분포정수회로 해석을 통한 지중케이블 고장거리 알고리즘 연구

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A fault location algorithm for underground cable by Distributed Parameter Circuit Analysis

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Abstract - This paper presents a new fault location algorithm for 3 phase underground cable based on distributed parameter circuit analysis, by which we establish the basic equations for each of core and sheath currents and voltages considering cross-bonding sheaths. The proposed algorithm need simulate by EMTP, and then the EMTP data need be compared with the calculation result in Matlab.

1. Introduction

With the rapid development of society, residents and industries demand more energy than ever. Modern power systems require larger capacity transmission and higher quality electric power. Overhead transmission line was mainly used in the power system. Nowadays so many cities are enlarged on account of the improvement of the industry, so more safe and stable power systems are needed. Taking into account these factors, we choose cable system, which is a feasible solution. Especially in the urban and industrial area underground cable is installed instead of overhead line. This makes the circumstance more beautiful and increases the reliability of the electric power system. Moreover, underground cable is installed in the substation, which can make the power systems expand. In general, now there are so many underground cables in electricity transmission and distribution systems[3].

Modern supplying systems require efficient methods for fault location. At the same time, it is so difficult to find the fault location because the cable systems have to be pulled down to check for defects in the underground cable sections and any wear and tear in the cable protection and sheaths. Utilities have to maintain these cables usually at great costs in order to minimize disruption in services due to cable failures. So fault location estimation and repair are more difficult than those of overhead transmission and distribution systems. Therefore, fast location method of the faulted section in cable systems networks is urgently desired. In recent years, many techniques and methods for the location of earth faults were reported, as for example, 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[4].

This paper presents a new algorithm for calculating the fault location in underground cable systems. In this algorithm, the source voltage and current and cable line parameters are as known factors based on distributed parameter circuit analysis.

2. Proposed fault location algorithm

2.1 What is the underground cable fault

Cable faults can be categorized into three main types: open-conductor faults, shorted faults, and high-impedance faults [5].

1) Open-Conductor Faults: An open-conductor fault is where the conductor of a cable is completely broken or interrupted at the location of the cable fault. It is possible to have a high-resistance shunted fault to ground on one or both sides of the faulted conductor's location.

2) Shorted Faults: A shorted fault is characterized by a low-resistance continuity path to ground (shunted fault). The resistance from conductor to ground is lower than the surge impedance of the cable for a shorted low-resistance fault.

3) High-Impedance Faults: A high-impedance fault contains a resistive path to ground (shunted fault) that is large in comparison to the cable's surge impedance. The fault type may also demonstrate non-linear resistive characteristics which allow the apparent resistance to vary with the level of applied voltage or current.

In comparison with overhead line, underground cable takes on some significantly characteristics such as larger capacitance and smaller inductance that should be taken into account in this algorithm.

2.2 Cross-bonded cable analysis using Zero-sequence

In the underground cable, some current still flows through the sheaths, so let the sheaths cross-bonding to reduce the sheath current, as shown in Fig.1.

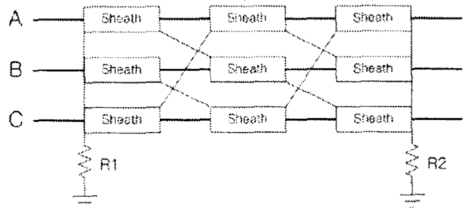

Fig.1 Cross-bonded sheaths

But after cross-bonding, the each phase sheath current is changed both in positive-sequence and negative-sequence. Only in zero-sequence the current does not be changed. Accordingly zero-sequence is chosen in the following analysis.

2.3 Fault location algorithm

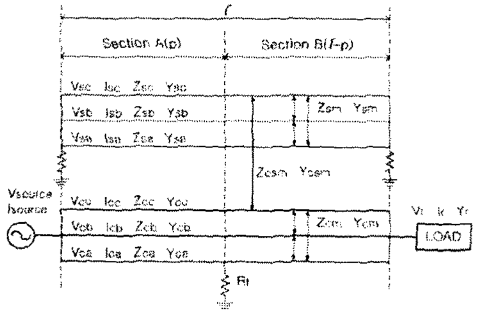

Fig.2 Cable equivalent circuit

※ Section A: from Sending End to Fault Location, the distance is p
Section B: from Fault Location to Receiving End, the distance is l-p

Vsource: Sending end voltage	Yc: self-conductor Admittance
Isource: Sending end current	Ycm: mutual-conductor Admittance
Vc: Conductor Voltage	Ys: self-sheath Admittance
Vs: Sheath Voltage	Ysm: mutual-conductor Admittance
Ic: Conductor Current	Ycsm: Sheath to Conductor mutual Admittance
Is: Sheath Current	Yscm: Conductor to Sheath mutual Admittance
Zc: self-conductor Impedance	l: Cable total distance
Zcm: mutual-conductor Impedance	p: Fault Location distance
Zs: self-sheath Impedance	Rf: Fault Impedance
Zsm: mutual-sheath Impedance	If: Fault Current
Zcsm: Sheath to Conductor mutual Impedance	Vr: Receiving end Voltage
Zscm: Conductor to Sheath mutual Impedance	Ir: Receiving end Current
	Yr: Receiving end admitance

In terms of the following basic equations of distributed parameter circuit analysis [1]:

$$\frac{dV}{dx} = ZI$$

$$\frac{dI}{dx} = YV$$

Cable section A voltage and current equations is expressed as follows [2]:

$$\begin{pmatrix} \frac{\partial V_{ca}}{\partial x} \\ \frac{\partial V_{cb}}{\partial x} \\ \frac{\partial V_{cc}}{\partial x} \end{pmatrix} = \begin{pmatrix} Z_{ca} & Z_{cm} & Z_{cm} \\ Z_{cm} & Z_{cb} & Z_{cm} \\ Z_{cm} & Z_{cm} & Z_{cc} \end{pmatrix} \begin{pmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{pmatrix} + \begin{pmatrix} Z_{csa} & Z_{csm} & Z_{csm} \\ Z_{csm} & Z_{csb} & Z_{csm} \\ Z_{csm} & Z_{csm} & Z_{csc} \end{pmatrix} \begin{pmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} \frac{\partial V_{sa}}{\partial x} \\ \frac{\partial V_{sb}}{\partial x} \\ \frac{\partial V_{sc}}{\partial x} \end{pmatrix} = \begin{pmatrix} Z_{sca} & Z_{scm} & Z_{scm} \\ Z_{scm} & Z_{scb} & Z_{scm} \\ Z_{scm} & Z_{scm} & Z_{scc} \end{pmatrix} \begin{pmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{pmatrix} + \begin{pmatrix} Z_{sa} & Z_{sm} & Z_{sm} \\ Z_{sm} & Z_{sb} & Z_{sm} \\ Z_{sm} & Z_{sm} & Z_{sc} \end{pmatrix} \begin{pmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{pmatrix} \quad (2)$$

$$\begin{pmatrix} \frac{\partial I_{ca}}{\partial x} \\ \frac{\partial I_{cb}}{\partial x} \\ \frac{\partial I_{cc}}{\partial x} \end{pmatrix} = \begin{pmatrix} Y_{ca} & Y_{cm} & Y_{cm} \\ Y_{cm} & Y_{cb} & Y_{cm} \\ Y_{cm} & Y_{cm} & Y_{cc} \end{pmatrix} \begin{pmatrix} V_{ca} \\ V_{cb} \\ V_{cc} \end{pmatrix} + \begin{pmatrix} Y_{csa} & Y_{csm} & Y_{csm} \\ Y_{csm} & Y_{csb} & Y_{csm} \\ Y_{csm} & Y_{csm} & Y_{csc} \end{pmatrix} \begin{pmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} \frac{\partial I_{sa}}{\partial x} \\ \frac{\partial I_{sb}}{\partial x} \\ \frac{\partial I_{sc}}{\partial x} \end{pmatrix} = \begin{pmatrix} Y_{sca} & Y_{scm} & Y_{scm} \\ Y_{scm} & Y_{scb} & Y_{scm} \\ Y_{scm} & Y_{scm} & Y_{scc} \end{pmatrix} \begin{pmatrix} V_{ca} \\ V_{cb} \\ V_{cc} \end{pmatrix} + \begin{pmatrix} Y_{sa} & Y_{sm} & Y_{sm} \\ Y_{sm} & Y_{sb} & Y_{sm} \\ Y_{sm} & Y_{sm} & Y_{sc} \end{pmatrix} \begin{pmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{pmatrix} \quad (4)$$

Eqn. (1), (2), (3), (4) are simplified as follows :

$$\frac{\partial Vc_{abc}}{\partial x} = Zc_{abc} Ic_{abc} + Zcs_{abc} Is_{abc} \quad (5)$$

$$\frac{\partial Vs_{abc}}{\partial x} = Zsc_{abc} Ic_{abc} + Zs_{abc} Is_{abc} \quad (6)$$

$$\frac{\partial Ic_{abc}}{\partial x} = Yc_{abc} Vc_{abc} + Ycs_{abc} Vs_{abc} \quad (7)$$

$$\frac{\partial Is_{abc}}{\partial x} = Ysc_{abc} Vc_{abc} + Ys_{abc} Vs_{abc} \quad (8)$$

And then Eqn. (5), (6), (7), (8)are transformed by symmetrical conversion :

$$\frac{\partial Vc_{012}}{\partial x} = 0 * Vc_{012} + 0 * Vs_{012} + Zc_{012} Ic_{012} + Zcs_{012} Is_{012} \quad (9)$$

$$\frac{\partial Vs_{012}}{\partial x} = 0 * Vc_{012} + 0 * Vs_{012} + Zsc_{012} Ic_{012} + Zs_{012} Is_{012} \quad (10)$$

$$\frac{\partial Ic_{012}}{\partial x} = Yc_{012} Vc_{012} + Ycs_{012} Vs_{012} + 0 * Ic_{012} + 0 * Is_{012} \quad (11)$$

$$\frac{\partial Is_{012}}{\partial x} = Ysc_{012} Vc_{012} + Ys_{012} Vs_{012} + 0 * Ic_{012} + 0 * Is_{012} \quad (12)$$

The following matrix form is from Eqn. (9), (10), (11), (12) in zero-sequence :

$$\begin{bmatrix} \frac{\partial Vc_0}{\partial x} \\ \frac{\partial Vs_0}{\partial x} \\ \frac{\partial Ic_0}{\partial x} \\ \frac{\partial Is_0}{\partial x} \end{bmatrix} = \begin{bmatrix} 0 & 0 & Zc_0 & Zcs_0 \\ 0 & 0 & Zsc_0 & Zs_0 \\ Yc_0 & Ycs_0 & 0 & 0 \\ Ysc_0 & Ys_0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Vc_0 \\ Vs_0 \\ Ic_0 \\ Is_0 \end{bmatrix} \quad (13)$$

By Laplace Transform, we get propagation constant α, β in Eqn. (13). According to distributed parameter circuit analysis, we can get V, I of cable section A and B (y=0 means x=p):

$$\begin{pmatrix} V_{cA}(x) \\ V_{sA}(x) \\ I_{cA}(x) \\ I_{sA}(x) \end{pmatrix} = \begin{pmatrix} \cosh\alpha x & \sinh\alpha x & \cosh\beta x & \sinh\beta x \\ C_1\cosh\alpha x & C_1\sinh\alpha x & C_2\cosh\beta x & C_2\sinh\beta x \\ C_3\sinh\alpha x & C_3\cosh\alpha x & C_4\sinh\beta x & C_4\cosh\beta x \\ C_5\sinh\alpha x & C_5\cosh\alpha x & C_6\sinh\beta x & C_6\cosh\beta x \end{pmatrix} \begin{pmatrix} A \\ B \\ C \\ D \end{pmatrix} \quad (14)$$

$$\begin{pmatrix} V_{cB}(y) \\ V_{sB}(y) \\ I_{cB}(y) \\ I_{sB}(y) \end{pmatrix} = \begin{pmatrix} \cosh\alpha y & \sinh\alpha y & \cosh\beta y & \sinh\beta y \\ C_1\cosh\alpha y & C_1\sinh\alpha y & C_2\cosh\beta y & C_2\sinh\beta y \\ C_3\sinh\alpha y & C_3\cosh\alpha y & C_4\sinh\beta y & C_4\cosh\beta y \\ C_5\sinh\alpha y & C_5\cosh\alpha y & C_6\sinh\beta y & C_6\cosh\beta y \end{pmatrix} \begin{pmatrix} E \\ F \\ G \\ H \end{pmatrix} \quad (15)$$

where

$$C_1 = \frac{\alpha^2 - Z_cY_c - Z_{cs}Y_{cs}}{Z_cY_{cs} + Z_{cs}Y_s}$$

$$C_2 = \frac{\beta^2 - Z_cY_c - Z_{cs}Y_{cs}}{Z_cY_{cs} + Z_{cs}Y_s}$$

$$C_3 = \frac{Y_c + Y_{cs}C_1}{\alpha}$$

$$C_4 = \frac{Y_c + Y_{cs}C_2}{\beta}$$

$$C_5 = \frac{Y_{cs} + Y_sC_1}{\alpha}$$

$$C_6 = \frac{Y_{cs} + Y_sC_2}{\beta}$$

Assuming fault location is p in this case, we get the following conditions:

Condition 1: when x=0, the voltage of the core is equal to V_{source}

Condition 2: when x=0, the current of the core is equal to I_{source}

Condition 3: when x=p, the core voltage of section A is equal to the core voltage of section B

Condition 4: when x=p, the current sum of section A is equal to the current sum of section B(including the core and the sheath)

Condition 5: when x=p, the sheath voltage of section A is equal to the sheath voltage of section B

Condition 6: at the receiving end (y=l-p), $Y_r V_r = I_r$

Condition 7: at the receiving end (x=0), the sheaths are grounded by the grounding resistance (named as R1)

Condition 8: at the sending end (y-l-p), the sheaths are grounded by the grounding resistance(named as R2)

Finally, we will get a equation in matrix form.

$$M = N * X \quad (16)$$

$$M = \begin{bmatrix} V_{source} & I_{source} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^{-1} \quad (17)$$

N is 8*8 matrix form as follows:

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & C_3 & 0 & C_4 & 0 & 0 & 0 & 0 \\ \cosh\alpha p & \sinh\alpha p & \cosh\beta p & \sinh\beta p & -1 & 0 & -1 & 0 \\ (C_3+C_5)*\sinh\alpha p & (C_3+C_5)*\cosh\alpha p & (C_4+C_6)*\sinh\beta p & (C_4+C_6)*\cosh\beta p & 0 & -C_3-C_5 & 0 & -C_4-C_6 \\ C_1\cosh\alpha p & C_1\sinh\alpha p & C_2\cosh\beta p & C_2\sinh\beta p & -C_1 & 0 & -C_2 & 0 \\ 0 & 0 & 0 & 0 & C_3\sinh\alpha q - Y_r\cosh\alpha q & C_3\cosh\alpha q - Y_r\sinh\alpha q & C_4\sinh\beta q - Y_r\cosh\beta q & C_4\cosh\beta q - Y_r\sinh\beta q \\ C_1 & -30R_1C_5 & C_2 & -30R_1C_6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & C_1\cosh\alpha q - 3R_2C_5\sinh\alpha q & C_1\sinh\alpha q - 3R_2C_5\cosh\alpha q & C_2\cosh\beta q - 3R_2C_6\sinh\beta q & C_2\sinh\beta q - 3R_2C_6\cosh\beta q \end{bmatrix} \quad (18)$$

Note: In this matrix, q=l-p

$$X = \begin{bmatrix} A & B & C & D & E & F & G & H \end{bmatrix}^{-1} \quad (19)$$

And then we get the values of all parameters (A, B, C, D, E, F, G, H), but each parameter is a function of unknown variable p. Analysis of fault conditions is as follows:

Condition A: the fault current is the difference between the core current of section A and the core current of the section B: $I_f = I_{cA}(p) - I_{cB}(0)$

Condition B: $V_{cA}(p) - V_{sA}(p) = V_{cB}(0) - V_{sB}(0)$

In terms of the two fault conditions above, we get a function of p & Rf as follows :

$$f(p,R_f) = (1-C_1)E + (1-C_2)G - (C_3B\cosh\alpha p + C_3A\sinh\alpha p + C_4D\cosh\beta p + C_4C\sinh\beta p - C_3F - C_4H)R_f = 0 \quad (20)$$

In the end we make use of Newton-Raphson method to solve this function. and then get the fault location p and fault impedance Rf.

3. Conclusion

In this paper, at first we discuss the characteristics of the cable system, and then proposes the cable fault location algorithm based on distributed parameter circuit analysis, by which we establish the basic equations for each of core and sheath currents and voltages taking into consideration cross-bonding sheaths. From these equations we can calculate the currents and voltages both in the sending end and the receiving end by Matlab. the result of this calculation will be compared with the EMTP data. Further research on this topic includes simulating by EMTP and testifying by Matlab.

[Acknowledgement]

Authors would like to thank Ministry of Science and Technology of Korea and Korea Science and Engineering Foundation for their support through ERC program.

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