TELKOMNIKA, Vol. 11, No. 2, February 2013, pp. 615~622
ISSN: 2302-4046

Fast Distance Protection for Proximal Fault of EHV Transmission Line

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Abstract

As the full length is considered in the traditional EHV line protection, proximal circuit fault can't be moved in an ideal short time. A fast distance protection algorithm for proximal fault of EHV transmission line is proposed in the paper. Based on differential equation model and power frequency variation principle, the method has fast response speed and small workload. And the protection for proximal fault of long distance EHV transmission lines can be correctly implemented in a very short time. The method is realized with a low pass prefilter and without digital filter. Finally, through the RTDS simulation platform, a variety of fault modes of 500kV transmission lines is realized, and the accuracy and rapidity of the algorithm is verified by the simulation result.

Keywords*: distance protection, proximal fault, differential equation algorithm, power frequency variation, EHV transmission line*

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1. Introduction

EHV transmission line plays a backbone role in the grid, and the improvement of its fault protection movement speed, which can effectively improve the margin of system stability. So, there are many strict requirements for the protection speed of EHV transmission line [1-2], and it has important practical significance on how to improve the protection speed of EHV transmission line.

Scholars have undertaken extensive research on the principle and algorithm of EHV transmission line protection [3-6]. Literature [7] proposes the distance protection principle of long-distance transmission line based on Bergeron model, Literature [8] discusses the implementation of a new algorithm of the ultra-high-speed directional relay for high voltage transmission line, Literature [9] presents an adaptive distance protection based on error of R-L model, Literature [10] comes up with a long-distance protection in time domain based on parameter identification. The above studies are analyzed for the full length of the EHV and achieve good results. EHV transmission line has the features of long transmission distance, easily affected by distributed capacitance, and the situation of double circuit line on the same pole [11-15],so relative complex algorithm has been taken into account for principles and algorithms of full length protection which leads to the fact that proximal circuits fault can't be moved in an ideal short time. In order to removal the proximal fault rapidly, rapid protection function for proximal fault has clearly reflected in the EHV protection technical specifications of State Grid and Southern Power Grid [16] [17]. In response to those issues, fast protection methods for proximal fault of EHV transmission line have been studied in this paper. Based on improved differential equation model and power frequency variation principle, the method has fast response speed in the proximal fault of EHV transmission line. Finally, through the RTDS model simulation test, the accuracy and rapidity of the algorithm is verified.

2. Protection Method

Distance protection has a wide range of applications in the high-voltage and EHV transmission lines, a perfect distance protection requires a variety of functions, such as Distance measurement, Fault phase selection, Fault direction discriminant, High resistance fault identification and so on. These contents will be represented in detail below.

Received October 5, 2012; Revised December 21, 2012; Accepted January 11, 2013

2.1. Measured Impedance Algorithm

Distributed capacitance of EHV transmission line can not be ignored, especially under the transient case, the impact of capacitive current will be more serious. Distributed parameter model should be used to analysis the full length line protection but in the situation of proximal fault, the frequency of current brought by distributed capacitance is very high and High-frequency components decay very fast, so, they can be filtered off by the low-pass filter and there's no need to add a digital filter. In hence, in this fault, line can be represented in R-L lumped parameter model. When single phase grounding fault occurs, the relationship between phase voltage u_φ and phase current i_φ can be expressed by the Formula (1), where i_0 represents Zero sequence compensation current; And when phase to phase fault happens, the relationship between line voltage $u_{\varphi\varphi}$ and line current $i_{\varphi\varphi}$ meets the Formula (2).

$$u_\varphi = \left(i_\varphi + k_r 3i_0\right)\times R_1 + \frac{d(i_\varphi + k_i 3i_0)}{dt}\times L_1 \tag{1}$$

$$u_{\varphi\varphi} = i_{\varphi\varphi}\times R_1 + \frac{di_{\varphi\varphi}}{dt}\times L_1 \tag{2}$$

where k_r represents the zero-sequence compensation factor of resistance and k_i represents the zero-sequence compensation of reactance, $k_r = (r_0 - r_1)/3r_1$、$k_i = (l_0 - l_1)/3l_1$; where r_0 is zero-sequence resistance of per kilometer of transmission line, l_0 is zero-sequence inductance of per kilometer of transmission line; r_1 is positive-sequence resistance of per kilometer of transmission line l_1 is positive-sequence inductance of per kilometer of transmission line

Based on the above differential equation, the algorithm has the advantages of short data window and will not be affected by the aperiodic component and the change of frequency of grid.

2.2. Fault Direction Discriminant

Power frequency variation only reflects fundamental frequency component of fault component and power frequency variation component is generated by the additional source at the fault point. When positive and reverse fault happen on the line, the system wiring diagram is shown in Figure1.

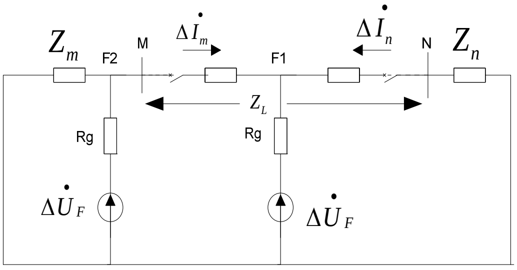

Figure 1. Line Fault System Diagram of Positive and Reverse Directions

For the case of positive and reverse fault, power frequency variable relay at the M side meets the basic relations shown in the Formula(3) and Formula(4).

$$\Delta\dot{U}_m = -\Delta\dot{I}_m \times Z_m \tag{3}$$

$$\Delta\dot{U}_m = \Delta\dot{I}_m \times (Z_n + Z_l) \tag{4}$$

where $\Delta\dot{U}_m$ represents fault component of line voltage and $\Delta\dot{I}_m$ represents fault component of line current, the positive direction of current is bus to protected line; Z_m represents the equivalent positive sequence impedance at the back of source and $Z_n + Z_l$ is the equivalent positive sequence impedance at the positive direction of the relay.

When short circuit happens in the positive and reverse direction, the angle between the voltage and current is opposite which has a clear directionality.

The angle between the voltage and current in the positive direction is:

$$\arg\frac{\Delta\dot{U}_m}{\Delta\dot{I}_m} = \arg\left(-Z_m\right) \approx -90° \tag{5}$$

The angle between the voltage and current in the reverse direction is:

$$\arg\frac{\Delta\dot{U}_m}{\Delta\dot{I}_m} = \arg\left(Z_n + Z_l\right) \approx 90° \tag{6}$$

When considered the angle of line impedance is 80°in the composition of directional relay, the operation equation of directional element in the positive direction is expressed in Formula (7). Where $\Delta\dot{U}_{\varphi\varphi}$ is line voltage variety and $\Delta\dot{I}_{\varphi\varphi}$ is line current variety.

$$-190° \leq \arg\frac{\Delta\dot{U}_{\varphi\varphi}}{\Delta\dot{I}_{\varphi\varphi}} \leq -10° \tag{7}$$

The operation equation of directional element in the reverse direction is:

$$-10° \leq \arg\frac{\Delta\dot{U}_{\varphi\varphi}}{\Delta\dot{I}_{\varphi\varphi}} \leq 170° \tag{8}$$

If we use fourier transform algorithm, the required data window will be longer and the amount of computation will be larger due to the above-mentioned directional relay need to calculate the voltage variety $\Delta\dot{U}$ and current variety $\Delta\dot{I}$ to carry on phase comparison. So, we also use the R-L lumped parameter model. In the single phase grounding fault case, power frequency variation equation based on differential equation is shown in Formula (9), where Δu_φ is power frequency variety of phase voltage and Δi_φ is power frequency variety of phase current. When phase-to-phase fault happens, it needs to meet formula (10), where $\Delta u_{\varphi\varphi}$ is power frequency variety of line voltage and $\Delta i_{\varphi\varphi}$ is power frequency variety of line current.

$$\Delta u_\varphi = \left(\Delta i_\varphi + k_r 3i_0\right) \times R_m + \frac{d(\Delta i_\varphi + k_l 3i_0)}{dt} \times L_m \tag{9}$$

$$\Delta u_{\varphi\varphi} = \Delta i_{\varphi\varphi} \times R_m + \frac{d\Delta i_{\varphi\varphi}}{dt} \times L_m \tag{10}$$

The impedance angle of line is φ_L. Because of the angle of Z_m 、Z_n is about 80°, the biggest sensitive angle of directional element is $\varphi_L + 180°$ when the fault happens in the positive direction and the biggest sensitive angle of directional element is φ_L when the fault happens in the reverse direction. Figure 2 shows the operating characteristics of directional relay.

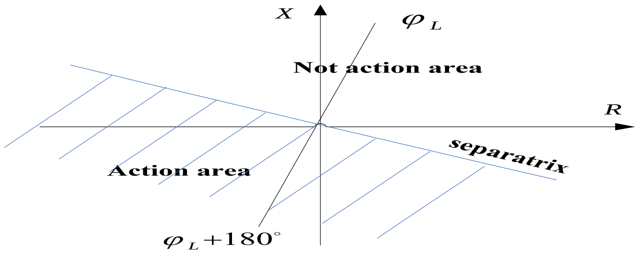

Figure 2. Action Characteristic Diagram of Directional Relay

The direction discrimination of power frequency variation proposed above has regardless of load current and system oscillation. It can reflect all faults in the operation of full phase and open-phase. It also has fast response speed and clear direction. Although it can only reflect the initial instant of the fault and cannot reflect the whole process, but has a good performance for the removal of proximal fault of EHV transmission line in a very short time.

2.3. Fault Phase Discriminant

In this paper, to distinguish the fault type and fault phase, the principle of mutation quantity of voltage is employed in the phase selection algorithm [18]. Obviously, ΔU of fault phase is bigger than ΔU of non-fault phase. For example, the fault happens in A phase:

$$\Delta U_{\mathrm{A}} > \Delta U_{\mathrm{AB}} = \Delta U_{\mathrm{CA}} > \Delta U_{\mathrm{B}} = \Delta U_{\mathrm{C}}, \ \ \Delta U_{\mathrm{BC}} = 0$$

2.4. Protection Operation Characteristic

The protection scheme in this paper is polygon direction impedance characteristics which has offset characteristic. The quadrilateral operating characteristic has the capability of bearing transition resistance on the impedance plane and the main factor limiting the protective range is the value of measurement reactance.

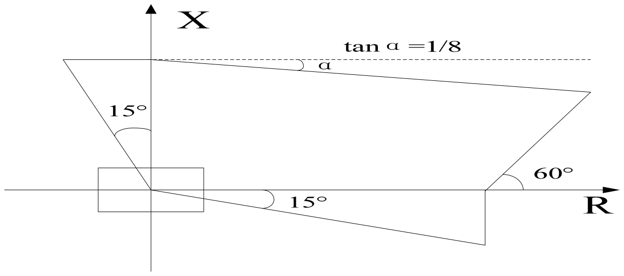

Figure 3. Protection Action Characteristic Diagram

3. The Inprovement Of Differential Equation Algorithm

As we can see from the above analysis, the problem of the fault protection or fast action for the EHV long line is attributed to the formula（1）（2）（9）（10）, and all of them are based on the R-L model in the form of the differential equation, the differential equation algorithm is very important to the calculation of protection.

Literature [19] makes a comparative analysis of the four kinds of algorithm which is for solving differential equation. Literature [20] analyzes the application of the least squares algorithm in solving the differential equation. In this paper, integral fast response, small computational workload characteristics, we use the integration algorithm as the main for its integral fast response, small computational workload characteristics to get the result of R and L.

In order to get the R and L, the two unknown quantities, we make the integration respectively in the two time intervals t1~t2、t3~t4:

$$\int_{t1}^{t2} udt = R_1 \times \int_{t1}^{t2} idt + L_1 \times (i_{t2} - i_{t1}) \tag{11}$$

$$\int_{t3}^{t4} udt = R_1 \times \int_{t3}^{t4} idt + L_1 \times (i_{t4} - i_{t3}) \tag{12}$$

Trapezoidal method is available for each integration above in an approximated level, so we can get the R and L from the linear equation in two unknowns

$$L_1 = (e \times d - c \times f) / ((a \times e - b \times c) \times f) \tag{13}$$

$$R_1 = (b \times d - a \times f) / (b \times c - a \times e) \tag{14}$$

where f is sampling rate, $a = i_{t2} - i_{t1}$, $b = i_{t4} - i_{t3}$, $c = \int_{t1}^{t2} idt$, $d = \int_{t1}^{t2} udt$, $e = \int_{t3}^{t4} idt$, $f = \int_{t3}^{t4} udt$ 。c、d、e、f each has the integral filtering property whereas, a、b has the differential filtering property. When the integration interval increases, it will have a certain function in filtering and the calculation accuracy at the same time will gradually improve, but also will increase operating time. In this article, the integration algorithm using variable interval ,of which the self-protection of the data window automatically increasing with the increasing sampling points, finally stable to half cycle integration.

The protection algorithm in this paper has a good operation characteristic in the trouble but does not participate in the calculation in normal operation, which effectively saves the calculation amount of the protection device. During normal operation, $\Delta u \approx 0$、$\Delta i \approx 0$, so the actuating element is required to start the device and the formula of the actuating element formula is:

$$\Delta I_{\varphi} > 1.25 \Delta I_T + \Delta I_{dz} \tag{15}$$

ΔI_{dz} is starting constant value of current mutation ΔI_T is floating threshold, automatically gradually increasing with the increasing output of the variation. If we take 1.25 times the ΔI_T , then the threshold current is always slightly higher than the unbalanced output.

4. RTDS Simulation Analysis

Through the RTDS, simulation system model has been structured to verify the protection algorithm this paper proposed. Figure 4 shows the system model. Voltage level is 500kV. The length of transmission line is 500km, so distributed parameter model should be developed. The system frequency is 50Hz and 100 points should be sampled a cycle. Protection is placed at the side of the M .The fault point K1 is bus fault, K2 is fault happens at the exit of line, and K3 is proximal fault at the 30% of the full line.

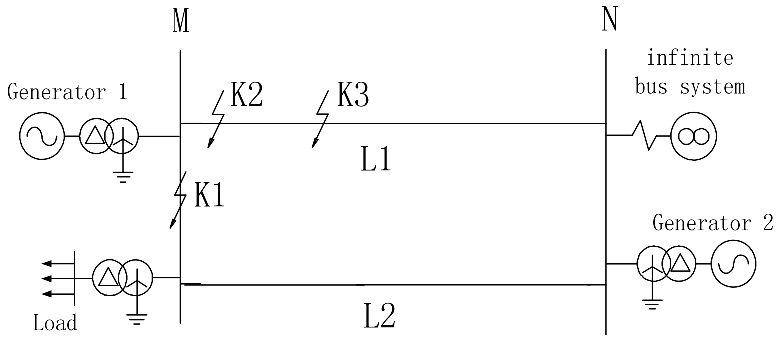

Figure 4. The Model of Simulation System

The model parameters of the simulation system is as shown in Table 1.

Table 1. Model Parameters of Simulation System

x1(Ω/km)	Φ1	C1(μF/km)	X0(Ω/km)	Φ0	C0(μF/km)
0.436Ω	81^0	0.0089μF	1.309Ω	76^0	0.00623μF

A large number of tests for single phase earth fault, inter-phase short circuit and phase-to-phase earth short circuit for different fault time have been conducted, and parts of simulation results have been shown in figure 5 to 7. Time is used as abscisya whose unit is ms and impedance amplitude is used as ordinate whose unit is Ω . Faults all occur at 0ms.

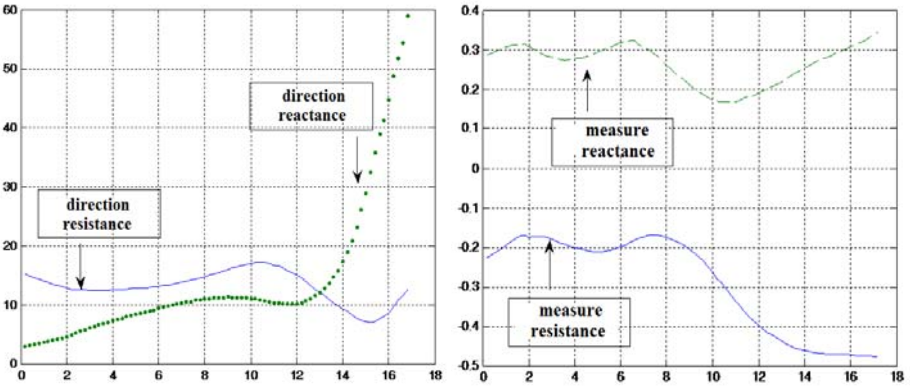

Figure 5. A-G Fault Simulation Result of Position K1

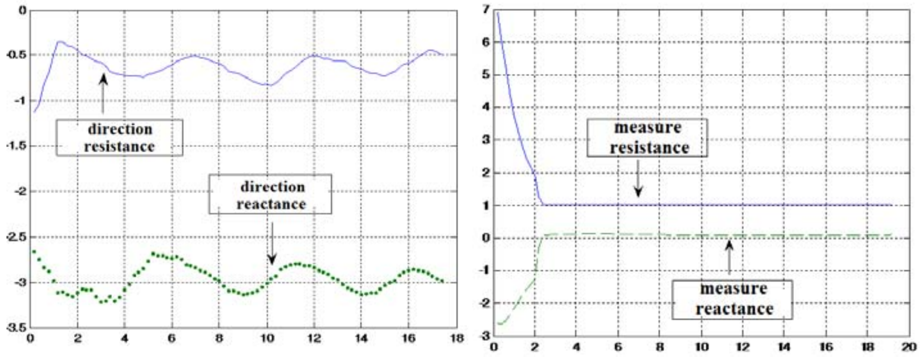

Figure 6. A-G Fault Simulation Result of Position K2

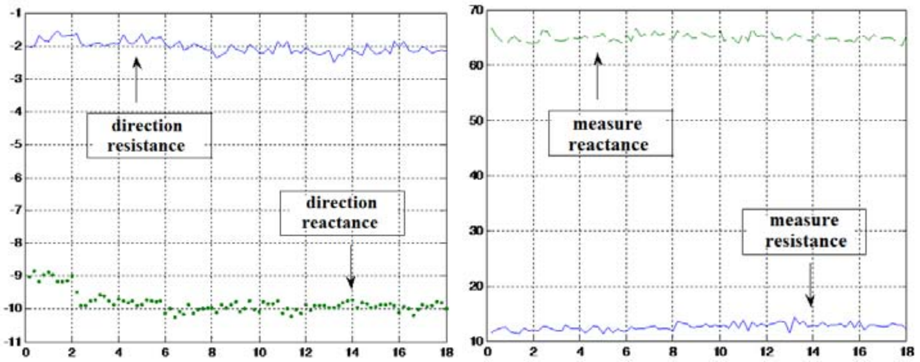

Figure 7. A-G fault Simulation Result of Position K3

The simulation results in Figure 5~7 show that the measured impedance curve converges to a straight curve by less than 3ms which shows a good convergence and verify the rapidity of protection effectively. At the fault point K1 and fault point K2, the measured impedance is too small which easily leads to maloperation, but at this moment, directional element has clear direction which ensures the correctness of the protection action.

In a large number of tests, when fault happens at the exit of line, correct operation of protection can occur in 3ms, and when fault happens at the 30% of the full line, the period of correct operation is also less than 5ms.

5. Conclusion

Based on differential equation model and power frequency variation principle, the method this paper proposed has fast response speed and small workload. And the protection for proximal fault of long distance EHV transmission lines can be correctly implemented in a very short time. Simulation results show that, this algorithm has the performance of reliable and fast action for Proximal Fault of EHV Transmission Line. The method is realized without digital filter. Integration algorithm has the characteristics of simple and fast which increase the action speed of protection effectively. In addition, it has regardless of system frequency change factors, a high reliability and a good practical significance.

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