The Application of Digital Relay in Fault Location Identification for Cable in Steel-pipe

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Abstract - The Electromagnetic Transients Program (EMTP) after minor adaptation is utilized to simulate the grounded fault of cable in steel-pipe. The zero sequence impedance became nonlinear during the fault period, because the zero sequence current in steel-pipe induced a magnetic saturation effect. Consequently, the zone protection of cable in steel-pipe has a serious error if a traditional distance relay is used. To correct this possible malfunction a novel idea by proposed digital relay is presented. The physical zero sequence impedance will dynamically be modified according to the zero sequence current in case of grounded fault. With such real cable data, an accurate fault location of cable in steel-pipe is accordingly estimated.

Introduction

Most transmission lines in metropolis are underground. It is very difficult to detect the fault location when the underground cables with short circuit fault, so it usually off-line uses the extra apparatus to find the fault position. On the other hand it often uses the steel-pipe to avoid the transmission lines are damaged by the frequently road maintenance. The zero sequence impedance has become nonlinear because the zero sequence current in steel-pipe induced a magnetic saturation effect. Using a traditional distance relay perform the zone protection of cable in steel-pipe will incur a considerable error, since the zero sequence impedance in a traditional relay is programmed to be a constant. To correct this possible malfunction a novel idea by proposed digital relay is presented. The physical zero sequence impedance will dynamically be modified according to the zero sequence current in case of grounded fault. The polynomial regression is described the nonlinear zero sequence impedance-current characteristic curve. Different zero sequence current flow through steel-pipe corresponds with different zero sequence impedance. As a result, an accurate fault location can accordingly be estimated.

Algorithm of Digital Distance Relay

The algorithm of digital distance relay contains fault detection, digital filtering, fault type classification, zero sequence impedance modification and fault location estimation[1]-[3].

Although the change of transmission line current follows the load demand, in normal system the change is small in a moment. The quantity of current sample change can detect fault occur or not. If the change is larger than setting value the fault maybe exist. Every sample after fault detection needs to perform digital filter till the algorithm been finished. The recursive Discrete Fourier Transform is able to recover the fundamental voltage and current signals. The next step is to decide the fault type. The zero sequence impedance must be dynamically justified if line to ground fault type is detected. As long as the fault is really exist, it can continue to find the same fault type three times. Finally, the fault location according to the fault type can be calculated. Figure 1 is the flowchart of the proposed digital distance relay for cable in steel-pipe.

Fig. 1 Digital distance relay flowchart

Zero Sequence Current Influence of the Cable in Steel-Pipe

The relative permeability of steel-pipe will change along with the magnetic flux density. When the magnetic flux density increases the relative permeability will be greater. But if the magnetic flux density is too large, the relative permeability will be decreased. It is due to the magnetic saturation effect. From equation (1) and (2), $R_p D_p$ and $X_p D_p$ are the function of square root of magnetic permeability[4]. If cable in steel-pipe with grounded fault and the zero sequence impedance will alter according to the zero sequence current flows in steel-pipe. Figure 2 is zero sequence current-zero sequence impedance relation curve based on 5 inches steel-pipe, 350MCM copper cable[5]. Equation (3) and (4) is the polynomial regression to approximate the nonlinear impedance characteristic curve.

$$R_p D_p = K_r \sqrt{u} \quad (\text{u}\Omega/\text{ft}) \quad (1)$$

$$X_p D_p = K_x \sqrt{u} \quad (\text{u}\Omega/\text{ft}) \quad (2)$$

where

u : steel-pipe magnetic permeability

D_p : steel-pipe inside diameter

K_r : correct affect, average is 29.9

K_x : correct affect, average is 18.1

$$R_0 / R_1 = \sum_{n=0}^5 a_n [\ln 3 I_0]^n \quad (3)$$

$$X_0 / X_1 = \sum_{n=0}^5 b_n [\ln 3 I_0]^n \quad (4)$$

Fig. 2 Zero sequence current-impedance curve

Grounded Fault Simulation of Underground Cable

Figure 3 is the one line diagram of simulation power system and Table 1 list the system parameters. E_a and E_b are the equivalent source voltage. Z_a and Z_b are the equivalent source impedance. Z_{tr} is the equivalent transfer impedance between BusA and BusB. Z_l is a unit impedance of underground cable. The length, L of cable is 20 kilometers. R represents relays that can obtain line voltage and current signals from PT and CT. The arc resistance of

grounded fault is R_f and the distance from BusA to fault point is X .

Figure 4 is the flowchart of EMTP simulation grounded fault in steel-pipe. First, iterative uses the EMTP to find the actual cable zero sequence impedance in fault condition. Equation (3) and (4) to simulate the grounded fault of underground cable in steel-pipe. Then the voltage and current signals from EMTP are regarded as input data for digital distance relay program. There are 32 samples in every cycle. Different fault type, resistance and distance will consider to verify the digital distance rely program which can accurately estimate the fault location.

Fig. 3 One line diagram of simulation power system

Fig. 4 Flowchart of EMTP simulation the grounded fault of cable in steel-pipe

Table 1 Power system parameters for simulation

System voltage: 345KV, 60Hz	
$E_a=1.0\angle 0^\circ$ $E_b=1.0\angle 10^\circ$	
$Z_{a1}=0.238+j5.7132$ ohm	
$Z_{a0}=2.738+j10.000$ ohm	
$Z_{b1}=0.238+j6.1900$ ohm	
$Z_{b0}=0.833+j5.1180$ ohm	
$Z_{tr1}=0.357+j2.1425$ ohm	
$Z_{tro}=4.999+j6.6654$ ohm	
Cable :	
positive sequence : $R=0.0321$ ohm/km	
$L=0.473$ mH/km $C=0.038$ uF/km	
zero sequence : $R=.3479$ ohm/km	
$L=1.37$ mH/km $C=.038$ uf/km	

Table 2 Fault location estimation

R \ X		5km	10km	15km
0.01Ω	A	X=4.98819 R=0.01039 T=0.05	X=9.97813 R=0.01046 T=0.05	X=14.9703 R=0.01047 T=0.05
	B	X=4.99698 R=0.01366 T=0.05	X=9.98949 R=0.01508 T=0.05	X=14.9663 R=0.01049 T=0.05
	C	X=5.03147 R=-0.00449 T=0.04792	X=10.0200 R=-0.00252 T=0.04739	X=14.9788 R=0.00467 T=0.05
10Ω	A	X=5.00022 R=9.9992 T=0.03438	X=10.0013 R=9.990 T=0.02448	X=15.0377 R=9.952 T=0.04739
	B	X=5.02008 R=9.9976 T=0.02604	X=10.03898 R=9.953 T=0.02656	X=14.9610 R=10.03 T=0.04219
	C	X=4.98058 R=10.01 T=0.03385	X=10.1091 R=9.90682 T=0.05	X=14.9656 R=10.03 T=0.03438
25Ω	A	X=5.01087 R=24.97 T=0.03646	X=10.00795 R=24.96 T=0.02552	X=15.0242 R=24.9138 T=0.05
	B	X=5.01072 R=24.96 T=0.04218	X=9.95232 R=25.09 T=0.033854	X=15.0683 R=24.8014 T=0.05
	C	X=5.02051 R=24.9540 T=0.05	X=10.0616 R=24.89 T=.033854	X=15.0231 R=24.91 T=0.04115

A: balance three phase fault
B: single phase-to-ground fault in unmagnetic-pipe
C: single phase-to-ground fault in steel-pipe
R: calculated fault resistance (ohm)
X: estimated fault location (km)
T: converge time (sec)

Fault Location Estimation

Figure 5 - Figure 7 are fault location estimation for balance three phase fault. Figure 8 - Figure 10 are fault location estimation for single phase-to-ground fault in unmagnetic-pipe. Figure 11 - Figure 13 are single phase-to-ground fault in steel-pipe. It assumes that the fault location occurs at 5km, 10km, 15km and the fault resistance assumes to be 0.01ohm, 10ohm and 25ohm individually. All faults happened at 0.001second. The numerical computer simulation results are shown on Table 2.

Fig. 5 Balance three phase fault and $R_f=0.01$ ohm

Fig. 6 Balance three phase fault and $R_f=10$ ohm

Fig. 7 Balance three phase fault and $R_f=25$ ohm

Fig. 8 Single phase-to-ground fault in unmagnetic-pipe and $R_f=0.01\text{ohm}$

Fig. 11 Single phase-to-ground fault in steel-pipe and $R_f=0.01\text{ohm}$

Fig. 9 Single phase-to-ground fault in unmagnetic-pipe and $R_f=10\text{ohm}$

Fig. 12 Single phase-to-ground fault in steel-pipe and $R_f=10\text{ohm}$

Fig.10 Single phase-to-ground fault in unmagnetic-pipe and $R_f=25\text{ohm}$

Fig. 13 single phase-to-ground fault in steel-pipe and $R_f=25\text{ohm}$

Discussion

Obviously, a serious error exists in unmodified distance estimation. The reason is that the cable zero sequence impedance in steel-pipe highly depend on the ground fault current during the fault period. A novel idea uses the polynomial regression to fit the nonlinear zero sequence current-impedance characteristic curves. Each case study approximately needs 3-5 iterations to get the correct zero sequence impedance. First, utilizes the default zero sequence impedance to compute the fault distance, next uses the distance to estimate the fault current, then calculation the new zero sequence impedance by means of polynomial regression. The iteration will not stop until the distance variation been converge.

Digital filter technique extremely influences converge speed of rebuild fundamental frequency signals, so do fault resistance and fault location. Easy realization and accurate effects are advantages of the recursive Discrete Fourier Transform. But its converge speed is often slow. However, an alternative method is used to improve the converge speed of fault location estimation. Equation (5) is obtained from the observation of all case study results.

$$X_k \approx X_o + dX \times e^{-k \Delta t / T} \times \sin(wk \Delta t + \alpha) \quad (5)$$

where

- X_k: the Kth distance estimation
- X_o: the final distance estimation
- dX: the maximum distance estimation violation
- T: the exponential decay period
- k: the Kth sample
- Δt: the sample period time
- w: the distance estimation oscillation frequency

If increases the sample frequency, the maximum distance estimation violation dX will decrease. The normal convergent condition is that the distance change is small than 3m and has lasted three time. There is a fast and approximate method to estimate the fault location. The average of all estimation during the third fault period is close the true value when normal convergent condition did not arrive. Table 2 shows the estimation result and converge time.

Conclusion

Underground cables utilize steel-pipe to protect themselves is quite often in power transmission system. Unfortunately, the zero sequence impedance of cable in steel-pipe is highly depend on the ground fault current during the fault period because of magnetic saturation effect. Using EMTP to find fault current and correcting zero sequence impedance by polynomial function are iterative performed for grounded fault simulation of cable in steel-pipe. The polynomial function described the zero sequence

current-impedance curve is set up in the memory of the proposed digital distance relay. Whenever ground fault exists between cable and steel-pipe, repeatedly used the function to correct the zero sequence impedance and then estimate the real fault location. The computer simulation shows that the fault location estimation can converge within three cycles with error less than 1%.

Reference

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Appendix I

Recursive Discrete Fourier Transform is able to obtain the fundamental signal by Equation (6) and (7).

$$Y_c^{(nw)} = Y_c^{(old)} + \frac{2}{N} [y_k - y_{k-N}] \cos(k\theta) \quad (6)$$

$$Y_s^{(nw)} = Y_s^{(old)} + \frac{2}{N} [y_k - y_{k-N}] \sin(k\theta) \quad (7)$$

where

$$\theta = 2\pi/N$$

$$Y_1 \angle \alpha_1 = Y_1 \cos \alpha_1 + j Y_1 \sin \alpha_1 = Y_c + j Y_s$$

Y_c: real part of the fundamental signal

Y_s: image part of the fundamental signal

N: the sample frequency

y_k: the kth sample

Appendix II

Balance three phase fault location estimation:

$$V_1 = I_1 X Z_{A1} + I_1 R_f \quad (8)$$

$$V_1 = I_1 X Z_{A1} + R_f \Delta I / D \quad (9)$$

where

$$I_f = \Delta I / D$$

$$\Delta I = I_1(\text{after fault}) - I_1(\text{before fault})$$

D: current distribute factor

$$D = \frac{Z_{g1}Z_{u1} + (L-X)Z_{11}(Z_{s1} + Z_{g1} + Z_{u1})}{(Z_{s1} + Z_{g1})Z_{u1} + LZ_{11}(Z_{s1} + Z_{g1} + Z_{u1})} \quad (10)$$

Using equation (9) and (10), obtain equation (11) - (12).

$$X^2 - (a_1 + jb_1)X + (a_2 + jb_2) - (a_3 + jb_3)R_1 = 0 \quad (11)$$

$$X^2 - (a_1 - \frac{a_2b_1}{b_3})X + (a_3 - \frac{a_2b_2}{b_3}) = 0 \quad (12)$$

$$R_1 = \frac{-b_1X + b_2}{b_3} \quad (13)$$

where

$$\begin{aligned} a_1 + jb_1 &= \frac{V_1}{I_1Z_{11}} + \frac{Z_{s1}Z_{u1}}{Z_{11}Z_{u1}} + L \\ a_2 + jb_2 &= \frac{V_1}{I_1Z_{11}Z_{12}Z_{13}} (Z_{s1}Z_{u1} + LZ_{12}Z_{13}) \\ a_3 + jb_3 &= \frac{\Delta I}{I_1Z_{11}Z_{12}Z_{13}} [(Z_{s1} + Z_{g1})Z_{u1} + LZ_{12}Z_{13}] \\ Z_{12} &= Z_{11}(Z_{s1} + Z_{g1} + Z_{u1}) \end{aligned}$$

Single phase-to-ground fault location estimation:

assume that phase A is fault phase

$$V_A = V_1 + V_2 + V_0 = (I_1XZ_{11} + I_2XZ_{12} + I_0XZ_{10}) + I_1R_f \quad (14)$$

$$I_f = \Delta I_1 / D_1 = \Delta I_0 / D_0$$

$$D_1 = \frac{1}{3} \frac{Z_{g1}Z_{u1} + (L-X)Z_{11}(Z_{s1} + Z_{g1} + Z_{u1})}{(Z_{s1} + Z_{g1})Z_{u1} + LZ_{11}(Z_{s1} + Z_{g1} + Z_{u1})} \quad (15)$$

$$D_0 = \frac{1}{3} \frac{Z_{g0}Z_{u0} + (L-X)Z_{10}(Z_{s0} + Z_{g0} + Z_{u0})}{(Z_{s0} + Z_{g0})Z_{u0} + LZ_{10}(Z_{s0} + Z_{g0} + Z_{u0})} \quad (16)$$

Similarly, use equation (14)-(16), obtain equation (17)-(19).

$$X^2 - (a_1 + jb_1)X + (a_2 + jb_2) - (a_3 + jb_3)R_1 = 0 \quad (17)$$

$$X^2 - (a_1 - \frac{a_2b_1}{b_3})X + (a_3 - \frac{a_2b_2}{b_3}) = 0 \quad (18)$$

$$R_1 = \frac{-b_1X + b_2}{b_3} \quad (19)$$

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