多重接地配電線路 고장에 기인한 인근 통신선로 電磁誘導電壓의 計算公式의 誘導

논 문
20〜6〜3

Derivations of Formulas for Electromagnetic Inductive Potentials in the Communication line by the Fault of Multi-Grounding Distribution System

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要 約

3相4線式 多重接地配電線路에서 高低壓混觸이나 1線地絡이 발생하면 인근 通信線路에 電磁誘導電壓이 誘起되는데 이 誘導電壓의 정확한 豫測은 電磁誘導障害의 防止策을 강구하는데 있어서 매우 중요하다. 따라서 본 논문은 이 誘導電壓을 계산하는 理論式을 제시하는 데 그 목적이 있다.

Abstract

This paper describes the derivation of formulas for the distribution of electromagnetic inductive interference potential on the communication line in the cases of both contact fault and one-line grounding of the three-phase, four-wire, multi-grounding distribution system.

Given the impedance of main transformer, the physical size and geometrical layout of the distribution lines, the distance between distribution system and communication line the distribution of multi-grounding conductance, and the distribution of earth conductivity, the distribution of electromagnetic inductive potential is determined by the formulas derived. The formulas are designed to be adequate for computer calculations

I. Introduction

In Korea existing three-phase, three-wire distribution systems will be converted to common-neutral, three-phase, four-wire, multi-grounding systems of primary 13.2-/22.9-KV and secondary 220-/380-V in the near future.

When the projected systems are materialized, it is anticipated that during the contact fault between phase and neutral line conductor or one-line-grounding the electromagnetic inductive potentials in the near communication line will present a problem in a sense of their exccessive magnitudes.

This paper, therefore, aims to develop the formulas for the prediction of the distributions of the inductive potentials in the communication line for practical use in field.

In the process of deriving them the following assumptions are made for simplicity:

(1) The entire line of distribution system is divided into equally spaced section intervals

(2) The distributions of both multi-grounding conductance density and earth conductivity are constant within each of section intervals.

(3) The distances between distribution system and communication line within each of section intervals are represented by geometric mean distance of the initial and ending location of the corresponding section interval.

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Ⅱ. Formulas for Neutral Line Potentials and Fault Current in the Multi-Grounding Distribution System

The fault conditions of the distribution system which result in remarkable rises of the electromagnetic inductive potentials in the adjacent communication line are classified into two categories—the one is the contact fault occurring between neutral line conductor and one of phase line conductors as shown in Fig. 1 and the other the grounding fault of one of phase line conductors as in Fig. 2.

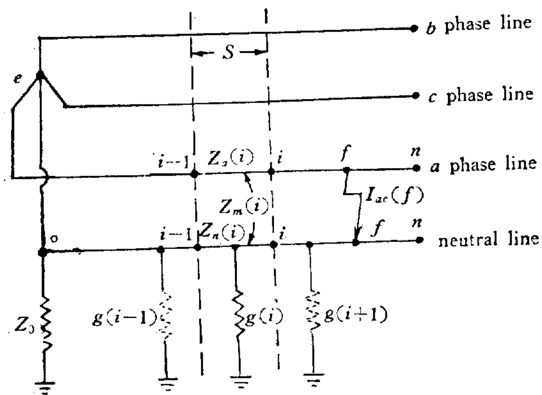

Fig.1. Contact fault in the multi-grounding distribution system.

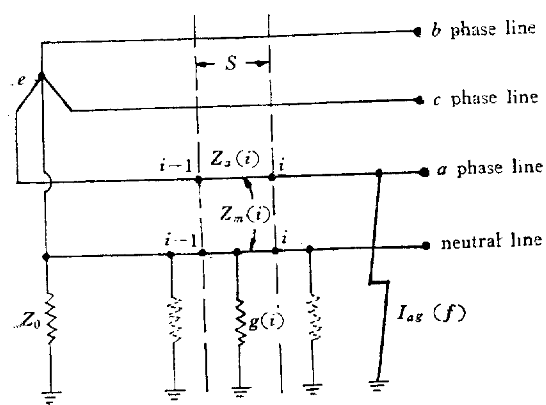

Fig.2. One-line-grounding fault in the multi-grounding system.

In order to predict the magnitudes of electromagnetic inductive potentials in the communication line it is required to know both the fault currents and the distribution of neutral line potentials in the distribution system. For calculating these quantities it is defined that

$$A(i+1,i) \triangleq \cos h\sqrt{Z_n(i+1)g(i+1)S^2} \quad (1)$$

$$B(i+1,i) \triangleq \sqrt{\frac{Z_n(i+1)}{g(i+1)}}\sin h\sqrt{Z_n(i+1)g(i+1)S^2} \quad (2)$$

$$C(i+1,i) \triangleq \sqrt{\frac{g(i+1)}{Z_n(i+1)}}\sin h\sqrt{Z_n(i+1)g(i+1)S^2} \quad (3)$$

$$D(i+1,i) \triangleq A(i+1,i) \quad (4)$$

$$E(i+1,i) \triangleq \frac{Z_m(i+1)}{Z_n(i+1)}\, B(i+1,i) \quad (5)$$

$$F(i+1,i) \triangleq \frac{Z_m(i+1)}{Z_n(i+1)}\, \cos h\sqrt{Z_n(i+1)g(i+1)S^2} \quad (6)$$

$$L(i+1,i) \triangleq \begin{Bmatrix} A(i+1,i) & -B(i+1,i) & -E(i+1,i) \\ -C(i+1,i) & D(i+1,i) & F(i+1,i) \\ 0 & 0 & 1 \end{Bmatrix} \quad (7)$$

$$L(j,i) \triangleq L(j,j-1)\cdot L(j-1,j-2)\cdots\cdots\cdots\cdots L(i+2,i+1)\cdot L(i+1,i)$$

$$\triangleq \begin{Bmatrix} A(j,i) & -B(j,i) & -E(j,i) \\ -C(i,i) & D(j,i) & F(j,i) \\ 0 & 0 & 1 \end{Bmatrix} \quad (8)$$

where i=end point of the i-th section interval in the distribution system as shown in Figs. 1 and 2

S=section interval length [km]

$Z_n(i)$=self impedance density [Ω/km] of neutral line in the i-th section

$g(i)$=multi-grounding conductance density [℧/km] in the i-th section

$Z_m(i)$=mutual impedance density [Ω/km] between neutral and phase line in the i-th section

$$Z_{sa} \triangleq \begin{cases} \dfrac{Z_{s1}+Z_{s2}+Z_{s0}}{3} & \text{for main transformer primary wye connection} \\ \dfrac{Z_{s1}+Z_{s2}}{3} & \text{for main transformer primary delta connection} \end{cases} \quad (9)$$

where Z_{s1}, Z_{s2} and Z_{s0}=positive, negative and zero sequence impedance [Ω] of primary (source) referred to the secondary side

$$Z_{lac}(f) \triangleq sf\sum_{j=1}^{f}\left\{Z_a(j)-\frac{Z_m(j)^2}{Z_n(j)}\right\}-\frac{Z_m(1)}{Z_m(2)}Z_{oc}(f)$$

$$-\frac{Z_m(f)}{Z_n(f)}Z_{fc}(f)+Z_{oc}(f)\sum_{j=1}^{f-1}\left\{\frac{Z_m(j)}{Z_n(j)}\right.$$

$$-\frac{Z_m(j+1)}{Z_n(j+1)}\Big\}\Big\{A(j,0)+\frac{B(j,0)}{Z_0}\Big\}$$
$$-\sum_{j=1}^{f-1}\Big\{\frac{Z_m(j)}{Z_n(j)}-\frac{Z_m(j+1)}{Z_n(j+1)}\Big\}\Big\{B(j,0)$$
$$-E(j,0)\Big\} \qquad (10)$$

where $Z_a(j)$=self impedance density [Ω/km] of phase line in the j-th section

$$Z_{lag}^{(f)} \triangleq s\sum_{j=1}^{f}\Big\{Z_a(j)-\frac{Z_m(j)^2}{Z_n(j)}\Big\}+Z_{og}(f)$$
$$\Big[\frac{Z_m(f)}{Z_n(f)}\Big\{A(f,0)+\frac{B(f,0)}{Z_0}\Big\}-\frac{Z_m(1)}{Z_n(1)}\Big]$$
$$-\frac{Z_m(f)}{Z_n(f)}\Big\{B(f,0)-E(f,0)\Big\}$$
$$+Z_{0g}(f)\sum_{j=1}^{f-1}\Big\{\frac{Z_m(j)}{Z_n(j)}-\frac{Z_m(j+1)}{Z_n(i+1)}\Big\}$$
$$\Big\{A(j,0)+\frac{B(j,0)}{Z_0}\Big\}-\sum_{j=1}^{f-1}\Big\{\frac{Z_m(j)}{Z_n(j)}$$
$$-\frac{Z_m(j+1)}{Z_n(j+1)}\Big\}\Big\{B(j,0)-E(j,0)\Big\} \qquad (11)$$

$$Z_{fc}(f)\triangleq\frac{D(n,f)[Z_0\{A(f,0)+A(f,0)F(f,0)-C(f,0)E(f,0)-1\}+\{B(f,0)+B(f,0)F(f,0)-D(f,0)E(f,0)\}]}{C(n,f)\{Z_0A(f,0)+B(f,0)\}+D(n,f)\{Z_0C(f,0)+D(f,0)\}} \qquad (12)$$

where Z_0=sending end neutral grounding impedance[Ω]

$$Z_{0c}(f)\triangleq\frac{Z_0[C(n,f)\{B(f,0)-E(f,0)\}+D(n,f)\{D(f,0)-F(f,0)-1\}]}{C(n,f)\{Z_0A(f,0)+B(f,0)\}+D(n,f)\{Z_0C(f,0)+D(f,0)\}} \qquad (13)$$

$$Z_{0g}(f)\triangleq\frac{Z_0[C(n,f)\{(B(f,0)-E(f,0)\}+D(n,f)\{D(f,0)-F(f,0)\}}{C(n,f)\{Z_0A(f,0)+B(f,0)\}+D(n,f)\{Z_0C(f,0)+D(f,0)\}} \qquad (14)$$

From the above defined quantities, in the case that the fault location is the end point of the f-th section, the contact fault current $I_{ac}(f)$ and the one-line-grounding current $I_{ag}(f)$ are, respectively, expressed as [1,2]

$$I_{ac}(f)=e/\{Z_{fc}(f)+Z_{0c}(f)+Z_{lac}(f)+Z_{sa}+Z_t+Z_r\} \qquad (15)$$

where Z_t=main transformer impedance[Ω] referred to the secondary side
Z_r=contact fault impedance(Ω)
e=source voltage in phase [V] referred to the secondary side

$$I_{ag}(f)=e/\{Z_{0g}(f)+Z_{lag}(f)+Z_{sa}+Z_t+R_f\} \qquad (16)$$

where R_f=grounding resistance [Ω] at fault location

And the distributions of neutral line potential $V_{nc}(j,f)$ for contact fault and those $V_{ng}(j,f)$ for one-line-grounding are also, expressed respectively, as [1,2]

$$V_{nc}(j,f)=\Big[-Z_{0c}(f)\Big\{A(j,0)+\frac{B(j,0)}{Z_0}\Big\}+\{B(j,0)-E(j,0)\}\Big]I_{ac}(f) \qquad (17)$$

where $j\leq f$

$$V_{nc}(j,f)=Z_{fc}(f)\Big\{\frac{D(n,f)A(j,f)-C(n,f)B(j,f)}{D(n,f)}\Big\}I_{ac}(f) \qquad (18)$$

where $j>f$

$$V_{ng}(j,f)=\Big[-Z_{0g}(f)\Big\{A(j,0)+\frac{B(j,0)}{Z_0}\Big\}\{+B(j,0)-E(j,0)\}\Big]I_{ag}(f) \qquad (19)$$

where $j\leq f$

$$V_{ng}(j,f)=\frac{D(n,f)A(j,f)-C(n,f)B(j,f)}{D(n,f)}\Big[-Z_{0g}(f)\Big\{A(f,0)+\frac{B(f,0)}{Z_0}\Big\}+\{B(f,0)-E(f,0)\}\Big]I_{ag}(f) \qquad (20)$$

where $j>f$

Ⅲ. Formula for Electromagnetic Inductive Potentials in the Case of Contact Fault

In the system configuration as shown in Fig. 3, it is assumed, for simplicity, that the entire line is divided into equally spaced n sections with every section interval length of s and that the multi-grounding conductance density $g(j)$ and the earth conductivity $\sigma(j)$ are assumed to be constant within each section. The communication line begins at point m, ends at point k and electromagnetically coupled with the distribution system with mutual impedance density $Z_{pc}(j)$ between both lines.

In the case that the contact fault occurs at the end point of the f-th section interval, or point f, the electromagnetic-inductive-potential inducing current $I_c(j,f)$ at point j can be written as

$$I_c(j,f)=I_{nc}(j,f)+I_{ac}(f) \qquad (21)$$

where $j\leq f$

$$I_c(j,f)=I_{nc}(j,f) \qquad (22)$$

where $j>f$

Accordingly, the inductive potential $V_c(j,f)$ at the point j of the communication line becomes

$$=\frac{Z_{pc}(m+1)}{Z_n(m+1)}V_{nc}(m,f)-\frac{Z_{pc}(i)}{Z_n(i)}V_{nc}(i,f)$$

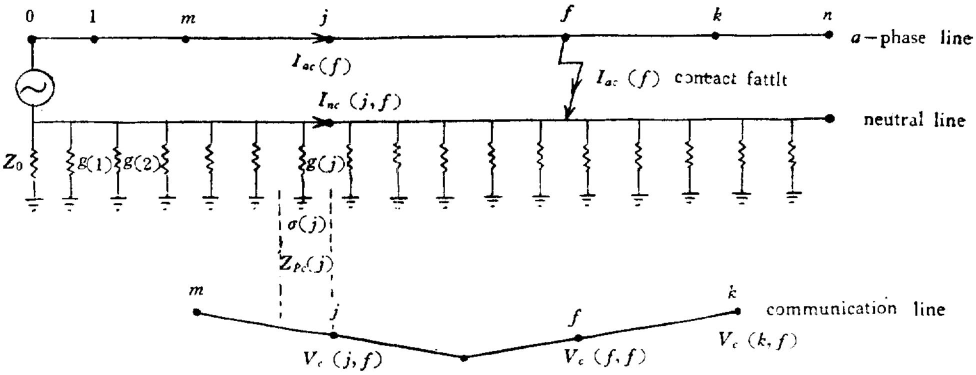

Fig. 3. Contact fault and inductive pontentials.

$$V_c(i,f)=S\int_m^{l} Z_{pc}(j)I_c(i,f)dj$$

$$=S\int_m^{i} Z_{pc}(j)I_{nc}(j,f)dj+SI_{ac}(f)\sum_{j=m+1}^{i} Z_{pc}(j) \qquad (23)$$

where $i\leq f$

$$V_c(i,f)=V_c(f,f)+S\int_f^{i}Z_{pc}(j)I_{nc}(j,f)dj$$

$$=S\int_m^{f}Z_{pc}(j)I_{nc}(j,f)dj+S\int_f^{i}Z_{pc}(j)I_{nc}(j,f)dj+S\,I_{ac}(f)\sum_{j=m+1}^{f}Z_{pc}(j) \qquad (24)$$

where $i>f$

The interval terms of Eqs. 23 and 24 can be integrated with the use of the multi-grounding system characteristics that

$$\frac{dV_{nc}(j,f)}{dj}=-S\left\{Z_n(j)I_{nc}(j,f)+Z_m(j)I_{ac}(f)\right. \qquad (25)$$

where $j\leq f$

$$\frac{dV_{nc}(j,f)}{dj}=-S\left\{Z_n(j)\,I_{nc}(i,f)\right\} \qquad (26)$$

where $j>f$

That is, the first integral term of Eq. 22 is calculated, from Eqs. 17 and 25, as

$$S\int_m^{i}Z_{pc}(j)I_{nc}(j,f)dj=-\int_m^{i}\frac{Z_{pc}(j)}{Z_n(j)}dV_{nc}(j,f)$$

$$-S\int_m^{i}\frac{Z_{pc}(j)Z_m(j)}{Z_n(j)}I_{ac}(f)dj$$

$$-\sum_{j=m+1}^{i-1}\left\{\frac{Z_{pc}(j)}{Z_n(j)}-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\right\}V_{nc}(j,f)$$

$$-SI_{ac}(f)\sum_{j=m+1}^{i}\frac{Z_{pc}(j)\,Z_m(j)}{Z_n(j)}$$

$$=\frac{Z_{pc}(m+1)}{Z_n(m+1)}\left[-Z_{oc}(f)\left\{A(m,0)+\frac{B(m,0)}{Z_o}\right\}+B(m,0)-E(m,0)\right]I_{ac}(f)$$

$$-\frac{Z_{pc}(i)}{Z_n(i)}\left[-Z_{0c}(f)\left\{A(i,0)+\frac{B(i,0)}{Z_0}\right\}+B(i,0)-E(i,0)\right]I_{ac}(f)$$

$$-\left[\sum_{j=m+1}^{i-1}\left\{\frac{Z_{pc}(j)}{Z_n(j)}-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\right\}\left\{-Z_{0c}(f)\left[A(j,0)+\frac{B(j,0)}{Z_0}\right\}+B(j,0)-E(j,0)\right\}\right]I_{ac}(f)$$

$$-\left[S\sum_{j=m+1}^{i}\frac{Z_{pc}(j)Z_m(j)}{Z_n(j)}\right]I_{ac}(f) \qquad (27)$$

where $i\leq f$

and the integral parts of Eq. 24 are calculated, from Eqs. 18, 26 and 27, as

$$S\int_m^{f}Z_{pc}(j)I_{nc}(j,f)dj+S\int_f^{i}Z_{pc}(j)I_{nc}(j,f)dj$$

$$=V_c(f,f)+\frac{Z_{pc}(f+1)}{Z_n(f+1)}V_{nc}(f,f)$$

$$-\frac{Z_{pc}(i)}{Z_n(i)}\,\frac{D(n,f)A(i,f)-C(n,f)B(i,f)}{D(n,f)}$$

$$V_{nc}(f,f)-\sum_{j=f+1}^{i-1}\left\{\frac{Z_{pc}(j)}{Z_n(j)}-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\right\}$$

$$\frac{D(n,f)A(j,f)-C(n,f)B(j,f)}{D(n,f)}V_{nc}(f,f)$$

$$=\frac{Z_{pc}(m+1)}{Z_n(m+1)}\Big[-Z_{0c}(f)\Big\{A(m,0)+\frac{B(m,0)}{Z_0}\Big\}$$

$$+B(m,0)-E(m,0)\Big]I_{ac}(f)$$

$$-\Big[\sum_{j=m+1}^{f}\Big\{\frac{Z_{pc}(j)}{Z_n(j)}-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\Big\}$$

$$\Big\{-Z_{0c}(f)\Big[A(j,0)+\frac{B(j,0)}{Z_0}\Big]$$

$$+B(j,0)-E(j,0)\Big\}\Big]I_{ac}(f)$$

$$-\Big[S\sum_{j=m+1}^{f}\Big\{\frac{Z_{pc}(j)Z_m(j)}{Z_n(j)}\Big]I_{ac}(f)$$

$$-Z_{fc}(f)\Big[\frac{Z_{pc}(i)}{Z_n(i)}\Big\{\frac{D(n,f)A(i,f)}{D(n,f)}$$

$$\frac{-C(n,f)B(i,f)}{}\Big\}+\sum_{j=f+1}^{i-1}\Big\{\frac{Z_{pc}(j)}{Z_n(j)}$$

$$-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\Big\}\Big\{\frac{D(n,f)A(j,f)}{D(n,f)}$$

$$\frac{-C(n,f)B(j,f)}{}\Big\}\Big]I_{ac}(f) \tag{28}$$

where $i>f$

Substituting Eq. 26 into Eq. 22 and Eq. 27 into Eq. 23, finally we obtain the inductive potential as

$$V_c(i,f)=Z_{indc}(i,f)I_{ac}(i,f) \tag{29}$$

where $i=m+1,\ m+2, \cdots\cdots,\ k$

Here, $Z_{indc}(i,f)$ is defined as

$$Z_{indc}(i,f)\triangleq\frac{Z_{pc}(m+1)}{Z_n(m+1)}\Big[-Z_{oc}(f)\Big\{A(m,0)$$

$$+\frac{B(m,0)}{Z_0}\Big\}+B(m,0)-E(m,0)\Big]$$

$$-\frac{Z_{pc}(i)}{Z_n(i)}\Big[-Z_{oc}(f)\Big\{A(i,0)+\frac{B(i,0)}{Z_0}\Big\}$$

$$+B(i,0)-E(i,0)\Big]-\sum_{j=m+1}^{i-1}\Big\{\frac{Z_{pc}(j)}{Z_n(j)}$$

$$-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\Big\}\Big[-Z_{oc}(f)\Big\{A(j,0)+\frac{B(j,0)}{Z_0}\Big\}$$

$$+B(j,0)-E(j,0)\Big]+S\sum_{j=m+1}^{i}\Big\{Z_{pc}(j)$$

$$-\frac{Z_{pc}(j)Z_m(j)}{Z_n(j)} \tag{30}$$

where $i\leq f$

$$Z_{indc}(i,f)\triangleq\frac{Z_{pc}(m+1)}{Z_n(m+1)}\Big[-Z_{oc}(f)\Big\{A(m,0)$$

$$+\frac{B(m,0)}{Z_o}\Big\}+B(m,0)-E(m,0)\Big]$$

$$-\sum_{j=m+1}^{f}\Big\{\frac{Z_{pc}(j)}{Z_n(j)}-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\Big\}$$

$$\Big[-Z_{oc}(f)\Big\{A(j,0)+\frac{B(j,0)}{Z_0}\Big\}+B(j,0)$$

$$-E(j,0)\Big]\frac{z_{fc}(f)}{D(n,f)}-\Big[\frac{Z_{pc}(i)}{Z_n(i)}$$

$$\{D(n,f)A(i,f)-C(n,f)B(i,f)\}$$

$$+\sum_{j=f+1}^{i-1}\Big\{\frac{Z_{pc}(j)}{Z_n(j)}-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\Big\}$$

$$\{D(n,f)\ A(j,f)-C(n,f)B(j,f)\}\Big]$$

$$+S\sum_{j=m+1}^{f}\Big\{Z_{pc}(j)-\frac{Z_{pc}(j)Z_m(j)}{Z_n(j)} \tag{31}$$

where $i>f$

IV. Formula for Electromagnetic Inductive Potentials in the Case of One-Line Grounding

In the case that the one-line grounding fault occurs at point f, the inducing current $I_g(j,f)$ at point j is expressed as

$$I_g(j,f)=I_{ng}(j,f)+I_{ag}(f) \tag{32}$$

where $j\leq f$

$$I_g(j,f)=I_{ng}(j,f) \tag{33}$$

where $j>f$

Accordingly, the inductive potential $V_g(i,f)$ at the point i of the communication can be simply obtained with the replacement of $Z_{oc}(f)$, $Z_{fc}(f)$ and $I_{af}(f)$ by $Z_{og}(f)$, $[-Z_{og}(f)\{A(f,0)+B(f,0)/Z_0\}+B(f,0)-E(f,0)]$ and $I_{ag}(f)$, respectively, in Eqs. 29, 30 and 31 according to analogical relations between both cases. That is,

$$V_g(i,f)=Z_{ing}(i,f)I_{ag}(i,f) \tag{34}$$

where $i=m+1,\ m+2, \cdots\cdots, k.$

Here, $Z_{ing}(i,f)$ is defined as

$$Z_{ing}(i,f)\triangleq\frac{Z_{pc}(m+1)}{Z_n(m+1)}\Big[-Z_{og}(f)\Big\{A(m,0)$$

$$+\frac{B(m,0)}{Z_0}\Big\}+B(m,0)-E(m,0)\Big]$$

$$-\frac{Z_{pc}(i)}{Z_n(i)}\Big[-Z_{og}(f)\Big\{A(i,0)+\frac{B(i,0)}{Z_0}\Big\}$$

$$+B(i,0)-E(i,0)\Big]-\sum_{j=m+1}^{i-1}\Big\{\frac{Z_{pc}(j)}{Z_n(j)}$$

$$-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\Big\}\Big[-Z_{og}(f)\Big\{A(j,0)$$

$$+\frac{B(j,0)}{Z_0}\Big\}+B(j,0)-E(j,0)$$

$$+S\sum_{j=m+1}^{i}\Big\{Z_{pc}(j)-\frac{Z_{pc}(j)Z_m(j)}{Z_n(j)} \tag{35}$$

where $i\leq f$

$$Z_{ing}(i,f)\triangleq\frac{Z_{pc}(m+1)}{Z_n(m+1)}\Big[-Z_{og}(f)\Big\{A(m,0)$$

$$+\frac{B(m,0)}{Z_o}\Big\}+B(m,0)-E(m,0)\Big]$$

$$-\sum_{j=m+1}^{f}\Big\{\frac{Z_{pc}(j)}{Z_n(j)}-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\Big\}$$

$$\left[-Z_{og}(f)\left\{A(j,0)+\frac{B(j,0)}{Z_0}\right\}+B(j,0)\right.$$
$$\left.-E(j,0)\right]-\frac{1}{D(n,f)}\left[-Z_{og}(f)\left\{A(f,0)\right.\right.$$
$$\left.\left.+\frac{B(f,0)}{Z_0}\right\}+B(f,0)-E(f,0)\right]$$
$$\left[\frac{Z_{pc}(i)}{Z_n(i)}\{D(n,f)A(i,f)-C(n,f)B(i,f)\}\right.$$
$$+\sum_{j=f+1}^{i-1}\left\{\frac{Z_{pc}(j)}{Z_n(j)}-\frac{Z_{pc}(j+1)}{Z_n(j+1)}\right\}$$
$$\left.\{D(n,f)\ A(j,f)-C(n,f)B(j,f)\}\right]$$
$$+S\sum_{j=m+1}^{f}\left\{Z_{pc}(j)-\frac{Z_{pc}(j)Z_m(j)}{Z_n(j)}\right\} \qquad (36)$$

where $i>f$

V. Formulas for Self Mutual Impedances

Eqs. 15, 16, 29 and 34 require the precalculations of neutral line self impedance density $Z_a(j)$, phase line self impedance density $Z_n(j)$, mutual impedance distribution $Z_m(j)$ between neutral and phase line and mutual impedance distribution $Z_{pc}(j)$ between distribution system and communication line.

The more commonly used methods for these quantities are based upon the well known Pollaczek-Carson's formulas, but are too complicated to apply to field calculations.

The author, therefore, suggests another type of modifications which is theoretically identical with the original Pollaczek-Carson's formulas but takes lesser time to calculate actual values.

In the conductors spacing as shown in Fig.4, the suggested formulas for the densities of respective impedances within the j-th section interval are as follows:

$$Z_a(j)=r_a(j)+[\{0.98696\times10^{-3}-2\times0.16646\times10^{-5}h_a\sqrt{\sigma(j)f}\}]f+i[\{0.81563\times10^{-2}-0.12566\times10^{-2}\log_e g_a-0.62832\times10^{-3}\log_e\{\sigma(j)f\}-2\times0.16646\times10^{-5}h_a\sqrt{\sigma(j)f}\}]\ f[\Omega/\mathrm{km}] \qquad (37)$$

where $i=\sqrt{-1}$

$r_a(j)$=resistance density [Ω/km] of phase line conductors in the j-th section

h_a=height [m] of phase line conductor

g_a=geometric mean radius [m] of phase line conductor

$\sigma(j)$=earth conductivity [℧/m]

f=system frequency [CPS]

$$Z_n(j)=r_n(j)+[\{0.98696\times10^{-3}-2\times0.16646\times10^{-5}h_n\sqrt{\sigma(j)f}\}]f+i\ [\{0.81563\times10^{-2}-0.12566\times10^{-2}\log_e g_n-0.62832\times10^{-3}\log_e\{\sigma(j)f\}-2\times0.16646\times10^{-5}\ h_n\sqrt{\sigma(j)f}\}]\ \ f[\Omega/\mathrm{km}] \qquad (38)$$

$r_n(j)$=resistance density [Ω/km] of neutral line conductor in the j-th section

h_a=height [m] of neutral line conductor

g_n=geometric mean radius [m] of neutral line conductor

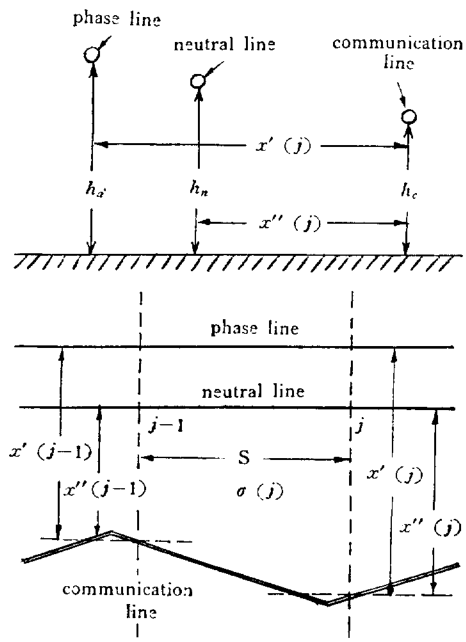

Fig.4. Conductor spacing.

$$Z_m(j)=[\{0.98696\times10^{-3}-0.16646\times10^{-5}\{h_a+h_n\}\sqrt{\sigma(j)f}\}]f+i[\{0.81563\times10^{-5}-0.12566\times10^{-2}\log_e l-0.62832\times10^{-3}\log_e\{\sigma(j)f\}+0.16646\times10^{-5}\{h_a+h_n\}\sqrt{\sigma(j)f}\}]f[\Omega/\mathrm{km}] \qquad (39)$$

where l=distance[m] between phase and neutral line conductor

$$Z_{pc}(j)=[\{0.98696\times10^{-3}-0.16646\times10^{-5}\{h_p+h_c\}\sqrt{\sigma(j)f}\}]f+i[\{0.81563\times10^{-5}-0.12566\times10^{-2}\log_e d(j)-0.62832\times10^{-3}\log_e\{\sigma(f)f\}+0.16646\times10^{-5}\{h_p+h_c\}\sqrt{\sigma(j)f}\}]f[\Omega/\mathrm{km}] \qquad (40)$$

where $0.28241\times10^{-4}\sqrt{\sigma(j)f}\ d(j)<0.5$

h_c=height [m] of communication line conductor

$h_p=(h_a+h_n)/2$

Herein, $d(j)$ is defined as

$$d(j) \triangleq [\{x'(j-1)^2+(h_a-h_c)^2\}\{x''(j-1)^2+(h_n-h_c)^2\}\{x'(j)^2+(h_a-h_c)^2\}\{x''(j)^2+(h_n-h_c)^2\}]^{\frac{1}{8}} \quad (41)$$

where x' and x''=horizontal distance[m] between phase and communication line and between neutral and communication line

$$Z_{pc}(j)=\left[0.25133\times10^{-2}\left\{\frac{K_{er}\{K_x(j)\}}{K_x(j)}+\frac{1}{K_x(j)^2}\right\}\right]f+i\left[0.25133\times10^{-2}\left\{\frac{K_{ei}\{K_x(j)\}}{K_x(j)}\right\}\right]f \quad [\Omega/\text{km}] \quad (42)$$

where $10>K_x(j)\geq0.5$

$$Z_{pc}(j)=\frac{0.25133\times10^{-2}f}{K_x(j)^2} \quad [\Omega/\text{km}] \quad (43)$$

$K_x(j)$ in Eqs. 39 and 40 is defined as

$$K_x(j) \triangleq 0.2824\times10^{-4}\sqrt{\sigma(j)f}\{x'(j-1)x''(j-1)x'(j)x''(j)\}^{\frac{1}{8}} \quad (44)$$

Ⅵ. Conclusions

This paper derives useful and practical formulas for calculating electromagnetic inductive potentials in the communication line caused by the faults of multi-grounding distribution system, and the derived formulas are adequate for calculations by digital computer. More specifically,

(1) Prior to calculations of the inductive potentials in the communication line, the distributions of self and mutual impedances and fault currents should be determined by the data of system parameter and the distribution of earth conductivity. Eqs. 37~44 are simple and practical formulas for determing each distribution of self and mutual impedances.

(2) Eqs. 15 and 16 are, respectively, formulas for calculating contact fault current and one-line-grounding current which are directly utilized for the determination of inductive potentials in the communication line.

(3) Eq. 29 is formula for caculating the distribution of the inductive potentials in the communication line in the case of contact fault.

(4) Eq. 34 is formula for calculating the distribution of the inductive potentials in the case of one-line-grounding.

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