The Identification Between Transient Faults and Permanent Faults on Transmission Lines Based on Power Spectrum

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Abstract

This paper studies the characteristic of recovery voltage when a ground fault occurs in the EHV transmission line with a shunt reactor, and then, the fault identification criterion is proposed. The recovery voltage contains a power frequency component and a low-frequency decaying component when the transient fault occurs, and it only contains a power frequency component when the permanent fault occurs. Using the orthogonality between a signal vector and a noise subspace, the power spectrum estimation algorithm based on matrix eigenvalue decomposition can accurately estimate power frequency components and low-frequency decaying components, and the system noise has no great effect on the accuracy of criterion. In this paper, voltage signal of a shunt reactor is measured for detecting power frequency component and low-frequency decaying components using this algorithm. In two lines (peaks) there are the transient faults, and in one line (peak) there are the permanent faults. In the series compensation system, although increasing series capacitor circuits, the fault identification criterion still can identify transient faults and permanent faults.

Keywords: EHV Transmission, Lines Transient Fault, Permanent Fault, Adaptive Reclosure, PSD Estimation

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1. Introduction

In the various components of the power system, transmission lines are the components which have the largest coverage area and the worst working conditions, and are influenced by all kinds of natural conditions. Their failure rate is the highest of all the equipment in the power system. It has great significant analyzing of transmission line faults to reduce the continuity and reliability of a power supply in system.

According to statistics, more than 90% of EHV transmission line faults are a single-phase grounding short circuit, and more than 80% of EHV are transient faults. Therefore, we can greatly improve the stability of a power system and power supply continuity when the transient fault happens making the fault phase circuit breaker close fast and restore the fault phase of power supply.

In order to put the line into operation fast after eliminating the transient faults, we widely use the automatic reclosing on the transmission line.

When traditional automatic reclosing blinds reclosing on permanent faults, it's a great threat for the whole power system transient stability impact two times short on circuit currents, and it will be more than the system short circuit caused by the consequences when reclosing on permanent faults impacts on a power system and power equipment.

To avoid reclosing on permanent faults, the domestic and foreign scholars do a lot of research in recent decades, and adaptive reclosing is proposed based on transient faults and permanent faults. When an adaptive reclosing is compared with the traditional automatic reclosing, the advantage in reclosing can accurately judge whether the fault is a transient fault or a permanent fault before action; when the transient fault occurs, the action is not blindly to reclose permanent faults, and avoids the negative effects when traditional reclosing action on the permanent fault occurs to the system, but also reduce the damage to the power equipment.

A shunt reactor can effectively inhibit the frequency increase of a light transmission line voltage, so the shunt reactor are generally used in EHV transmission lines, reducing line overvoltage and improving voltage distribution. The effect of a series capacitor is to offset the line reactance, reducing the angle difference of voltage phases on both ends in a transmission line, so as to improve the transmission capacity of a transmission line over a long distance, improving the stability of the system to reduce the system voltage deviation and the distribution of the energy transmission.

In this paper, we study the EHV transmission line with the shunt reactor compensation; when the single-phase grounding fault occurs through the analysis frequency components and freedom components of the fault disconnect phase recovery voltage power, the criterion of distinguishing transient fault and permanent fault is put forward. Further we study the transmission line fault identification with the series capacitor compensation.

2. The Characteristics of Fault Phase Recovery Voltage

2.1 The Analysis of Recovery Voltage Power Frequency Components

As shown in Figure 1, with a phase fault, for example, when the transient fault happens, it will disconnect on both ends of the line fault phase. As the short circuit point arc is gradually extinguished, the transmission line gets into two phase running states. In diagram, Cm is circuit capacitance, C0 is relatively capacitance, L is the inductance of a shunt reactor and Ln is the inductance of neutral point small reactance.

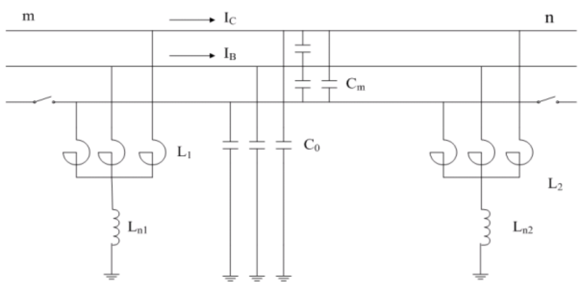


Figure 1: Equivalent circuit of the structure with a shunt reactor line

A certain size of induction voltage is given between the sound phase and disconnect phase. Because of electromagnetic and capacitive coupling on, referred to as recovery voltage, power frequency components are the vector sum of electromagnetic coupling voltage and capacitance coupling voltage.

2.2 Free Oscillation Components Analysis in the Recovery Voltage

1). Transient fault

In an EHV or UHV transmission line with the shunt capacitor compensation, after the arc extinguishing, it disconnects phase electromagnetic energy stored by the capacitance and inductance energy storage components and will produce free oscillation components.

Under the dual function of condenser type (zero state response) and sound phase voltage (zero input response) in arc instant, the transient response of the capacitance coupling voltage attenuation on fault disconnect phase have three kinds of components which are decaying dc components, decaying cycle components, and power frequency components.

2). Permanent fault

When a permanent ground fault occurs, regardless of transition resistance, the recovery voltage of a fault phase contains decaying dc components and power frequency components. The decaying dc components may be neglected.

3. Power Spectrum Estimation Based on Characteristics of Matrix Decomposition

Modern power spectrum estimation is one of hotspots in the field of signal processing research for nearly 30 years. It can give the distribution of energy along with the frequency with which the object being analyzed. Therefore, getting the power spectrum of fault phase voltage can get this waveform section which contains all of the signal frequency.

The characteristics decomposition of the correlation matrix is mainly used in the frequency and power spectrum estimation of the sinusoidal signal mixed with white noises. Set signal *x*(n) consisting of M repetition sinusoid added white noises [7], and then the autocorrelation function is

$$r_x(k) = \sum_{i=1}^{M} A_i \exp(j\omega_i k) + \rho_w \delta(k) \qquad (1)$$

A_i and ω_i are the ith power and frequency of the repetition sinusoidal (sine signal amplitude is $\sqrt{A_i}$), and ρ_w is the power of white noise. If a correlation matrix R_P is composed of ($p+1$) $r_x(k)$

And define the signal vector

$$e_i = [1, \exp(j\omega_i), \cdots, \exp(j\omega_i p)]^T, i = 1, 2, \cdots, M \qquad (2)$$

So

$$R_p = \sum_{i=1}^{M} A_i e_i e_i^H + \rho_w I \qquad (3)$$

Where I *is an Unit matrix of* $(p+1) \times (p+1)$. R_P*, a feature decomposition, is*

$$\begin{aligned} R_p &= \sum_{i=1}^{M} \lambda_i V_i V_i^H + \rho_w \sum_{i=1}^{p+1} V_i V_i^H \\ &= \sum_{i=1}^{M} (\lambda_i + \rho_w) V_i V_i^H + \sum_{i=M+1}^{p+1} \rho_w V_i V_i^H \end{aligned} \qquad (4)$$

Among, V_1，V_2，…，V_M are called the main feature vector.

As signal vector e_i is orthogonal to V_{M+1}，V_{M+2} …, V_{p+1} are every vector of noise space. Therefore, their linear combinations are orthogonal, namely

$$e_i^H \left(\sum_{k=M+1}^{p+1} \alpha_k V_k \right) = 0，i = 1，2，…，M \qquad (5)$$

Make

$$e(\omega) = [1, \ e^{j\omega}, \cdots, \ e^{j\omega M}]^T \qquad (6)$$

So $e(\omega_i) = e_i$ .According to the formula 5, we have

$$e^H(\omega)[\sum_{k=M+1}^{p+1} \alpha_k V_k V_k^H] e(\omega) = \sum_{k=M+1}^{p+1} \alpha_k \left| e^H(\omega) V_k \right|^2 \qquad (7)$$

Formula 7 is zero at this point of $\omega = \omega_i$ .And

$$\hat{P}_x(\omega) = \frac{1}{\sum_{k=M+1}^{p+1} \alpha_k \left| e^H(\omega) V_k \right|^2} \qquad (8)$$

Formula 8 is infinite at this point of $\omega = \omega_i$. But because it is made of the correlation matrix decomposition, the correlation matrix is estimated, and there will be an error. Therefore, $\hat{p}_x(\omega_i)$ is a limited value, but present sharp peak, the peak corresponds to the frequency is the frequency of the sinusoidal signal. This method can get the signal power spectrum estimation.

If $\alpha_k = 1$ in formula 8, Among, $k = M+1, \cdots, \ p+1$, What you get is multiple signal classification, MUSIC, namely

$$\hat{P}_{MUSIC}(\omega) = \frac{1}{e^H(\omega)(\sum_{k=M+1}^{p+1} V_k V_k^H) e(\omega)} \qquad (9)$$

By using the orthogonality of the vector signal and noise subspace, it can accurately estimate the work frequency steady component and the frequency of the power frequency attenuation components.

4. The Adaptive Reclosing Criterion Based on Power Spectrum

With the expansion of the construction of an ultra-high voltage grid, a certain amount of a shunt reactor must be installed in EHV transmission lines. To avoid the resonance, compensation degree of a shunt reactor is generally lower than 80% so that the frequency of low-frequency decaying component is lower than the frequency of the power frequency component, which is less than 50 Hz. And through the power spectrum estimation, the signal of low-frequency decaying component and power frequency component will be detected.

Shunt reactors are generally installed in the substation bus bars which are at the end of the lines on the head or end, and close to the ground. They are generally installed on EHV transformer to easily acquire signal; the shunt reactor's rated current value is much smaller than the transmission line's, and its measuring accuracy is higher than the transmission line for transformer. Therefore, there has a big advantage sampling signal on the shunt reactors than the EHV transmission lines. Because shunt reactors are connected to the transmission line, its voltage is the same as the transmission line. When transient fault or permanent fault occurs in transmission line, measuring EHV voltage signal will be able to identify fault types.

For the line with a shunt reactor, EHV voltage characteristic is tested using the power spectrum estimation, The recovery voltage contains power frequency component and low-frequency decaying component when a transient fault occurs, where the corresponding power spectrum has two line (peak), and it only contains power frequency component when a permanent fault occurs, where the corresponding power spectrum has only one line (peak).

The criterion can be expressed: In two lines (peaks) there are the transient faults, and in one line (peak) there are the permanent faults.

To prevent miscarriage and enhance the correctness of the criterion, we prescribe and scan detection ranges for the power spectrum. Prescribe the minimum of detection ranges is less than the minimum frequency of the low-frequency decaying component value, and the maximum of detection ranges is greater than the maximum frequency of power frequency components. Because the frequency of the low-frequency decaying component is associated with shunt reactor compensation degrees, and considering the system frequency offset, power frequency component is not strictly equal to 50 Hz. In general, detection range can be set to the range from 10 Hz to 55 Hz according to the operation of system.

In series capacitor compensated lines with a shunt reactor, the series capacitor, which lowers line impedance, forms a resonance circuit with a shunt reactor. After line faults occurs, the fault phase voltage is affected by the coupling effect between phases inductance and capacitance, and by the shunt reactor energy storage, and also is affected by the series capacitor energy storage. And recovery voltage is stacked capacitor's residual voltage, so it will be increased. However, since the fault phase equivalent circuit is still the resonant circuit of the capacitance and the inductance, it will inevitably produce free oscillation components. Therefore, in the case of transient fault, the power spectrum in a shunt reactor is still two lines (peak), and in the case of permanent fault, it is still a line (peak).

5. Simulations

The simulation models of high voltage transmission lines are established in the platform of ATP-EMTP. The line faults are simulated in the platform about EHV transmission lines, respectively, for single circuit with single-ended shunt reactor, and single circuit with a double-side shunt reactor, two-circuit with single-ended shunt reactor, two-circuit with double-side shunt reactor. The EHV voltage signal data from results of ATP-EMTP simulation were imported into MATLAB, and power spectrums are calculated through MATLAB program to verify this criterion of fault identification. Simulation results show that the criterion can reliably distinguish transient faults and permanent faults of both single circuit line and double circuit line, unaffected by fault locations or transition resistances.

The simulation model is listed only in this paper: the simulation model of the Wanxian-Longquan 500 kV transmission line with single-ended shunt reactor compensation circuit in Chongqing municipality. The length of the line is 358 km, the parameters of equivalent double power system are as follows:

$X_{1P} = 49.34\Omega$ ， $X_{0P} = 41.34\Omega$ ， $X_{1Q} = 46.03\Omega$ ， $X_{0Q} = 103.36\Omega$ 。

The line parameters are as follows:

$R_1 = 0.0195\Omega / km$, $L_1 = 0.9134 mH / km$, $C_1 = 0.014 \mu F / km$, $R_0 = 0.1675\Omega / km$, $L_0 = 2.7191 mH / km$, $C_0 = 0.00834 \mu F / km$ 。

Shunt reactor's equivalent parameters are as follows: $X_L = 1680.56\Omega$ ， $X_N = 343\Omega$ 。

EMTP simulation model is shown in Figure 2,

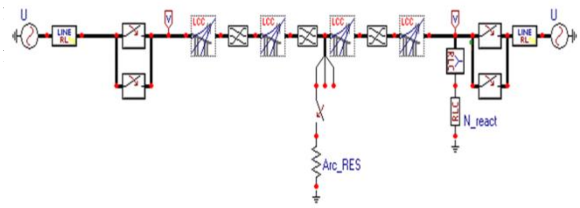


Figure 2: The EMTP simulation model with shunt reactor at the end of the line

5.1 The Simulation Faults of the Transient Fault

Fault phase voltage waveform is shown in Figure 3 when single phase grounding transient fault occurs:

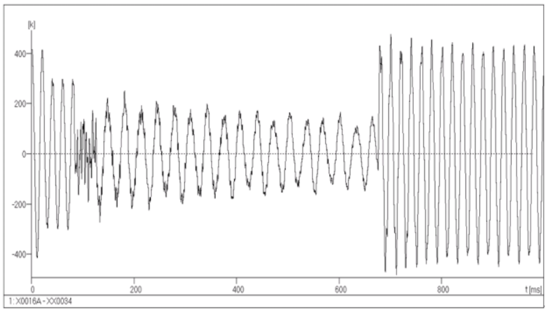


Figure 3: Voltage waveform figure when single phase grounding transient fault occurs

Figure 4 is the power spectrum calculated through programming. From the figure 4, the power spectrum is two spectral lines, one line's frequency is 32 Hz, and another line's frequency is 50 Hz.

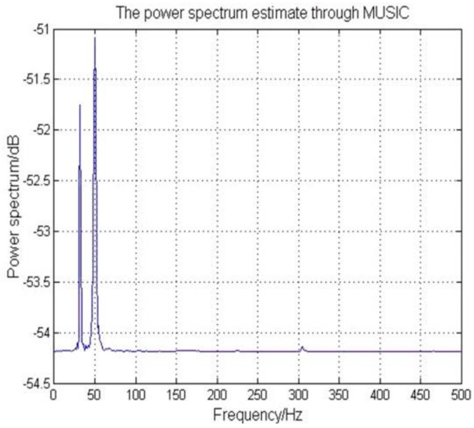


Figure 4: Power spectrum of faulted phase voltage when transient fault occurs

5.2 The Simulation Results of the Permanent Fault

Fault phase voltage waveform is shown in Figure 5 when single phase grounding permanent fault occurs:

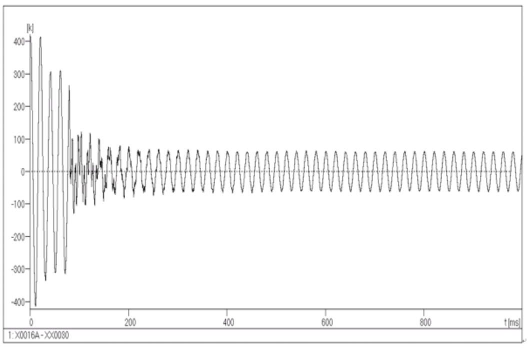


Figure 5: Voltage waveform figure when single phase grounding permanent fault occurs

Figure 6 is the simulation results when the grounding resistance is 40Ω. From the Figure 6, the power spectrum is one line, and frequency is 50 Hz.

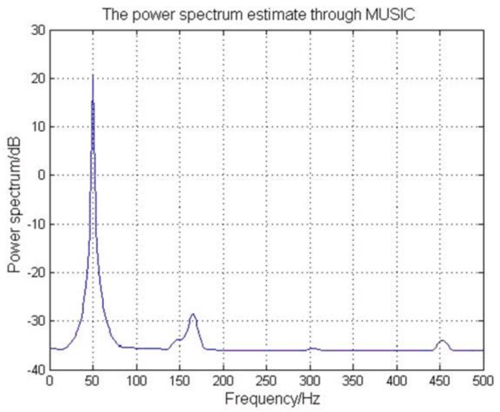


Figure 6: Power spectrum of faulted phase voltage when permanent non-metallic fault occurs

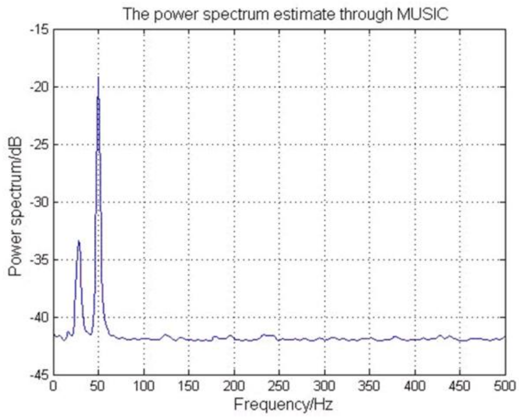
Table 1: The simulation results of single-ended transmission line with a shunt reactor

Locations	Fault types	Lines 1(Hz)	Lines2 (Hz)	The results
sending end	Transient	31	50	Transient fault
	Permanent (0Ω)		50	Permanent fault
	Permanent (200Ω)		50	Permanent fault
	Permanent (500Ω)		50	Permanent fault
middle	Transient	32	50	Transient fault
	Permanent (0Ω)		50	Permanent fault
	Permanent (200Ω)		50	Permanent fault
	Permanent (500Ω)		50	Permanent fault
receiving end	Transient	31	50	Transient fault
	Permanent (0Ω)		50	Permanent fault
	Permanent (200Ω)		50	Permanent fault
	Permanent (500Ω)		50	Permanent fault

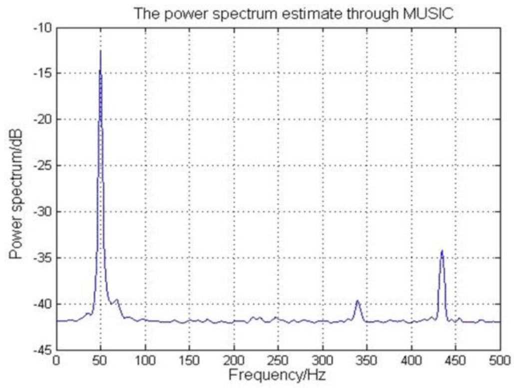
When line Ⅰ phase A and line Ⅱ phase A earth fault occur for the double-circuit transmission lines with both sides shunt reactor compensation, we validate the criterion by adding noise.

The signal power spectrum estimation is done adding 2% of the amplitude of voltage signal amplitude noise, SNR 34 db.

Figure 7 is the power spectrum of EHV faulted phase. It has little effect to identify the fault adding the noise about power spectrum estimation based on matrix characteristics decomposition.



(a) Power spectrum of faulted phase voltage when transient fault occurs and adding noise



(b) Power spectrum of faulted phase voltage when permanent fault occurs and adding noise

Figure 7: The shunt reactor power spectrum adding noise

6. Conclusions

Using the orthogonality between a signal vector and noise subspace, the power spectrum estimation algorithm based on matrix eigenvalue decomposition can accurately estimate power frequency components and low-frequency decaying component, and the system noise has no great effect on the accuracy of criterion. According to different locations of faults, there are different transition resistances when transient fault and permanent fault occurs, and the simulation were done using EMTP. And the fault identification accuracy is high and unaffected by fault locations or transition resistance. In microcomputer protection, adaptive reclose features can be achieved by the method of the power spectrum estimation algorithm.

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