Method for Line Selection of Single-phase Arc Grounding Fault in Distribution Network Based on Extracting Fault Arc Characteristics

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Abstract. Single-phase arc grounding fault is the most important fault form of the medium voltage in distribution network. Once the arc grounding fault occurs, the faulty point generates an arc, and the system generates an arc grounding over-voltage, so it is very necessary to analyze the faulty arc. The faulty arc current has obvious "zero rest phenomenon" at the zero point, and the voltage at this time rises suddenly. This characteristic can be used to analyze the fault. This paper analyzes the current of the faulty arc in MATLAB/Simulink, and extracts transient information of arc current through wavelet transform. According to the singular characteristics, the line selection is carried out by comparing the maximum value of the fourth scale of zero-sequence current of fault line and non-fault line under different "zero rest ratio".

The result shows that the extraction of the arc feature is participating in the arc grounding fault to correctly select the fault line, and the principle is reliable, accurate and suitable for distribution networks in different grounding methods.

Keywords: Distribution network; Arc grounding fault; Fault arc characteristics; Wavelet transform

1. Introduction

Once the ground fault occurs, the grounding point will flow through the short circuit current. The fault current is greater, the damage of air medium is more severe. Once the air is broken, the fault point will generate an arc. If the energy accumulated in this process, the arc is constantly burning. For cable routes, the overvoltage on the non-fault phase may reach 4 to 71 times the primary voltage at the moment of arc grounding fault, and finally damage the line insulation, causing dangerous accidents such as forest fire, power station explosion [1-2]. So, it is essential to launch research on the distribution network fault model, further grasp the ground fault characteristics, facilitates the line selection of the distribution network line, and enhance the power supply reliability of distribution network.

At present, the study of faulty arc is mainly analyzed by simulation model. Document [3-4] proposed a thermal balanced Cassie and Mayr model, but the Cassie model is not suitable for describing low resistance characteristics of faulty arc. The Mayr model is not suitable for describing the high resistance characteristics of faulty arc, and cannot fully reflect the arc characteristics. Document [5-6] proposed a Cassie-Mayr combinational model to solve the dynamic allocation of two models, with a good "zero rest phenomenon", and the voltage and current characteristics of arc at the moment of arc ignition and arc extinction are accurately described. Wavelet transform can be used to analyze the "zero rest phenomenon" and extract the transient information of faulty arc [7-9].
Method for line selection of fault can be divided into several types, some is based on amount of fault steady information, and the other is based on the amount of fault transient information [10]. The steady-state line selection method is greatly affected by grounding resistance. When a high-resistance failure occurs, the zero-sequence current value is lowered, which will cause the system to fail to determine the failure [11-12]. The transient quantity is weak in resonant grounding system in the process of transient-state line selection, and the transition process is short, lead to difficulty in line selection [13-14].

This paper proposes a method to extract fault arc characteristics through wavelet transform and participate in line selection. The fault characteristic “zero rest ratio” is extracted from the fault arc current wavelet. Due to the change of line zero-sequence current caused by the distortion of fault arc current, the modulus maximum of the fourth scale detail component of fault line zero-sequence current is greater than that of non-fault line. Taking this as the fault line selection criterion, the arc characteristics are used to participate in the simulation verification of single-phase grounding fault line selection in MATLAB/Simulink. The results show that this method is accurate and feasible.

2. Fault Arc Analysis

2.1. Arc Model Based on Breakdown Gap

According to a large number of experiments, Tomson’s gas discharge theory has been proposed in the early 20th century, which is suitable for short gap gas discharge. The initial free electron is constantly caused impact ion during exercise, and the number of electrons reached the end is $e^{ad}$. It can be expressed as equation (1):

$$ad \geq \text{Int}(1+1/\gamma)$$  

In the equation (1), $a$ is the collision ionization coefficient, $d$ is the gas gap length and $\gamma$ is the average free travel. Meanwhile, the branch fault current can be expressed as the equation (2):

$$i_f = I_S e^{ad}$$  

In the equation (2), the saturation current caused by $I_S$. Due to the approximate proportion of $a$ and $E$ in the air, The equation (3) can be derived according to principles:

$$\begin{align*}
a &= kE \\
u_j &= Ed
\end{align*}$$

Joint vertical equation (2), equation (3), the arc voltage can be expressed by equation (4):

$$u_j = \text{sgn}(i_j) \sqrt{k \cdot \text{Int}\left(\frac{|i_j|}{I_S}\right) + 1}$$

When the arc grounding fault is eliminated, the arc voltage is shown in equation (5):

$$u_j = 0$$

Therefore, the breakdown gap arc model can be represented as equation (6):

$$\begin{align*}
u_j &= \text{sgn}(i_j) \sqrt{k \cdot \text{Int}\left(\frac{|i_j|}{I_S}\right) + 1}, t \leq T_2 \\
u_j &= 0, t > T_2
\end{align*}$$

In the equation (6), $T_2$ is the time from arc grounding fault to resistance grounding fault or no fault. According to the grounding fault characteristics of the distribution grid, the grounding fault model
based on variable resistance and breakdown gap arc is proposed. Compared with the existing model, the process of fault is considered can adapt to various grounding fault types.

2.2. Fault Electrical Arc Simulation Analysis
In the MATLAB/Simulink environment, a simple arc model circuit is established. The simulation parameters of the arc mathematical model are: the power voltage is 10kV, frequency is 50Hz, and the fault arc occurs at 0.02s. The fault arc voltage and current waveform simulated in the case of the bluffing load are shown in figure 1 and figure 2:

![Figure 1. Fault arc voltage waveform under resistive load.](image1.png)  
![Figure 2. Fault arc current waveform under resistive load.](image2.png)

According to the figure 1, the arc voltage is mutated after the 0.02 second fault arc is started under resistive inductive load, the magnitude is several times the original voltage. There is a long time to shoulder, so the voltage waveform is similar to the square waveform. The current waveform of the faulty arc is basically consistent with the original waveform, and generate ”zero rest phenomenon” in the zero point.

The voltage and current waveform of the fault arc obtained in the case of the pure resistive load are shown in figure 3 and figure 4:

![Figure 3. Fault arc voltage waveform under pure resistance load.](image3.png)  
![Figure 4. Fault arc current waveform under pure resistance load.](image4.png)

Under the pure resistive load, the arc parameter waveforms are shown as figure 3 and figure 4. After the faulty arc start, the fault arc voltage waveform is substantially consistent with the bluffing load, and the ”zero rest phenomenon” of the failed arc current waveform is more obvious.

Depending on the sequential fault arc simulation waveform of the displacement load and the resistive load conditions. The following conclusions can be obtained from figure 1 to figure 4:

- When an arc fault occurs on the line, the current signal in the line has a small shoulder area in the zero point. It is the "zero rest phenomenon".
- The arc voltage waveform is no longer a sine wave but is similar to the square wave, and the voltage signal is also distorted at the zero region of the line current signal, and the change rate...
of the voltage is the largest. When the fault arc is stabilized, the arc voltage is maintained around 1 kV.

- In addition, the current signal in the line has the same phase as the arc voltage signal.

2.3. Extract Fault Arc Features

The line current will be distorted when the fault arc current crosses zero. The influence of the "zero rest phenomenon" of the fault arc on the sinusoidal fault current can be quantitatively expressed as "zero rest ratio". It can be expressed as the equation (7):

$$\alpha = \frac{t_0}{T}$$

In the equation (7), T is the cycle time, t0 is the zero rest time in a cycle. Under resistive inductive load, the fault current has only small distortion at zero crossing, and the "zero rest ratio" is less than 1%; Under pure resistive load, the fault current will last for a period of time when it crosses zero, and "zero rest ratio" is in the range of 5% - 10%. According to this principle, the flow chart of fault line selection can be designed.

3. Wavelet Analysis Fault Arc

3.1. Discrete Wavelet Analysis Method

Wavelet analysis is a time-frequency domain analysis method, which has different distinctive adjustable time. At the time-frequency domain, there is a localization capability, and the signal can be decomposed to a different frequency band. When the signal has a mutation, the coefficients after the wavelet transform have the modulus mode, and can determine the time of the arc to occur by monitoring the modulus large value point.

The fault arc voltage and current data used in this paper is sampled discrete data. Discrete wavelet transform (DWT) is needed to transform the discrete current signal. Therefore, it is necessary to discretize the expansion factor a and displacement factor b, so that the wavelet transform can be realized for the discrete current signal, that can be expressed as equation (8):

$$\psi_{mn}(t) = \frac{1}{\sqrt{a_0^m}} \psi(a_0^{-m}t - nb_0)$$

The expression of discrete wavelet transform (DWT) is as shown in equation (9):

$$W_f(a_j^k, b_k) = \int f(t)\psi(a_j^k t - b_k) dt$$

When S is close to zero, the signal f(x) wavelet transform W_S f(x) changes most intensely will generate the modulus maximum. The binary wave transforms of the digital signal, the singular point of the signal of the signal corresponds to a large value of the wavelet transform. This paper obtains the singular point of the failed arc signal in this paper to determine the strange point of the fault arc signal, and then can be analyze the fault arc.

$$\begin{align*}
S_1^j f(n) &= \sum_{k \in z} h_k S_2^{j-1} f(n - 2^{j-1} k) \\
W_2^j f(n) &= \sum_{k \in z} g_k S_2^{j-1} f(n - 2^{j-1} k)
\end{align*}$$

In the equation (10), $W_2^j f(n)$ is a binary wavelet transform of signal $f(n)$; \( \{ h_k | k \in z \} \) and \( \{ g_k | k \in z \} \) are low-pass filter H (ω) and high pass filter G (ω) coefficient, H (ω) and G (ω) can be represented as equation (11):
The voltage and current of the faulty arc can be analysed by the binary wavelet transform, and the singular characteristics of the failed arc can be extracted with small-bands.

### 3.2. Wavelet Analysis Fault Arc Characteristics

As long as an arc fault is found in the power system, the arc current signal waveform will have a significant mutation, and there is a large strangeness in the fault [15]. The fault information can be obtained from a rich transient waveform, thereby determining the Fourier transform has always been a basic tool for research function, but the Fourier transform lacks space localities, only the overall nature of the functionality can be determined.

DB wavelet transform is used to conduct one-dimensional multi-scale analysis of arc current waveform, which is decomposed to the fourth scale. Arc is a nonlinear pure resistance, so arc voltage and arc current cross zero at the same time. The above shows that the characteristic quantity of fault arc can be effectively extracted by wavelet transformation of arc voltage and current waveform. Wavelet transform of failed arc voltage and current are shown in figure 5 and figure 6.

![Figure 5. Wavelet transform of failed arc voltage.](image1)

![Figure 6. Wavelet transform of failed arc current.](image2)

According to the wavelet transform analysis of fault arc voltage and current, at the time of zero crossing, the fault arc voltage will suddenly change, and the fault arc current will have an obvious "zero break phenomenon". According to the time-frequency duality principle of wavelet transform, there are obvious singular points in the fault arc voltage and current signals at the time of zero crossing, indicating that an arc fault has occurred in the circuit.

### 4. Simulation Analysis

The simulation model of the Single-phase arc grounding fault in distribution network built using the Matlab / Simlink simulation software. Simulation can analyze the impact of fault in the system. The distribution circuit model includes two cable lines, one overhead line. The length is 10km, and the fault is set at the midpoint of L3 line as shown in figure 7.
Figure 7. Arc ground fault simulation model.

Setting the C phase of the L3 at 0.0045S occurs fault, the zero-sequence current waveform of the L1, L2, L3 lines and the wavelet analysis diagram. The zero-sequence current wavelet transform of the sound line L1 and L2 are shown in the figure 8 and figure 9. The zero-sequence current wavelet transform of the fault line L3 is shown in the figure 10.

Figure 8. L1 line zero-sequence current wavelet transform.

Figure 9. L2 line zero-sequence current wavelet transform.

Figure 10. L3 line zero-sequence current wavelet transform.

In the case, the L3 line C phase plug-in ground, and the wavelet transform of the non-fault lines L1, L2 and the fault line L3. It can be found that the d4 value of the sound lines L1, L2 is only increasing in the moment of fault, and then stabilize in zero. The d4 value of the fault line L3 has been in the upper and lower fluctuations after the fault occurs, and its magnitude is gradually reduced. The d4 value of the comparative fault line and sound lines can be found that the non-fault line d4_MAX does not exceed 1, and the d4_MAX of the fault line reaches more than 1 or more.

Using fault line’s d4_MAX is greater than the characteristics of sound line’s d4_MAX as a linear criterion, a single-phase arc grounding fault verifies the accuracy of this optional line method in the case of zero shunt ratio of 2% and 5%, respectively. The fault arc characteristics participate in line selection, and the result is shown in table 1.
Table 1. Fault arc characteristics participate in line selection results.

| Zero Hugh ratio | Faulty line | Fault phase | Zero sequence current $d_{4\text{MAX}}$ |
|-----------------|-------------|-------------|-----------------|
|                 |             | L1          | L2              | L3              |
| 2%              | L1          | A           | 1.21            | 0.33            | 0.28            |
|                 |             | B           | 1.18            | 0.43            | 0.36            |
|                 |             | C           | 1.23            | 0.37            | 0.43            |
|                 |             | A           | 0.46            | 0.37            | 1.35            |
| 2%              | L3          | B           | 0.34            | 0.46            | 1.28            |
|                 |             | C           | 0.34            | 0.38            | 1.21            |
|                 |             | A           | 0.66            | 0.67            | 1.65            |
| 5%              | L3          | B           | 0.64            | 0.66            | 1.58            |
|                 |             | C           | 0.74            | 0.58            | 1.48            |

The zero-sequence current is greater when “zero rest ratio” is 5% than when “zero rest ratio” is 2%, and the maximum value $d_{4\text{MAX}}(LX)$ of the fault line is greater than the maximum value $d_{4\text{MAX}}(Li)$ of the non-fault line, which is proposed in this paper to perform an effective line by extracting the fault arc feature single-phase fault line, and the accuracy of the option is high.

5. Conclusion

In this paper, the fault arc model is established to analyse the voltage and current waveform of the fault arc. The arc current has a "zero rest phenomenon" at the time of zero crossing, and the fault feature "zero rest ratio" is extracted. According to the singular characteristics caused by fault arc, the fourth scale maximum of zero sequence current of fault line is greater than that of non-fault line in the case of single-phase arc grounding fault. The results show that extracting arc features to participate in line selection can correctly select fault lines in arc fault. The extracted eigenvalues are used to quantify the arc state, which lays a good foundation for the next arc fault analysis of distribution network with different neutral grounding modes.

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