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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 - In this paper, a novel algorithm of underground cable fault location based on the analysis of distributed parameter circuit is proposed. The proposed method makes voltage and current equations about core and sheath, and then establishes a function of the fault distance according to the analysis of fault conditions. Finally gets the solution of this function through Newton-Raphson iteration method. The effectiveness of proposed algorithm has been verified by Matlab program, and the cable parameters such as *impedance and admittance are from EMTP simulation.*

Keyword: Underground cable, fault location, distributed parameter circuit

1. Introduction

Electric power systems becomes more complicated and diversified with rapid economic growth during last several decades. Modern power systems require larger capacity transmission and higher quality electric power, and in order to supply much stable electric power without injuring fine view, a lot of underground cables are installed so far, which gradually comes into being complex cable systems.

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 more difficult than those of overhead transmission and distribution systems. Therefore, an efficient fault location method is urgently needed in the cable system networks. For this purpose, *many researches about the analysis of underground cable* using the EMTP are in progress [1]. In recent years, many techniques and methods for the location of earth faults have been reported [2,3]. For instance, one of the fault location method is using Traveling Wave. 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 it is difficult to apply in practice.

This paper proposes a novel algorithm of underground cable fault location estimation based on the analysis of distributed parameter circuit and fault conditions of the cable system.

2. Cable Fault Location Algorithm

2.1 Analysis Of Distributed Parameter Circuit [4]

Cable impedance Z and admittance Y are distributed parameter on every dx of the cable line. The basic equation of distributed parameter circuit(called "DPC" afterwards) is as follows:

$$\frac{dV}{dx} = -ZI,\ \frac{dI}{dx} = -YV \qquad (1)$$

The solution of Eqn.(1) is as follows:

$$V = a\varepsilon^{-\sqrt{ZY}x} + b\varepsilon^{+\sqrt{ZY}x},\ I = c\varepsilon^{-\sqrt{ZY}x} + d\varepsilon^{+\sqrt{ZY}x} \qquad (2)$$

Exponential function can be transformed to hyperbolic function, the formula is as follows:

$$\varepsilon^{\pm\gamma x} = \cosh\gamma x \pm \sinh\gamma x \qquad (3)$$

So the solution can be transformed as follows:

$$V = a'\cosh\sqrt{ZY}x + b'\sinh\sqrt{ZY}x \qquad (4)$$

$$I = c'\cosh\sqrt{ZY}x + d'\sinh\sqrt{ZY}x \qquad (5)$$

2.2 Proposed Algorithm Based On DPC

Proposed algorithm is based on the analysis of distributed parameter circuit. And in this case, the cable type is a single-core(SC) coaxial cable, and the cable consists of core and sheath. There are mutual impedance and admittance between core and sheath. Generally the cable inductance is 1/3 of that at the overhead line, but the capacitance of the cable *is 30 times of that at the overhead line. That means the influence* of the cable capacitance has to be considered

The equivalent circuit model of underground cable system is illustrated as Figure 1.

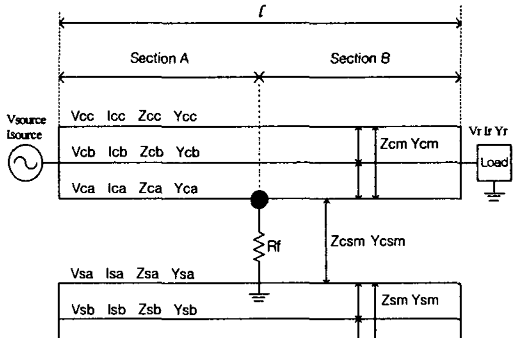

Fig.1 Cable system equivalent circuit model

Cable section A voltage and current equations is expressed as follows [5]:

$$\begin{pmatrix} \partial V_{ca}/\partial x \\ \partial V_{cb}/\partial x \\ \partial V_{cc}/\partial x \end{pmatrix} = \begin{pmatrix} Z_{ca} & Z_{cm} & Z_{cm} \\ Z_{cm} & Z_{cb} & Z_{cm} \\ Z_{cm} & Z_{cm} & Z_{cc} \end{pmatrix} \begin{pmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{pmatrix} + \begin{pmatrix} Z_{csa} & Z_{csm} & Z_{csm} \\ Z_{csm} & Z_{csb} & Z_{csm} \\ Z_{csm} & Z_{csm} & Z_{csc} \end{pmatrix} \begin{pmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{pmatrix} \qquad (6)$$

$$\begin{pmatrix} \partial V_{sa}/\partial x \\ \partial V_{sb}/\partial x \\ \partial V_{sc}/\partial x \end{pmatrix} = \begin{pmatrix} Z_{sca} & Z_{scm} & Z_{scm} \\ Z_{scm} & Z_{scb} & Z_{scm} \\ Z_{scm} & Z_{scm} & Z_{scc} \end{pmatrix} \begin{pmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{pmatrix} + \begin{pmatrix} Z_{sa} & Z_{sm} & Z_{sm} \\ Z_{sm} & Z_{sb} & Z_{sm} \\ Z_{sm} & Z_{sm} & Z_{sc} \end{pmatrix} \begin{pmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{pmatrix} \qquad (7)$$

$$\begin{pmatrix} \partial I_{ca}/\partial x \\ \partial I_{cb}/\partial x \\ \partial I_{cc}/\partial x \end{pmatrix} = \begin{pmatrix} Y_{ca} & Y_{cm} & Y_{cm} \\ Y_{cm} & Y_{cb} & Y_{cm} \\ Y_{cm} & Y_{cm} & Y_{cc} \end{pmatrix} \begin{pmatrix} V_{ca} \\ V_{cb} \\ V_{cc} \end{pmatrix} + \begin{pmatrix} Y_{csa} & Y_{csm} & Y_{csm} \\ Y_{csm} & Y_{csb} & Y_{csm} \\ Y_{csm} & Y_{csm} & Y_{csc} \end{pmatrix} \begin{pmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{pmatrix} \quad (8)$$

$$\begin{pmatrix} \partial I_{sa}/\partial x \\ \partial I_{sb}/\partial x \\ \partial I_{sc}/\partial x \end{pmatrix} = \begin{pmatrix} Y_{sca} & Y_{scm} & Y_{scm} \\ Y_{scm} & Y_{scb} & Y_{scm} \\ Y_{scm} & Y_{scm} & Y_{scc} \end{pmatrix} \begin{pmatrix} V_{ca} \\ V_{cb} \\ V_{cc} \end{pmatrix} + \begin{pmatrix} Y_{sa} & Y_{sm} & Y_{sm} \\ Y_{sm} & Y_{sb} & Y_{sm} \\ Y_{sm} & Y_{sm} & Y_{sc} \end{pmatrix} \begin{pmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{pmatrix} \quad (9)$$

By symmetrical conversion and expressed in matrix:

$$-\begin{bmatrix} \bar{V}_{012} \\ \bar{V}c_{012} \\ \bar{I}_{012} \\ \bar{I}c_{012} \end{bmatrix} = \begin{bmatrix} 0 & 0 & Zc_{012} & Zcs_{012} \\ 0 & 0 & Zsc_{012} & Zs_{012} \\ Yc_{012} & Ycs_{012} & 0 & 0 \\ Ysc_{012} & Ys_{012} & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{012} \\ Vc_{012} \\ I_{012} \\ Ic_{012} \end{bmatrix} \quad (10)$$

Then the eigenvalues of this matrix equation can be calculated respectively for each sequence, which are defined as α_0, β_0 for zero-sequence, α_1, β_1 for positive-sequence, α_2, β_2 for negative-sequence.

Based on distributed parameter circuit analysis, hyperbolic function can be used to express for cable voltage and current equations which are listed as follows.

(1) Equations of cable Section A For zero-sequence, positive-sequence, and negative-sequence

$$\begin{pmatrix} V_{cA0}(x) \\ V_{sA0}(x) \\ I_{cA0}(x) \\ I_{sA0}(x) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_0 x & \sinh\alpha_0 x & \cosh\beta_0 x & \sinh\beta_0 x \\ C_{10}\cosh\alpha_0 x & C_{10}\sinh\alpha_0 x & C_{20}\cosh\beta_0 x & C_{20}\sinh\beta_0 x \\ C_{30}\sinh\alpha_0 x & C_{30}\cosh\alpha_0 x & C_{40}\sinh\beta_0 x & C_{40}\cosh\beta_0 x \\ C_{50}\sinh\alpha_0 x & C_{50}\cosh\alpha_0 x & C_{60}\sinh\beta_0 x & C_{60}\cosh\beta_0 x \end{pmatrix} \begin{pmatrix} A_0 \\ B_0 \\ C_0 \\ D_0 \end{pmatrix} \quad (11)$$

$$\begin{pmatrix} V_{cA1}(x) \\ V_{sA1}(x) \\ I_{cA1}(x) \\ I_{sA1}(x) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_1 x & \sinh\alpha_1 x & \cosh\beta_1 x & \sinh\beta_1 x \\ C_{11}\cosh\alpha_1 x & C_{11}\sinh\alpha_1 x & C_{21}\cosh\beta_1 x & C_{21}\sinh\beta_1 x \\ C_{31}\sinh\alpha_1 x & C_{31}\cosh\alpha_1 x & C_{41}\sinh\beta_1 x & C_{41}\cosh\beta_1 x \\ C_{51}\sinh\alpha_1 x & C_{51}\cosh\alpha_1 x & C_{61}\sinh\beta_1 x & C_{61}\cosh\beta_1 x \end{pmatrix} \begin{pmatrix} A_1 \\ B_1 \\ C_1 \\ D_1 \end{pmatrix} \quad (12)$$

$$\begin{pmatrix} V_{cA2}(x) \\ V_{sA2}(x) \\ I_{cA2}(x) \\ I_{sA2}(x) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_2 x & \sinh\alpha_2 x & \cosh\beta_2 x & \sinh\beta_2 x \\ C_{12}\cosh\alpha_2 x & C_{12}\sinh\alpha_2 x & C_{22}\cosh\beta_2 x & C_{22}\sinh\beta_2 x \\ C_{32}\sinh\alpha_2 x & C_{32}\cosh\alpha_2 x & C_{42}\sinh\beta_2 x & C_{42}\cosh\beta_2 x \\ C_{52}\sinh\alpha_2 x & C_{52}\cosh\alpha_2 x & C_{62}\sinh\beta_2 x & C_{62}\cosh\beta_2 x \end{pmatrix} \begin{pmatrix} A_2 \\ B_2 \\ C_2 \\ D_2 \end{pmatrix} \quad (13)$$

(2) Equations of cable Section B For zero-sequence, positive-sequence, and negative-sequence

$$\begin{pmatrix} V_{cB0}(y) \\ V_{sB0}(y) \\ I_{cB0}(y) \\ I_{sB0}(y) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_0 y & \sinh\alpha_0 y & \cosh\beta_0 y & \sinh\beta_0 y \\ C_{10}\cosh\alpha_0 y & C_{10}\sinh\alpha_0 y & C_{20}\cosh\beta_0 y & C_{20}\sinh\beta_0 y \\ C_{30}\sinh\alpha_0 y & C_{30}\cosh\alpha_0 y & C_{40}\sinh\beta_0 y & C_{40}\cosh\beta_0 y \\ C_{50}\sinh\alpha_0 y & C_{50}\cosh\alpha_0 y & C_{60}\sinh\beta_0 y & C_{60}\cosh\beta_0 y \end{pmatrix} \begin{pmatrix} E_0 \\ F_0 \\ G_0 \\ H_0 \end{pmatrix} \quad (14)$$

$$\begin{pmatrix} V_{cB1}(y) \\ V_{sB1}(y) \\ I_{cB1}(y) \\ I_{sB1}(y) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_1 y & \sinh\alpha_1 y & \cosh\beta_1 y & \sinh\beta_1 y \\ C_{11}\cosh\alpha_1 y & C_{11}\sinh\alpha_1 y & C_{21}\cosh\beta_1 y & C_{21}\sinh\beta_1 y \\ C_{31}\sinh\alpha_1 y & C_{31}\cosh\alpha_1 y & C_{41}\sinh\beta_1 y & C_{41}\cosh\beta_1 y \\ C_{51}\sinh\alpha_1 y & C_{51}\cosh\alpha_1 y & C_{61}\sinh\beta_1 y & C_{61}\cosh\beta_1 y \end{pmatrix} \begin{pmatrix} E_1 \\ F_1 \\ G_1 \\ H \end{pmatrix} \quad (15)$$

$$\begin{pmatrix} V_{cB2}(y) \\ V_{sB2}(y) \\ I_{cB2}(y) \\ I_{sB2}(y) \end{pmatrix} = \begin{pmatrix} \cosh\alpha_2 y & \sinh\alpha_2 y & \cosh\beta_2 y & \sinh\beta_2 y \\ C_{12}\cosh\alpha_2 y & C_{12}\sinh\alpha_2 y & C_{22}\cosh\beta_2 y & C_{22}\sinh\beta_2 y \\ C_{32}\sinh\alpha_2 y & C_{32}\cosh\alpha_2 y & C_{42}\sinh\beta_2 y & C_{42}\cosh\beta_2 y \\ C_{52}\sinh\alpha_2 y & C_{52}\cosh\alpha_2 y & C_{62}\sinh\beta_2 y & C_{62}\cosh\beta_2 y \end{pmatrix} \begin{pmatrix} E_2 \\ F_2 \\ G_2 \\ H_2 \end{pmatrix} \quad (16)$$

where,

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

In this case, assuming fault distance is p, the cable total length is l, and then analyzing all conditions to establish 24 equations to calculate A_0, B_0, C_0, D_0, E_0, F_0, G_0, H_0, and A_1, B_1, C_1, D_1 E_1, F_1, G_1, H_1, and A_2, B_2, C_2, D_2, E_2, F_2, G_2, H_2. The 24 conditions are summarized as follows.

zero-sequence	positive-sequence	negative-sequence
$V_{cA0}(0) = V_{s0}$	$V_{cA1}(0) = V_{s1}$	$V_{cA2}(0) = V_{s2}$
$I_{cA0}(0) = I_{s0}$	$I_{cA1}(0) = I_{s1}$	$I_{cA2}(0) = I_{s2}$
$V_{sA0}(0) = 0$	$V_{sA1}(0) = 0$	$V_{sA2}(0) = 0$
$V_{sA0}(p) = V_{sB0}(0)$	$V_{sA1}(p) = V_{sB1}(0)$	$V_{sA2}(p) = V_{sB2}(0)$
$V_{cA0}(p) = V_{cB0}(0)$	$V_{cA1}(p) = V_{cB1}(0)$	$V_{cA2}(p) = V_{cB2}(0)$
$I_{cB0}(l-p) = Y_{r0}V_{cB0}(l-p)$	$I_{cB1}(l-p) = Y_{r1}V_{cB1}(l-p)$	$I_{cB2}(l-p) = Y_{r2}V_{cB2}(l-p)$
$V_{sB0}(l-p) = 0$	$V_{sB1}(l-p) = 0$	$V_{sB2}(l-p) = 0$
$I_{cAb}(p) = I_{cBb}(0)$	$I_{sAb}(p) = I_{sBb}(0)$	$I_{cAc}(p) = I_{cBc}(0)$

And then establishing the equation:

$$SS = MM \times NN \quad (17)$$

Where,

$$SS_{(24\times1)} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \end{bmatrix} \quad and \quad \begin{cases} S_0 = [V_{s0} \ \ I_{s0} \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0]' \\ S_1 = [V_{s1} \ \ I_{s1} \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0]' \\ S_2 = [V_{s2} \ \ I_{s2} \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0]' \end{cases}$$

$$NN_{(24\times1)} = \begin{bmatrix} N_0 \\ N_1 \\ N_2 \end{bmatrix} \quad and \quad \begin{cases} N_0 = [A_0 \ \ B_0 \ \ C_0 \ \ D_0 \ \ E_0 \ \ F_0 \ \ G_0 \ \ H_0]' \\ N_1 = [A_1 \ \ B_1 \ \ C_1 \ \ D_1 \ \ E_1 \ \ F_1 \ \ G_1 \ \ H_1]' \\ N_2 = [A_2 \ \ B_2 \ \ C_2 \ \ D_2 \ \ E_2 \ \ F_2 \ \ G_2 \ \ H_2]' \end{cases}$$

$$MM_{(24\times24)} = \begin{bmatrix} M11_{(8\times8)} & M12_{(8\times8)} & M13_{(8\times8)} \\ M21_{(8\times8)} & M22_{(8\times8)} & M23_{(8\times8)} \\ M31_{(8\times8)} & M32_{(8\times8)} & M33_{(8\times8)} \end{bmatrix}$$

And then,

$$NN = inv(MM) \times SS \quad (18)$$

Note: A_0, B_0, C_0, D_0, E_0, F_0, G_0, H_0, E_1, F_1, G_1, H_1, E_1, F_1, G_1, H_1, A_2, B_2, C_2, D_2, E_2, F_2, G_2, H_2, expressed as the functions of fault distance p.

In this case, a core-to-sheath to ground fault is assumed in phase A as shown in Figure 2.

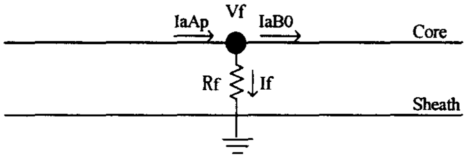

Fig.2 core-to-sheath to ground fault in phase A

And it is easy to know fault equation is $V_f = I_f \times R_f$. In Figure 2, the following equation can be made.

$$f(p, R_f) = Va_{Ap} - (Ia_{Ap} - Ia_{B0})R_f = 0 \quad (19)$$

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 Eqn.(19) can be divide as follows:

$$f(p, R_f) = f_r(p, R_f) + jf_i(p, R_f) = 0 \quad (20)$$

That means,

$$f_r(p, R_f) = 0, \ f_i(p, R_f) = 0 \quad (21)$$

At last, Newton-Raphson iteration method is dedicated in getting the final solution of Eqn.(21).

3. Case Study

3.1 SC Cable System Model in EMTP

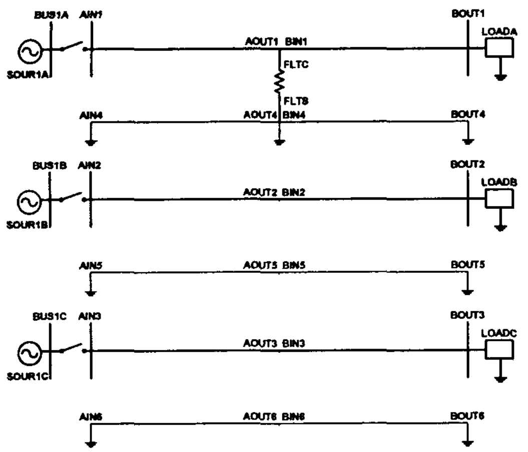

Fig.3 cable system model in EMTP

The cable type is SC coaxial cable consisting of core and sheath (of 2000㎟, kraft), and the voltage level is 154 KV. The cable total length is 10km. All these situations can be set some corresponding parameters in the EMTP subroutine to get the distributed parameters such as cable impedance and admittance.

In this case, assuming core-to-sheath to ground fault in phase A. Because of the EMTP own problem, EMTP simulation can not be used for testifying this proposed algorithm. But a new way is found out, which is assuming V_{f012} and I_{fL012} to estimate exact V_{s012}, I_{s012} and Y_{r012} through analytic method. All work have been done by MATLAB program.

3.2 Test Result

In each case, nine different fault distances vary from 0.1[pu] to 0.9[pu] by 0.1 step with four different fault resistances such as 0.1[Ω], 10[Ω], 30[Ω], 50[Ω].

The error of the fault location is calculated by the following equation.

$$\%Error = \frac{|P_{real} - P_{est}|}{P_{real}} \times 100 \qquad (22)$$

Table 1 illustrates the estimated fault distance p [pu] with different fault resistance.

Table 1. estimated fault distance with different fault resistance

p[pu] \ Rf[Ω]	0.1	10	30	50
0.1	0.09999	0.09999	0.09999	0.10000
0.2	0.20000	0.20000	0.19999	0.20000
0.3	0.29999	0.30000	0.30000	0.29999
0.4	0.39999	0.39999	0.39999	0.39999
0.5	0.50000	0.50000	0.49999	0.49999
0.6	0.59999	0.59999	0.59999	0.60000
0.7	0.70000	0.70000	0.69999	0.69999
0.8	0.80000	0.80000	0.79999	0.79999
0.9	0.90000	0.89999	0.89999	0.89999

And the corresponding figure is shown as follows.

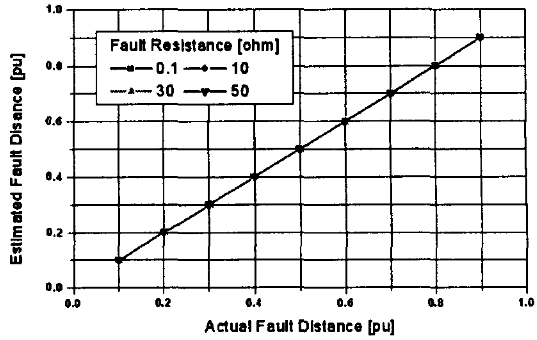

Fig.4 estimated fault distance with different fault resistance

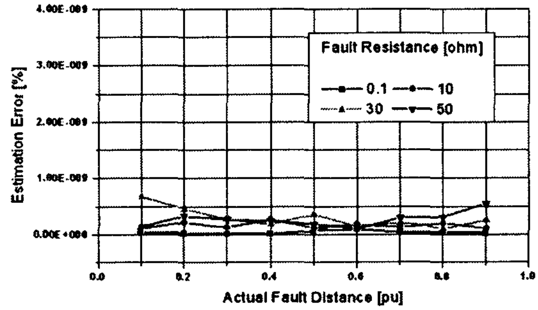

Fig.5 estimated error [%] with different fault resistance

4. Conclusion

This paper proposes a novel algorithm of underground cable fault location based on the analysis of distributed parameter circuit. Proposed method makes voltage and current equations about core and sheath, and then establishes a function of the fault distance according to the analysis of fault conditions. Finally gets the solution of the function using Newton-Raphson iteration method.

This algorithm has taken into account most conditions when fault occurs in the complicated cable system. So that proposed method is able to estimate the fault distance more efficiently.

[Acknowledgement]

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