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Fault Line Selection with Correlation Analysis of Zero Sequence Current and Voltage under High-Low Frequency

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Fault Line Selection with Correlation Analysis of Zero Sequence Current and Voltage under High-Low Frequency

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Abstract—When a single-phase ground fault occurs near the zero or maximum point,the fault line selection of resonance grounding system is not sensitive enough.After analyzing the transient current and line impedance characteristics of zero sequence network, and making full use of the decaying DC component, power frequency component and high frequency component of the transient zero sequence current of the feeder, a fault line selection method based on correlation analysis of zero sequence current and bus zero sequence voltage derivative in high and low frequency band is proposed.The effectiveness of the method is verified by the examples from the aspects of fault closing angle, transition resistance.

1. Introduction

In the medium-voltage power system with the neutral point grounded through arc suppression coil, the fault current is very small under single-phase ground fault. In addition to the compensation effect of arc suppression coil, it is difficult to accurately select the fault line[1].However, failure to remove fault line in time will lead to fault spread, and affect the stable operation of power system. Therefore, accurate and reliable fault line selection is an important issue to be solved urgently.

Commonly used fault line selection methods can be divided into steady-state information method and transient information method. Among them, the steady-state information method[2,3]includes amplitude comparison,phase comparison,group ratio amplitude comparison and fifth harmonic,but these methods are easily affected by the operation mode, the unbalanced current of current transformer,whose applicability are limited. Considering the moment when fault occurs, the system contains abundant fault transient characteristic information, and the line selection methods based on transient information such as zero-sequence admittance[4]and wavelet energy[5]have become research hot-spots. The state information method does not consider the situation that the fault occurs at the zero-crossing point of the phase voltage and the maximum value of the phase voltage. Once this happens, the accurate line selection cannot be achieved. Most of the existing line selection methods only select high-energy frequency bands, and only consider information such as power frequency steady state, while avoiding other frequency band information and zero-sequence current components. In view of this, this paper makes full use of the attenuated DC component, power frequency component and high frequency component of the transient zero-sequence current of the feeder, and considers the high frequency and low frequency at the same time, and proposes a correlation analysis fault line selection method to solve the phase voltage problem.

2. Analysis of Transient Characteristics of Zero Sequence Network fault

2.1. Analysis of current characteristics

The zero-sequence network of the resonant grounding system with single-phase grounding fault is shown in Fig.1.Where U_{f0} is the virtual power supply at the point of failure. L_{0k} is the zero-sequence inductance per unit length. R_{0k} is resistance. C_{0k} is distributed capacitance. k is the k_{th} feeder, k=1, 2, ..., m. m is the total number of feeders. L_{arc} is inductance of the arc suppression coil. R_{arc} is the series connection resistance. R_f is the transition resistance. i_L is the current through the arc suppression coil. i_{0k} is the zero-sequence current. u_0 is zero-sequence voltage of the bus.

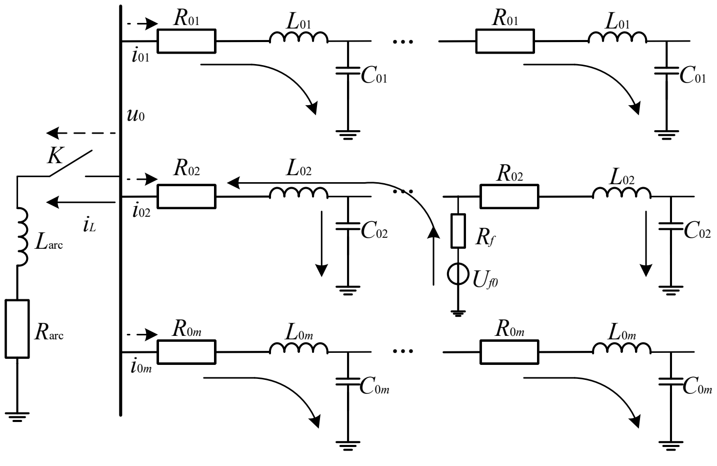


Fig.1 Zero Sequence system under single-phase ground fault

From the differential formula and initial conditions of single-phase ground fault, it can be obtained that fault transient zero-sequence current i_d is composed of capacitor current i_C and inductor current i_L:

$$i_d = i_C + i_L = \left(I_C - I_L\right)\cos\left(\omega t + \theta\right) + I_C\left(\frac{\omega_f}{\omega}\sin\theta\sin\left(\omega_f t\right) - \cos\theta\cos\left(\omega_f t\right)\right)e^{-t/\tau C} + I_L e^{-t/\tau L}\cos\theta \tag{1}$$

Where I_L is the inductor current amplitude, I_C is capacitor current amplitude, τ_L and τ_C are corresponding time constants, ω is angular frequency, ω_f is frequency of transient free oscillation component, θ is fault closing angle.It can be seen that the steady-state, transient inductance attenuation DC and transient free oscillation component simultaneously constitute the zero-sequence current. When θ=0°, the DC component of transient inductance attenuation is the largest under fault near the zero-crossing point of the phase voltage, and it is zero when θ=90°. Therefore, attenuating DC component can clearly distinguish the zero-sequence current waveform of fault and healthy lines.

2.2. Analysis of line impedance characteristics

2.2.1. Healthy line impedance characteristics

When the end of the healthy line is open, the input impedance Z is as follow.Where Z_C is the characteristic impedance of the line, γ is propagation coefficient,l is the length of the line.

$$Z_{OC}\left(\omega\right) = Z_C C\coth\left(\gamma l\right) \tag{2}$$

Substitute $\omega=2\pi f$ in (2) to simplify the input impedance of feeder k:

$$Z_{ock}\left(f\right)=-j\sqrt{\frac{L_{0k}}{C_{0k}}}\cot\left(2\pi fl_k\sqrt{L_{0k}C_{0k}}\right) \tag{3}$$

When the line k first occurs series resonance, the input impedance is equal to zero, and the frequency at this time is denoted as f_k. When the frequency is $0<f<f_k$, the line k impedance is capacitive; when $f>f_k$, the zero-sequence impedance is alternately inductive and capacitive as the frequency increases, and fault line selection cannot be achieved[6]. The minimum series resonance frequency fhigh is selected as the minimum value of the frequency f_k at which the series resonance first occurs in each feeder, then all line impedances are capacitive when $0<f<f_{high}$, and f_{high} can be derived from :

$$f_{high}=\frac{\operatorname{arccot}\left(Z_{cok}^2C_{0k}/L_{0k}\right)}{2\pi l_kL_{0k}C_{0k}} \tag{4}$$

2.2.2. fault line impedance characteristics
Once the line is fault, the impedance of the healthy line within $0<f<f_{high}$ is the lumped parameter capacitance related to the parameters of the healthy line, and the impedance of the fault line can be regarded as multiple capacitors and an inductance connected in parallel. The equivalent admittance of the fault line can be obtained from the analysis as:

$$Y_k\left(f\right)=-\frac{1}{j2\pi fL_{arc}}-j2\pi f\sum_{i=1,i\neq k}^{m}l_iC_{0i} \tag{5}$$

From (4), it can be obtained that as the frequency gradually increases from zero, the ratio of the admittance to impedance of the fault line changes from inductive to capacitive. Parallel resonance occurs when the equivalent admittance of the fault line is zero. Let this resonant frequency be f_{low} and f_{low} is much larger than the power frequency and much smaller than f_{high}. Therefore, the fault line impedance is inductive when $0<f<f_{low}$, and capacitive when $0<f<f_{high}$. The f_{low} can be derived from (5):

$$f_{low}=\frac{\pi L_{arc}Y_kj-\sqrt{4\pi L_{arc}\sum L_iC_{0i}-\pi^2l_i^2Y_k^2}}{4\pi L_{arc}\sum L_iC_{0i}} \tag{6}$$

Therefore, $0<f<f_{low}$is set as the low frequency band, and $f_{low}<f<f_{high}$ as the high frequency band,and the impedance characteristics of the healthy line are capacitive in the high and low frequency bands; while the fault line is capacitive in the high frequency band and inductive in the low frequency band.

3. Correlation Analysis and Line Selection Principle

3.1. Correlation coefficient of healthy lines
The healthy line k is capacitive in all frequency bands, so the waveform of the zero-sequence current of the feeder and the waveform of the derivative of the zero-sequence voltage of the bus are similar in both high and low frequency bands. Assuming that the correlation coefficients of the low and high frequency bands are ρ_{kl} and ρ_{kh}, respectively, there are:

$$\rho_{k1}=\rho_{kh} \tag{7}$$

$$\rho_{k1}=\frac{\sum_{n=1}^{N}\frac{du_{01(n)}}{dt}i_{0k1}\left(n\right)}{\left[\sum_{n=1}^{N}(\frac{du_{01(n)}}{dt})^2\sum_{n=1}^{N}i_{0k1}^2\left(n\right)\right]^{1/2}}\qquad \rho_{kh}=\frac{\sum_{n=1}^{N}\frac{du_{0h(n)}}{dt}i_{0kh}\left(n\right)}{\left[\sum_{n=1}^{N}(\frac{du_{0h(n)}}{dt})^2\sum_{n=1}^{N}i_{0kh}^2\left(n\right)\right]^{1/2}} \tag{8}$$

Where u_{0h} and u_{0l} are the zero-sequence voltages in the high and low frequency bands, i_{0kh} and i_{0kl} are both zero-sequence currents.The value range of the correlation coefficients ρ_{kl} and ρ_{kh} is [-1, 1]. The larger the absolute value is, the more correlated the two signals are. A positive value is a positive correlation, and a negative value is a negative correlation. If the value is ± 1, it means that the two signals are completely similar. If the value is 0, the two signals are not correlated.

3.2. Correlation coefficient of fault lines

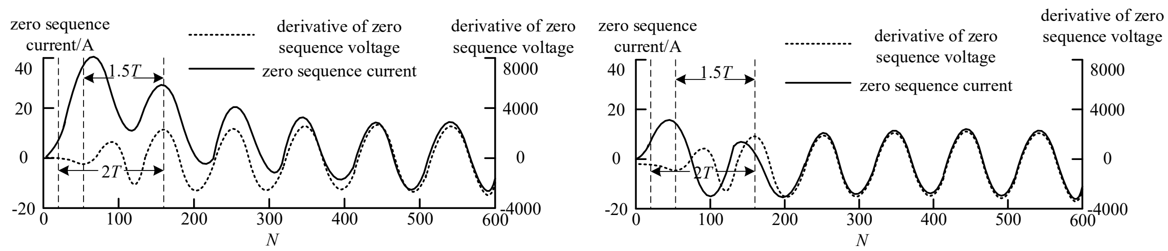
3.2.1. Correlation coefficient of high frequency fault line

The impedance of the fault line feeder k is capacitive in the high frequency band, and the zero-sequence current of the fault line is equal to the inverse of the sum of the zero-sequence currents of all sound lines. Therefore, the zero-sequence current of the fault line is negatively correlated with the derivative of the zero-sequence voltage of the bus:

$$-1 < \rho_{kh} < 0 \tag{9}$$

3.2.2. Correlation coefficient of low frequency fault line

The impedance of the fault line k is inductive in the low frequency band. At this time, considering the existence of the DC component attenuated by the inductance, the low-frequency correlation coefficient of the fault line is discussed according to the situation: ①θ=0°. The zero-sequence current waveform is shown in Figure 2(a). It can be seen from Figure 2(a) that the reason for the different waveform is that the polarities of the first half-waves of the two signals are different[7]. The zero-sequence current ρ_{kl} is positive. Since the zero-sequence current has the largest attenuation component when θ=0°, and the attenuation can last for multiple cycles (T), and the length of the low-frequency data window is only two cycles, it can be seen that the correlation is very small, and ρ_{kl} is a positive value close to zero. ②θ=90°. The zero-sequence current waveform is shown in Figure 2(b). It can be seen from Figure 2(b) that the attenuated DC component hardly exists, and only the first half-wave principle affects the waveform. The polarity of the zero-sequence current in the second half cycle of the fault is opposite to that of the sound line, and the polarity is reversed in about 1.5 cycles. The same, it can be seen that the two waveforms are very similar. At this time, ρ_{kl} has a maximum value, which is about 0.5 to 1.0. ③0°<θ<90°. ρ_{kl} is between the two cases of θ=0° and 90°.



(a)θ=0° (b)θ=90°

Fig.2 Low Frequency Transient Waveform when θ=0° and 90°

To sum up, it can be seen that the correlation coefficient of the low frequency band is:

$$\begin{aligned} &0 < \rho_{k1} < 0.5 \quad \theta = 0^\circ \\ &0 < \rho_{k1} < 1.0 \quad 0^\circ < \theta < 90^\circ \\ &0.5 < \rho_{k1} < 1 \quad \theta = 90^\circ \end{aligned} \tag{10}$$

3.3. Criterion of line selection

The line selection correlation coefficient P_k is defined as:

$$P_k = 1/\rho_{k1} - 1/\rho_{kh} \tag{11}$$

The analysis shows that the P_k of the healthy line is zero, and the P_k of the fault line is greater than 2, which can form the line selection criterion. Based on the difference of the correlation coefficient P_k between the healthy line and the fault line, the judgment threshold P_{set}=1 is set, and the correlation coefficient of each feeder is compared with the judgment threshold, so as to select the fault line. Specifically, when $P_k > P_{set}$, the feeder k is a fault line. When $P_k < P_{set}$, the feeder k is a healthy line.

4. Case Study

4.1. Simulation model and parameters

Fig.3 shows an example of a resonant grounding system. The transformer in the system is the main transformer with a ratio of 110kV/10kV, and the connection group is YN/d11. The line model adopts a total of 6 feeder lines of overhead and cable. l_1, l_2 are cable lines, l_3-l_6 are overhead lines. Zero sequence and positive sequence parameters of cable line: R_0=2.7 Ω/km, L_0=1.0 mH/km, C_0=0.3 μF/km, R_1=0.3 Ω/km, L_1=0.2 mH/km, C_1=0.4 μF/km. Overhead line parameters: R_0=0.3 Ω/km, L_0=5.5mH/km, C_0=0.1 μF/km, R_1=0.2 Ω/km, L_1=1.2 mH/km, C_1=0.1 μF/km. The neutral point is grounded by an arc suppression coil with an inductance of 0.74H, with 10% over-compensation, and the active power loss is 5% of the reactive power loss. The active power of the load is set to 1 MW, the power factor is set to 0.89, and the model is a three-phase symmetrical linear load.

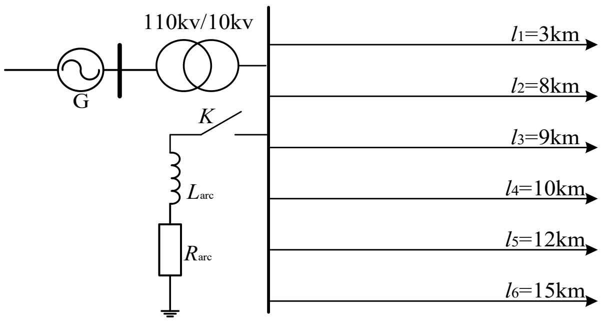


Fig.3 Simulation model of case study system

Extract low-frequency and high-frequency components of transient signals through low-pass and band-pass digital filters. The sampling frequency of the system is 4kHz, the cutoff frequency of the low frequency band is 60Hz, and the cutoff frequency of the high frequency band is [200,1000]Hz.

4.2. Simulation result and analysis

After simulation, l_3 is the fault line, and l_1, l_2, l_4, l_5 and l_6 are the healthy lines. Comparing the correlation coefficient between the healthy line and the fault line in the high and low frequency bands, it can be seen that the zero-sequence current and voltage derivative waveforms of the sound line in the transient signal of the high and low frequency bands are almost completely similar, that is, the correlation coefficients of the high and low frequency bands of the healthy line are close to 1. The waveforms of transient zero-sequence current and zero-sequence voltage derivative of fault line l_3 are quite different in the low frequency band, so the correlation coefficient is a positive number close to 0. In high frequency band, the two waveforms are opposite, and the correlation coefficient is about -1.

(1) Comparison of simulation results under different fault closing angles. l_3 ground fault occurs at 5km away from the bus through a transition resistance of 3Ω. The simulation results under different fault closing angles are shown in Tab.1.

Tab.1 Simulation results of different θ

N	θ/(°)	Correlation coefficient of line selection						Result
		P_1	P_2	P_3	P_4	P_5	P_6	
160	0	-0.05	-0.04	12.84	-0.05	-0.05	-0.05	Correct
	15	-0.05	-0.04	8.54	-0.05	-0.05	-0.05	Correct
	30	-0.05	-0.04	7.35	-0.05	-0.05	-0.05	Correct
	45	-0.05	-0.04	5.50	-0.05	-0.05	-0.06	Correct
	60	-0.05	-0.04	4.44	-0.05	-0.06	-0.06	Correct
	75	-0.05	-0.04	5.49	-0.05	-0.06	-0.05	Correct
	90	-0.05	-0.04	3.01	-0.05	-0.05	-0.06	Correct

It can be seen from Tab.1 that under different θ, when l_3 fails, the healthy line P_k is almost unchanged, while the fault line P_3 decreases with the increase of θ. When θ=0° and 90°, the sensitivity of fault line selection is the highest, it can be seen that The method in this paper can accurately select the line near the zero-crossing point and the maximum value of the phase voltage.

(2) Comparison of simulation results under different transition resistances. For l_3, a single-phase grounding fault occurs at a distance of 7km from the busbar at θ=0°. The simulation results under different transition resistances are shown in Tab.2. It can be seen from Tab.2 that when R_f increases, the healthy line P_k is basically unchanged, while P_4 first decreases and then increases. It can be seen that the method in this paper can still select the line reliably under different R_f, and the line selection under the high resistance ground fault more sensitive.

Tab.2 Simulation results of different R_f

N	R_f/(Ω)	Correlation coefficient of line selection						Result
		P_1	P_2	P_3	P_4	P_5	P_6	
160	1	-0.03	-0.03	-0.03	12.56	-0.04	-0.04	Correct
	10	-0.04	-0.03	-0.04	7.98	-0.04	-0.04	Correct
	100	-0.06	-0.05	-0.06	3.45	-0.06	-0.06	Correct
	300	-0.06	-0.05	-0.07	3.33	-0.07	-0.07	Correct
	1000	-0.07	-0.06	-0.07	4.21	-0.07	-0.08	Correct

5. Conclusion

The line selection is realized by using the correlation coefficient between the zero-sequence current and the zero-sequence voltage derivative in different frequency bands, and comprehensively considering various fault transient information to improve the line selection sensitivity near the zero-crossing point and the maximum value of the phase voltage. However, because the high-resistance fault current is weak, easily affected by disturbance, and the amplitude of the transient high-frequency component is small, the applicability of the line selection method needs to be improved.

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