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분포정수회로 해석 방법을 이용한 지중선로 고장점 추정 알고리즘

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A Novel Algorithm of Underground Cable Fault Location based on the analysis of Distributed Parameter Circuit

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Abstract- This paper proposes a new algorithm of underground cable fault location based on the analysis of distributed parameter circuit. The proposed method firstly makes voltage and current equations for each of cores and sheathes respectively, and then establishes an equation of the fault distance according to the analysis of the fault conditions. Finally the solution of this equation is calculated by Newton-Raphson iteration method. The effectiveness of this proposed algorithm has been proven through PSCAD/EMTDC simulations.

1. Introduction

During last several decades electric power systems became more complicated and diversified with rapid economic growth. Nowadays modern power systems demand larger capacity transmission and higher quality electric power than ever. With an increased environmental concern, there is an upsurge in demand for underground cables, which are installed a lot now even though the underground system costs more for initial construction. Because the cable systems have to be pulled down to check for defects in the underground faulted section and any wear and tear in the cable sheaths. In order to minimize disruption in services, utilities have to maintain these cables usually at great costs. That is why fault location estimation and repair are much harder than those of overhead transmission and distribution systems. Therefore, this inevitably leads to a demand for accurate cable fault detection and location technique

So far many techniques and methods of cable fault location have been reported. The two categories of fault location are terminal methods and tracer methods [1]. The terminal methods are performed from one or both ends of the cable line. The tracer methods require walking the route to locate an audible or electromagnetic signal. For instance, one of the fault location methods is using Traveling Wave [2]. But in this method, there is a problem that the fault data sampling frequency should be in high band because when the data is filtered the data attenuation phenomenon happens, so that means it is difficult to apply in practice. The other of the fault location methods is using combined fuzzy logic & wavelet analysis [3], which presents the results of investigations into a new fault location technique using advanced signal processing technique based on wavelet technology to extract useful information. Thirdly, there have been many researches in progress about the analysis of underground cable for the EMTP [4].

This paper proposes a new algorithm calculating the fault distance for one-phase to ground fault on an underground power cable. And the circuit is a balanced three-phase circuit. The fault distance is using the sending-end voltage and current values that are from PSCAD/EMTDC simulations. And the proposed algorithm has been tested with various fault distances and fault impedance.

2. Proposed algorithm

Proposed algorithm is based on the analysis of distributed parameter circuit [5], which is the essence of this algorithm. In this case, the cable type is a single-core (SC) coaxial cable, which is composed of core and sheath. In general, the cable inductance is around 1/3 of that at the overhead line, but the capacitance of the cable is about 30 times of that at the overhead line. So this proposed algorithm has attached importance to the influence of the cable capacitance. In the following, distributed parameter circuit will be briefly introduced, and then the configuration of the used cable will be also depicted.

2.1 Distributed Parameter Circuit (DPC)

Cable impedance and admittance are distributed parameter on every delta x of the cable line. A typical differential section of line length *dx* is shown in Fig. 1. The series impedance of the differential section is *z dx*. The shunt admittance is *y dx* its location within the differential section is of no consequence.

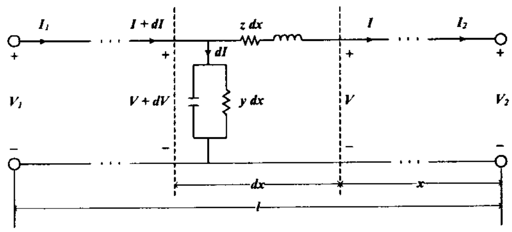

Fig. 1 Cable model of the distributed parameter circuit

Applying Kirchhoff's voltage law (KVL) and Kirchhoff's current law (KCL) to the section, and then can get.

$$dV = I\,z\,dx$$
$$dI = (V + dV)ydx \approx Vydx \qquad (1)$$

In (1), neglect the products of differential quantities, and then get two second-order linear differential equations.

$$\frac{d^2V}{dx^2} = yzV = \gamma^2 V \quad \text{or} \quad \frac{d^2I}{dx^2} = yzI = \gamma^2 I \qquad (2)$$

Using the standard method of solving linear ordinary differential equations, determine that the characteristic equation is $s^2 - \gamma^2 = 0$, and the characteristic roots are thus $s_1, s_2 = \pm\gamma$. The general solution for V is then

$$V = k_1 e^{\gamma x} + k_2 e^{-\gamma x}$$
$$= (k_1 + k_2)\frac{e^{\gamma x} + e^{-\gamma x}}{2} + (k_1 - k_2)\frac{e^{\gamma x} - e^{-\gamma x}}{2}$$
$$= K_1 \cosh\gamma x + K_2 \sinh\gamma x \qquad (3)$$

2.2 Configuration of Underground Power Cable

In this proposed algorithm, the underground power cable is assumed two conductors, which are core and sheath. There are mutual impedance and admittance between each of conductors, such as those of core-to-core, core-to-sheath, and sheath-to-sheath. And the three-phase SC coaxial cables are installed under the earth surface like a triangle shape.

2.3 Proposed Algorithm based on DPC

The equivalent circuit model of underground cable system is illustrated above in Fig. 3. In comparison with overhead line system, underground cable system takes on significant characteristics such as a little smaller inductance and quite larger capacitance. The model system is consists of three parts. The first part is Thevenin's equivalent source. The second part is the cable line in which a kind of faults occurs. The third part is the equivalent load.

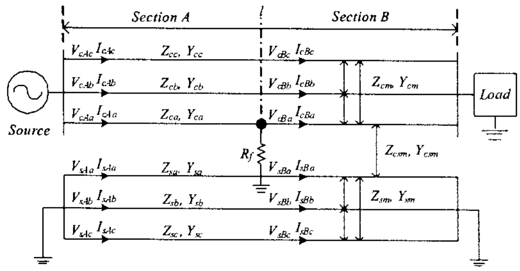

Fig. 3 Equivalent circuit model of the cable system

This algorithm considers the fault type is the single core-to-sheath to ground fault. The faulted cable system can be divided into two sections which are section A and section B. Section A is from sending-end to fault point, and section B is from fault point to receiving-end. At first, cable section A is analyzed. If extending the SC coaxial cable analysis to describe in section 2-1, the voltage and current equations of section A can be established as (4), (5), (6), and (7).

$$-\frac{\partial Vc_{abc}}{\partial x} = Zc_{abc} Ic_{abc} + Zcs_{abc} Is_{abc} \quad (4)$$

$$-\frac{\partial Vs_{abc}}{\partial x} = Zcs_{abc} Ic_{abc} + Zs_{abc} Is_{abc} \quad (5)$$

$$-\frac{\partial Ic_{abc}}{\partial x} = Yc_{abc} Vc_{abc} + Ycs_{abc} Vs_{abc} \quad (6)$$

$$-\frac{\partial Is_{abc}}{\partial x} = Ycs_{abc} Vc_{abc} + Ys_{abc} Vs_{abc} \quad (7)$$

And then can be expressed in matrix form by symmetrical conversion as illustrated in (8).

$$\begin{bmatrix} \dot{V}c_{012} \\ \dot{V}s_{012} \\ \dot{I}c_{012} \\ \dot{I}s_{012} \end{bmatrix} = -\begin{bmatrix} 0 & 0 & Zc_{012} & Zcs_{012} \\ 0 & 0 & Zcs_{012} & Zs_{012} \\ Yc_{012} & Ycs_{012} & 0 & 0 \\ Ycs_{012} & Ys_{012} & 0 & 0 \end{bmatrix} \begin{bmatrix} Vc_{012} \\ Vs_{012} \\ Ic_{012} \\ Is_{012} \end{bmatrix} \quad (8)$$

Equation (8) is matrix equations for zero-sequence, positive-sequence, and negative-sequence. Their eigenvalues are defined as α_0, β_0, α_1, β_1, α_2, β_2. Due to Distributed parameter circuit, the solution of (1) can be illustrated by hyperbolic function in (3). So the proposed algorithm also follows this way to get the following equations.

Equation (9), (10), (11), (12) are for zero-sequence,

$$V_{cA0}(x) = A_0 \cosh \alpha_0 x + B_0 \sinh \alpha_0 x + C_0 \cosh \beta_0 x + D_0 \sinh \beta_0 x \quad (9)$$

$$V_{sA0}(x) = A_0' \cosh \alpha_0 x + B_0' \sinh \alpha_0 x + C_0' \cosh \beta_0 x + D_0' \sinh \beta_0 x \quad (10)$$

$$I_{cA0}(x) = a_0 \cosh \alpha_0 x + b_0 \sinh \alpha_0 x + c_0 \cosh \beta_0 x + d_0 \sinh \beta_0 x \quad (11)$$

$$I_{sA0}(x) = e_0 \cosh \alpha_0 x + f_0 \sinh \alpha_0 x + g_0 \cosh \beta_0 x + h_0 \sinh \beta_0 x \quad (12)$$

Equation (13), (14), (15), (16) are for positive-sequence,

$$V_{cA1}(x) = A_1 \cosh \alpha_1 x + B_1 \sinh \alpha_1 x + C_1 \cosh \beta_1 x + D_1 \sinh \beta_1 x \quad (13)$$

$$V_{sA1}(x) = A_1' \cosh \alpha_1 x + B_1' \sinh \alpha_1 x + C_1' \cosh \beta_1 x + D_1' \sinh \beta_1 x \quad (14)$$

$$I_{cA1}(x) = a_1 \cosh \alpha_1 x + b_1 \sinh \alpha_1 x + c_1 \cosh \beta_1 x + d_1 \sinh \beta_1 x \quad (15)$$

$$I_{sA1}(x) = e_1 \cosh \alpha_1 x + f_1 \sinh \alpha_1 x + g_1 \cosh \beta_1 x + h_1 \sinh \beta_1 x \quad (16)$$

Equation (17), (18), (19), (20) are for negative-sequence,

$$V_{cA2}(x) = A_2 \cosh \alpha_2 x + B_2 \sinh \alpha_2 x + C_2 \cosh \beta_2 x + D_2 \sinh \beta_2 x \quad (17)$$

$$V_{sA2}(x) = A_2' \cosh \alpha_2 x + B_2' \sinh \alpha_2 x + C_2' \cosh \beta_2 x + D_2' \sinh \beta_2 x \quad (18)$$

$$I_{cA2}(x) = a_2 \cosh \alpha_2 x + b_2 \sinh \alpha_2 x + c_2 \cosh \beta_2 x + d_2 \sinh \beta_2 x \quad (19)$$

$$I_{sA2}(x) = e_2 \cosh \alpha_2 x + f_2 \sinh \alpha_2 x + g_2 \cosh \beta_2 x + h_2 \sinh \beta_2 x \quad (20)$$

At last, through undetermined coefficient method, all coefficients can be solved as shown in table 1.

Table 1 Coefficients

zero-sequence	positive-sequence	negative-sequence
$A_0' = C_{10} A_0$	$A_1' = C_{11} A_1$	$A_2' = C_{12} A_2$
$B_0' = C_{10} B_0$	$B_1' = C_{11} B_1$	$B_2' = C_{12} B_2$
$C_0' = C_{20} C_0$	$C_1' = C_{21} C_1$	$C_2' = C_{22} C_2$
$D_0' = C_{20} D_0$	$D_1' = C_{21} D_1$	$D_2' = C_{22} D_2$
$a_0 = C_{30} B_0$	$a_1 = C_{31} B_1$	$a_2 = C_{32} B_2$
$b_0 = C_{30} A_0$	$b_1 = C_{31} A_1$	$b_2 = C_{32} A_2$
$c_0 = C_{40} D_0$	$c_1 = C_{41} D_1$	$c_2 = C_{42} D_2$
$d_0 = C_{40} C_0$	$d_1 = C_{41} C_1$	$d_2 = C_{42} C_2$
$e_0 = C_{50} B_0$	$e_1 = C_{51} B_1$	$e_2 = C_{52} B_2$
$f_0 = C_{50} A_0$	$f_1 = C_{51} A_1$	$f_2 = C_{52} A_2$
$g_0 = C_{60} D_0$	$g_1 = C_{61} D_1$	$g_2 = C_{62} D_2$
$h_0 = C_{60} C_0$	$h_1 = C_{61} C_1$	$h_2 = C_{62} C_2$

So the following matrix equations are depicted for cable section A in each sequence.

$$\begin{pmatrix} V_{cA0}(x) \\ V_{sA0}(x) \\ I_{cA0}(x) \\ I_{sA0}(x) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_0 x & \sinh\alpha_0 x & \cosh\beta_0 x & \sinh\beta_0 x \\ C_{10}\cosh\alpha_0 x & C_{10}\sinh\alpha_0 x & C_{20}\cosh\beta_0 x & C_{20}\sinh\beta_0 x \\ C_{30}\sinh\alpha_0 x & C_{30}\cosh\alpha_0 x & C_{40}\sinh\beta_0 x & C_{40}\cosh\beta_0 x \\ C_{50}\sinh\alpha_0 x & C_{50}\cosh\alpha_0 x & C_{60}\sinh\beta_0 x & C_{60}\cosh\beta_0 x \end{pmatrix} \begin{pmatrix} A_0 \\ B_0 \\ C_0 \\ D_0 \end{pmatrix} \quad (21)$$

$$\begin{pmatrix} V_{cA1}(x) \\ V_{sA1}(x) \\ I_{cA1}(x) \\ I_{sA1}(x) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_1 x & \sinh\alpha_1 x & \cosh\beta_1 x & \sinh\beta_1 x \\ C_{11}\cosh\alpha_1 x & C_{11}\sinh\alpha_1 x & C_{21}\cosh\beta_1 x & C_{21}\sinh\beta_1 x \\ C_{31}\sinh\alpha_1 x & C_{31}\cosh\alpha_1 x & C_{41}\sinh\beta_1 x & C_{41}\cosh\beta_1 x \\ C_{51}\sinh\alpha_1 x & C_{51}\cosh\alpha_1 x & C_{61}\sinh\beta_1 x & C_{61}\cosh\beta_1 x \end{pmatrix} \begin{pmatrix} A_1 \\ B_1 \\ C_1 \\ D_1 \end{pmatrix} \quad (22)$$

$$\begin{pmatrix} V_{cA2}(x) \\ V_{sA2}(x) \\ I_{cA2}(x) \\ I_{sA2}(x) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_2 x & \sinh\alpha_2 x & \cosh\beta_2 x & \sinh\beta_2 x \\ C_{12}\cosh\alpha_2 x & C_{12}\sinh\alpha_2 x & C_{22}\cosh\beta_2 x & C_{22}\sinh\beta_2 x \\ C_{32}\sinh\alpha_2 x & C_{32}\cosh\alpha_2 x & C_{42}\sinh\beta_2 x & C_{42}\cosh\beta_2 x \\ C_{52}\sinh\alpha_2 x & C_{52}\cosh\alpha_2 x & C_{62}\sinh\beta_2 x & C_{62}\cosh\beta_2 x \end{pmatrix} \begin{pmatrix} A_2 \\ B_2 \\ C_2 \\ D_2 \end{pmatrix} \quad (23)$$

According to the same analysis, the equation of cable section B can be deducted as follows.

$$\begin{pmatrix} V_{cB0}(y) \\ V_{sB0}(y) \\ I_{cB0}(y) \\ I_{sB0}(y) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_0 y & \sinh\alpha_0 y & \cosh\beta_0 y & \sinh\beta_0 y \\ C_{10}\cosh\alpha_0 y & C_{10}\sinh\alpha_0 y & C_{20}\cosh\beta_0 y & C_{20}\sinh\beta_0 y \\ C_{30}\sinh\alpha_0 y & C_{30}\cosh\alpha_0 y & C_{40}\sinh\beta_0 y & C_{40}\cosh\beta_0 y \\ C_{50}\sinh\alpha_0 y & C_{50}\cosh\alpha_0 y & C_{60}\sinh\beta_0 y & C_{60}\cosh\beta_0 y \end{pmatrix} \begin{pmatrix} E_0 \\ F_0 \\ G_0 \\ H_0 \end{pmatrix} \quad (24)$$

$$\begin{pmatrix} V_{cB1}(y) \\ V_{sB1}(y) \\ I_{cB1}(y) \\ I_{sB1}(y) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_1 y & \sinh\alpha_1 y & \cosh\beta_1 y & \sinh\beta_1 y \\ C_{11}\cosh\alpha_1 y & C_{11}\sinh\alpha_1 y & C_{21}\cosh\beta_1 y & C_{21}\sinh\beta_1 y \\ C_{31}\sinh\alpha_1 y & C_{31}\cosh\alpha_1 y & C_{41}\sinh\beta_1 y & C_{41}\cosh\beta_1 y \\ C_{51}\sinh\alpha_1 y & C_{51}\cosh\alpha_1 y & C_{61}\sinh\beta_1 y & C_{61}\cosh\beta_1 y \end{pmatrix} \begin{pmatrix} E_1 \\ F_1 \\ G_1 \\ H \end{pmatrix} \quad (25)$$

$$\begin{pmatrix} V_{cB2}(y) \\ V_{sB2}(y) \\ I_{cB2}(y) \\ I_{sB2}(y) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_2 y & \sinh\alpha_2 y & \cosh\beta_2 y & \sinh\beta_2 y \\ C_{12}\cosh\alpha_2 y & C_{12}\sinh\alpha_2 y & C_{22}\cosh\beta_2 y & C_{22}\sinh\beta_2 y \\ C_{32}\sinh\alpha_2 y & C_{32}\cosh\alpha_2 y & C_{42}\sinh\beta_2 y & C_{42}\cosh\beta_2 y \\ C_{52}\sinh\alpha_2 y & C_{52}\cosh\alpha_2 y & C_{62}\sinh\beta_2 y & C_{62}\cosh\beta_2 y \end{pmatrix} \begin{pmatrix} E_2 \\ F_2 \\ G_2 \\ H_2 \end{pmatrix} \quad (26)$$

A_0, B_0, C_0, D_0, E_0, F_0, G_0, H_0 are unknown parameters of zero-sequence; A_1, B_1, C_1, D_1, E_1, F_1, G_1, H_1 are unknown parameters of positive-sequence; A_2, B_2, C_2, D_2, E_2, F_2, G_2, H_2 are unknown parameters of negative-sequence. Also, through undetermined coefficient method, all constants can be solved as shown in table 2.

Table 2 Constants

zero-sequence	$C_{10} = \frac{\alpha_0^2 - Z_{c0}Y_{c0} - Z_{cs0}Y_{cs0}}{Z_{c0}Y_{cs0} + Z_{cs0}Y_{s0}}$, $C_{40} = -\frac{Y_{c0} + Y_{cs0}C_{20}}{\beta_0}$ $C_{20} = \frac{\beta_0^2 - Z_{c0}Y_{c0} - Z_{cs0}Y_{cs0}}{Z_{c0}Y_{cs0} + Z_{cs0}Y_{s0}}$, $C_{50} = -\frac{Y_{cs0} + Y_{s0}C_{10}}{\alpha_0}$ $C_{30} = -\frac{Y_{c0} + Y_{cs0}C_{10}}{\alpha_0}$, $C_{60} = -\frac{Y_{cs0} + Y_{s0}C_{20}}{\beta_0}$
positive-sequence	$C_{11} = \frac{\alpha_1^2 - Z_{c1}Y_{c1} - Z_{cs1}Y_{cs1}}{Z_{c1}Y_{cs1} + Z_{cs1}Y_{s1}}$, $C_{41} = -\frac{Y_{c1} + Y_{cs1}C_{21}}{\beta_1}$ $C_{21} = \frac{\beta_1^2 - Z_{c1}Y_{c1} - Z_{cs1}Y_{cs1}}{Z_{c1}Y_{cs1} + Z_{cs1}Y_{s1}}$, $C_{51} = -\frac{Y_{cs1} + Y_{s1}C_{11}}{\alpha_1}$ $C_{31} = -\frac{Y_{c1} + Y_{cs1}C_{11}}{\alpha_1}$, $C_{61} = -\frac{Y_{cs1} + Y_{s1}C_{21}}{\beta_1}$
negative-sequence	$C_{12} = \frac{\alpha_2^2 - Z_{c2}Y_{c2} - Z_{cs2}Y_{cs2}}{Z_{c2}Y_{cs2} + Z_{cs2}Y_{s2}}$, $C_{42} = -\frac{Y_{c2} + Y_{cs2}C_{22}}{\beta_2}$ $C_{22} = \frac{\beta_2^2 - Z_{c2}Y_{c2} - Z_{cs2}Y_{cs2}}{Z_{c2}Y_{cs2} + Z_{cs2}Y_{s2}}$, $C_{52} = -\frac{Y_{cs2} + Y_{s2}C_{12}}{\alpha_2}$ $C_{32} = -\frac{Y_{c2} + Y_{cs2}C_{12}}{\alpha_2}$, $C_{62} = -\frac{Y_{cs2} + Y_{s2}C_{22}}{\beta_2}$

The fault distance is assumed as p. The total length of the cable is l. $x = p$ is the same point with $y = 0$.

2.4 Analysis of the fault conditions

In this case, a core-to-sheath to ground fault is assumed in phase aas depicted in Fig. 4.

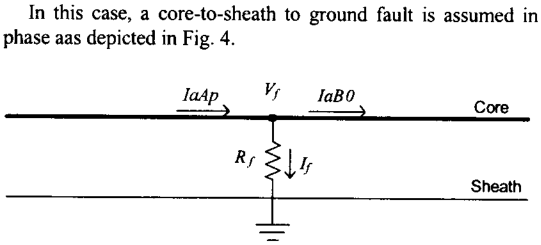

Fig. 4 Core-to-sheath to ground fault in phase a

In order to calculate unknown parameters, through the analysis of the whole system, all conditions can be summarized as follows:

(a) Sequence conditions;

The following conditions are analyzed at the sending-end.

i) Core voltage is equal to source voltage.

ii) Core current is equal to source current.

iii) If the grounding resistance is zero, the sheath voltage is equal to zero. Otherwise, the sheath voltage is equal to three times of the multiplication of the grounding resistance and the sheath current.

The following conditions are analyzed at the fault point.

iv) Core voltage of section A is equal to that of section B.

The following conditions are analyzed at the receiving-end.

v) Core current is equal to the multiplication of the load admittance and the core voltage.

vi) If the grounding resistance is zero, the sheath voltage is equal to zero. Otherwise, the sheath voltage is equal to three times of the multiplication of the grounding resistance and the sheath current.

(b) Phase Conditions;

The all following conditions are analyzed at the fault point.

i) In the faulted phase a, the sheath voltage of section A is equal to zero.

ii) The sheath voltage of the faulted phase a in the section B is equal to zero.

iii) In the non-faulted phase b, core current of section A is equal to that of section B.

iv) In the non-faulted phase c, core current of section A is equal to that of section B.

v) In the non-faulted phase b, sheath current of section A is equal to that of section B.

vi) In the non-faulted phase c, sheath current of section A is equal to that of section B.

All equations are established and listed in table 3

Table 3 Fault conditions

Sequence conditions (18)		
$V_{cA0}(0) = V_{s0}$	$V_{cA1}(0) = V_{s1}$	$V_{cA2}(0) = V_{s2}$
$I_{cA0}(0) = I_{s0}$	$I_{cA1}(0) = I_{s1}$	$I_{cA2}(0) = I_{s2}$
$V_{sA0}(0) = 0$	$V_{sA1}(0) = 0$	$V_{sA2}(0) = 0$
$V_{cA0}(p) = V_{cB0}(0)$	$V_{cA1}(p) = V_{cB1}(0)$	$V_{cA2}(p) = V_{cB2}(0)$
$I_{cB0}(l-p) = Y_{r0}V_{cB0}(l-p)$	$I_{cB1}(l-p) = Y_{r1}V_{cB1}(l-p)$	$I_{cB2}(l-p) = Y_{r2}V_{cB2}(l-p)$
$V_{sB0}(l-p) = 0$	$V_{sB1}(l-p) = 0$	$V_{sB2}(l-p) = 0$
Phase conditions (6)		
$V_{sAa}(p) = 0$	$V_{sBa}(0) = 0$	$I_{cAb}(p) = I_{cBb}(0)$
$I_{cAc}(p) = I_{cBc}(0)$	$I_{sAb}(p) = I_{sBb}(0)$	$I_{sAc}(p) = I_{sBc}(0)$

And then according to all conditions, 24 equations can be established to get all unknown parameters which are expressed as the functions of fault distance p.

2.5 Solution of fault distance by Newton-Raphson method

In Fig. 4, it is easy to get the fault equation $V_f = I_f \times R_f$, and then the following equation can be made.

$$f(p, R_f) = Va_{Ap} - (Ia_{Ap} - Ia_{B0})R_f = 0 \quad (27)$$

where, $Va_{Ap} = V_{cA0}(p) + V_{cA1}(p) + V_{cA2}(p)$

$Ia_{Ap} = I_{cA0}(p) + I_{cA1}(p) + I_{cA2}(p)$

$Ia_{B0} = I_{cB0}(0) + I_{cB1}(0) + I_{cB2}(0)$

And then (27) can be divided as follows,

$$f(p,R_f)=f_r(p,R_f)+jf_i(p,R_f)=0 \qquad (28)$$

That means, $f_r(p,R_f)=0$, $f_i(p,R_f)=0$

At last, Newton-Raphson iteration method is dedicated in getting the value of fault distance p.

3. Simulation result

3.1 Underground Cable System Model

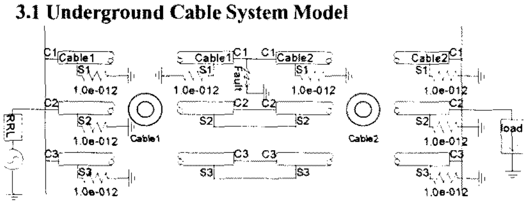

Fig. 5 Simulation model system in PSCAD/EMTDC

The cable type is SC coaxial cable consisting of core and sheath (of 2000㎟, kraft) [6],the voltage level is 154[kV]. The cable total length is 4km. The parameters of the tested cable impedance and admittance are obtained from PSCAD/EMTDC simulation. Fig. 6 shows the disposition and cross-section of the three-phase SC coaxial cables, which are buried under earth surface as 3 meters. Their installation is like an equilateral triangle.

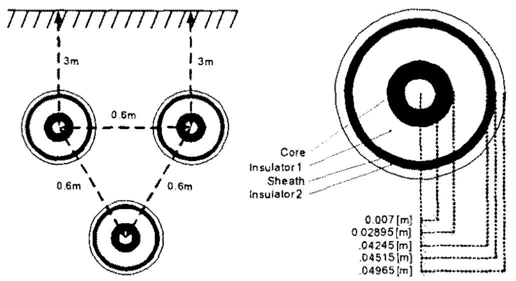

Fig.6 Disposition and cross-section of the 3Φ SC coaxial cables

3.2 Test Results

In this test, the fault type is assumed core-to-sheath to ground fault in phase A In each case, nine different fault distances varying from 0.1[pu] to 0.9[pu] by 0.1[pu] step and four fault resistances of 0.1[Ω], 10[Ω], 30[Ω], 50[Ω] have been considered. PSCAD/EMTDC simulation has been performed. The phasors of the core voltages and currents of the sending-end point are obtained by the Discrete Fourier Transform (DFT) having one cycle data window. The error of the fault location is calculated by the following equation.

$$Error(\%)=\frac{|\text{estimated distance}-\text{actual distance}|}{\text{total length of cable}}\times 100 \qquad (29)$$

Fig. 7 shows the estimation error with four different fault resistances. The maximum error of 0.3[%] is observed for a fault resistance less than 30[Ω], especially the maximum error of 0.6[%] is observed for a fault resistance of 50[Ω]. Therefore, the proposed algorithm can estimate a fault location efficiently.

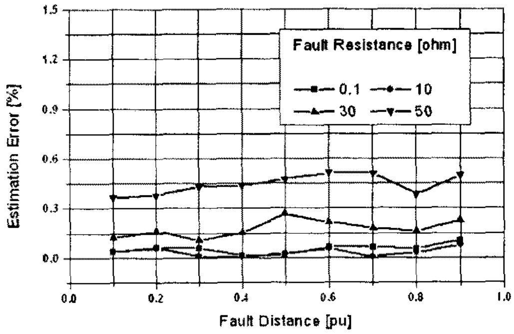

Fig. 7 Estimation error [%] with various fault resistance

4. Conclusion

This paper proposes a new algorithm of underground cable fault location based on the analysis of distributed parameter circuit. Through PSCAD/EMTDC simulation, these test results are quite precise through this proposed algorithm. That means, considering distributed parameter in the cable system is an ideal method, which is able to estimate the fault distance more accurately. Furthermore, this proposed algorithm based on distributed parameter circuit will be verified in other more complicated cable system.

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