | $D_{f}$      | $D_{s}$      |
| Ungrounded      | 5                   | 0.25 | 4.918 | 0.082 | 0.165 | 4.835 |
| Ungrounded      | 1000                | 0.50 | 4.921 | 0.079 | 0.159 | 4.841 |
| Ungrounded      | 5000                | 0.75 | 4.917 | 0.083 | 0.166 | 4.834 |
| HRG             | 5                   | 0.50 | 4.809 | 0.225 | 0.451 | 4.618 |
| HRG             | 1000                | 0.25 | 4.808 | 0.217 | 0.434 | 4.616 |
| HRG             | 5000                | 1.00 | 4.812 | 0.221 | 0.442 | 4.624 |

By the results in Table 6, the faulty Manhattan distance for the faulty Powerformer 3 is close to 0, and the sound Manhattan distance is close to 5, normally, the former is less than the later. However, the character for sound Powerformer 1 is on the contrary. So it is known that the stator single-phase grounding fault occurs in Powerformer 3 according to Figure 1. Therefore, this discrimination can identify the faulty Powerformer in parallel Powerformers for ungrounded system and high-resistance grounding system. It does not need to set the threshold value artificially, also enhances the faulty boundary to a certain extent, and it is less affected by noise, so it is applicable to a wider range.

5. Conclusions

In this paper, a new discrimination of stator single-phase grounding fault based on multi-dimensional fusion for Powerformer is proposed. The discrimination that fuses four feature quantities through the Manhattan distance can identify the faulty Powerformer in parallel Powerformers by comparing the sizes of the faulty and the sound Manhattan distances about each Powerformer for ungrounded system and high-resistance grounding system. If the faulty Manhattan distance is less than the sound
Manhattan distance for the Powerformer, the Powerformer can be judged as the fault, otherwise it is judged to be sound. The discrimination has the following characteristics:

1) It does not need to set the threshold value artificially, and the practicability of the method is improved.
2) A variety of fault characteristics are integrated to enhance the applicability of the method.
3) There is no need to collect a large amount of data as support, which reduces the workload and the time of faulty identification.
4) It is suitable for ungrounded system and high-resistance grounding system, but it is no applicable when neutral is grounded with arc suppression coil.

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