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DISTRIBUTION OF 60 HZ GROUND FAULT CURRENTS ALONG TRANSMISSION LINES (AN IMPROVED ALGORITHM)

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Hoay Beng Gooi, B.S., M.Sc.E.

* * * * *

The Ohio State University

1983

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LIST OF PRINCIPAL SYMBOLS

$Z_p, Z_{pk}, Z_{PA}, Z_{PB}$  
phase conductor impedance

$Z_c, Z_{ck}, Z_{CA}, Z_{CB}$  
ground wire impedance

$Z_m, Z_{mk}$  
mutual impedance between phase conductor and ground wire

$R_t, R_{tk}$  
tower impedance

$Z_g, Z_{gk}, Z_{GA}, Z_{GB}$  
ground return path impedance

$Z_{FL}$  
resultant impedance of faulty tower and ladder network

$R_{FP}, R_{FPA}, R_{FPB}$  
source station ground impedance

$Z_n$  
equivalent impedance of external system

$Z_{11k}, Z_{21k}, Z_{22k}$  
driving point impedance at span $k$

$Z_{11kA}, Z_{12kA}, Z_{21kA}, Z_{22kA}$

$Z_{11kB}, Z_{12kB}, Z_{21kB}, Z_{22kB}$

$I_p, I_{pA}, I_{pB}$  
phase current

$I_{t1}, I_{tk}$  
tower current

$I_c, I_{ck}, I_{cA}, I_{cB}$  
ground wire current

$I_k$  
loop current
\( V_{pk}, V_{pA}, V_{pB} \)  
\( V_{ck}, V_{cA}, V_{cB} \) 
\( E \) 
\( \Delta x \) 
\( N \) 
\( d \) 
\( n \) 
\( k \) 
\( M_k \) 
\( X_k \) 
\( E_k, F_k, A_k, B_k, C_k, G_k, H_k, \) 
\( P_k, Q_k, R_k, S_k, T_k, U_k \) 
\( \Theta_k \)

voltage of phase conductor  
ground wire voltage  
source voltage  
span  
number of towers per unit length  
fault-station distance  
number of spans  
kth span  
4x4 matrix  
4x1 matrix  
current coefficients at span \( k \)  
phase angle of a complex variable
1.1 GENERAL INFORMATION

When a ground fault occurs on a transmission line in a power network with grounded neutral, the fault current (zero-sequence current) returns to the grounded neutral through the tower structures, ground return paths, and ground wires if the latter are present. The type of ground faults most likely to occur (about 90 percent of them) in an overhead power transmission network is the line-to-ground fault. Determining the magnitude of the fault current and its distribution in an effectively grounded network is of prime importance to the successful operation of modern power systems.

The major practical applications of this work are mostly in grounding installation designs in which a system engineer and/or a telecommunication engineer can:

(1) determine the ground wire current for ground fault conditions
(2) select the proper size of ground wires to withstand the thermal stresses imposed by large fault currents
(3) calculate the potential rise in station and tower grounds
(4) evaluate the performance and reliability of grounding installations
(5) compute the electromagnetic interference between power lines and nearby telecommunication lines, pipeline and railways.

The practical method for large system fault current studies is the simulation of consecutive spans of a transmission line from the source station to the fault location following a ground fault. This emphasis on simulation necessarily requires adequate line, tower structure, and soil model representations to ensure a more accurate engineering analysis of the ground current distribution problem.

As the length of the transmission line in a network increases and the number of current-carrying conductors becomes increasingly large, the analysis of the ground current in the system becomes so complex that it is impossible to represent a large transmission system in detail due to the constraints of available memories in a digital computer. Moreover, significant round-off errors may occur and much
computer CPU time would be wasted if the computations on the entire system were carried out.

To get around this problem, a boundary is usually drawn between the study system and the external system. In practice, the study system consists of a portion of a network stretching from the fault location to nearby source stations. The study system may be represented in detail while the external system which extends beyond the source station and away from the fault location may be represented by an equivalent Thevenin impedance in series with an ideal voltage source. In addition, proper computational techniques are needed so that less computer CPU time is needed while still maintaining the accuracy of the simulation results.

The method used in the ground wire current calculation is the major topic of this dissertation and will be discussed throughout Chapters 3, 4, and 5. The calculation method introduced in Chapter 3 is based on the following assumptions: 1) Zero-sequence self and mutual impedances are computed by means of Carson's equations [Appendix A]. 2) Impedances are considered as lumped parameters in every span of the transmission line. 3) Line capacitances are neglected.
4) The network is assumed to be linear and in the sinusoidal state, only the fundamental frequency is considered.

5) The contact resistance between the tower and the ground wires, and the impedance between the ground wires and the faulty phase conductor are neglected.

1.2 REVIEW OF PREVIOUS WORK

Extensive work has been undertaken in the past six decades to model power transmission and distribution systems for ground fault current analysis.


In 1969, Sebo [5] proposed the use of two methods, first an equivalent star method and then the use of a 4x4 matrix, for solving zero-sequence current distribution along transmission lines. DeSieno [6] assumed uniform distributed line parameters and constant tower-footing impedances between
ground wires and ground, and introduced the hyperbolic function method. Dawaiibi [7] used the double-sided elimination method based on the loop equations of the ground wire and ground system. In 1981, Daavettila [8] in his M.S. thesis revealed that the 4x4 matrix approach may cause numerical instabilities in a computer program when more than 30 spans of a typical steel ground wire were computed.

For the past two years, a series of projects have been conducted by EPRI to look into the transmission line and station grounding problems [12,21,22]. Several computer programs were developed to meet the needs of utility companies for current distribution calculations in ground wires and substation grounding systems. The simulation results from these programs were verified by the field test data. At OSU, electrolytic tanks of different sizes were designed and used to test different grounding configurations in both uniform and non-uniform soil. This permits the use of scale models for evaluating the performance of grounding grids.

Appendix A lists the fundamental equations derived by Carson for an overhead conductor with ground return path. The methods suggested by Sebo, DeSieno, and Dawaiibi for ground current calculations will be reviewed in Chapter 2.
1.3 PROPOSED WORK

(1) A general driving point impedance method based on the equivalent model of overhead lines, tower structures, ground wires and ground return paths will be developed. Multi-circuit systems, different ground wire configurations, and iterative methods for steel ground wire impedance corrections due to the change of ground wire currents will be discussed and illustrated with examples.

(2) Using the data of the EPRI 345 kV Transmission Line Reference Book [10], simulations of the above method will be implemented on a digital computer. Ground faults will be introduced along the transmission line, and the resultant current distribution in the system will be investigated.

(3) End-effect phenomena of the ground wire system, ladder network that extends beyond the fault, ground wire material, varying tower-footing impedances, soil resistivities, phase conductor arrangements, tower structure configurations, and the distance between the source station and the fault location are among the various cases examined in this dissertation.

(4) A general computer program which includes fault current calculations for different fault conditions will be developed. The algorithm used shall have low computer CPU
time and small memory space requirements. Results from the computer program developed will be compared with those of the most recent EPRI's computer program for fault current calculations [11,12].

In summary, the main objective of this study is to seek an efficient and computer-oriented calculating method for current distribution computations in ground wire systems. Later, it will be shown that the proposed method when compared to five existing methods requires the least number of arithmetic operations in the course of calculations while still maintaining the accuracy of the simulation results.

A portion of this research work involves the use of an iterative method for steel ground wire systems and the study of open ground wires in the neighborhood of the fault location. These studies are published for the first time in the literature. They are important to the grounding installation engineers to design a more accurate and reliable grounding system since this is a fundamental requirement for the successful operation of modern power systems.
Chapter II
EXISTING METHODS

2.1 GENERAL REVIEW

When a ground fault occurs due to an insulator flashover between a phase conductor and a tower structure, or a line-to-ground contact caused by an external grounded structure such as a tree or a crane, the fault current usually returns to the grounded neutral of a source station (or stations) of the transmission line under examination through the ground and ground wires. In classical short-circuit studies, the ground return impedance is assumed to be zero. Calculations based on zero ground impedance usually lead to a higher magnitude of fault current and provide no information as to how the distribution of ground return current can be computed.

For the past sixty years, much work [1-20] have been done in an effort to pursue a more suitable technique for ground return current computations. Each of these techniques were based on the fundamental Kirchhoff's laws. The difference lies in the methodology used to obtain the final solutions. A knowledge of these techniques not only enhances an under-
standing of the nature of the problems, but also provides a further insight into the mechanics involved.

In more recent years, the techniques used were basically classified into two main categories [12], namely the constant line parameter and varying line parameter methods. The former assumes uniform distributed line parameters. In the latter, the line parameters are allowed to vary. A more substantial treatment of these methods will be presented in the following sections.

2.2 CONSTANT LINE PARAMETERS

2.2.1 DeSieno's Method

In 1970, DeSieno, Marchenko, and Vassell [5] proposed the use of a closed form solution for ground wire current calcu-
lations. In their method, they assumed that a fault can only occur at some distance far away from the source stations so that the phase conductor impedance \( Z_p \), ground wire impedance \( Z_c \), and mutual impedance between phase conductor and ground wire \( Z_m \) can all be considered as uniform distributed parameters with values expressed in ohms per unit length. In Figure 2.1, the equivalent impedance of an external system is denoted by \( Z_n \). The impedance of the tower structure \( R_t \) is assumed to be constant throughout the entire length of the transmission line. The distance \( \Delta x \) between two consecutive tower structures is called a span of the power network. All spans of the network are treated to be equal.

Since \( \Delta x \) is negligible small when compared to the length of the transmission line, it is then possible to write two differential equations relating the voltage and current of the ground wire. These are

\[
\frac{dI(x)}{dx} = \lim_{\Delta x \to 0} \frac{I(x+\Delta x) - I(x)}{\Delta x} = \frac{V(x)}{R_t \Delta x} = G_t V(x) \tag{2.1}
\]

\[
\frac{dV(x)}{dx} = \lim_{\Delta x \to 0} \frac{V(x+\Delta x) - V(x)}{\Delta x} = \frac{I(x)Z_c - I_p Z_m}{\Delta x} \tag{2.2}
\]

where \( G_t = 1/(R_t \Delta x) = N/R_t \) mho per unit length, and \( N \) is the number of towers per unit length. Here \( I_p \) is the fault current in the phase conductor.
From equations (2.1) and (2.2), two second order differential equations can be obtained. These are

\[
\frac{d^2 I}{dx^2} - \alpha^2 I = -\alpha^2 \frac{ZmI_p}{Z_c} \tag{2.3}
\]

\[
\frac{d^2 V}{dx^2} - \alpha^2 V = 0 \tag{2.4}
\]

where \( \alpha^2 = Z_c G_t \).

Note that each of the two equations has only one dependent variable, either \( I \) or \( V \) but not both. Each equation expressed in this form can be solved independent of the other.

Integrate equation (2.3) twice:

\[
I = A_1 e^{\alpha x} + A_2 e^{-\alpha x} + \frac{Z_m I_p}{Z_c} \tag{2.5}
\]

where \( A_1 \), and \( A_2 \) are the two constants associated with a second order differential equation in (2.3). It then follows from equations (2.1), and (2.5) that

\[
V = \frac{1}{G_t} \frac{dI}{dx} = \frac{\alpha}{G_t} (A_1 e^{\alpha x} - A_2 e^{-\alpha x}) \tag{2.6}
\]

The constants \( A_1 \), and \( A_2 \) may be solved using the boundary conditions at both the source station and the fault location. These are

\[
V(d) = I_{t_1} R_t \tag{2.7}
\]
where \( d \) is the distance between the source station and the fault location. \( I_{t1} \) is the current flowing through the tower structure at the fault location and is equal to \( I_p - I(d) \). Here \( I(d) \) is the ground wire current at a distance \( d \) from the fault location.

Apply equations (2.7), and (2.8) to equation (2.6):

\[
I_{t1}R_t = \frac{\alpha}{G_t}(A_1e^{\alpha d} - A_2e^{-\alpha d}) \quad (2.9)
\]

\[
0 = \frac{\alpha}{G_t}(A_1 - A_2) \quad (2.10)
\]

It is clear from equation (2.10) that \( A_1 = A_2 \). Substitute equation (2.10) into equation (2.9):

\[
A_1 = A_2 = \frac{NI_{t1}}{2\alpha \sinh(\alpha d)} \quad (2.11)
\]

Replacing \( A_1 \), and \( A_2 \) in equations (2.5), and (2.6) by expression (2.11), the final closed form solutions are obtained:

\[
I = \frac{NI_{t1}\cosh(\alpha x)}{\alpha \sinh(\alpha d)} + \frac{Z_mI_p}{Z_c} \quad (2.12)
\]

\[
V = R_{t1}I_{t1}\frac{\sinh(\alpha x)}{\sinh(\alpha d)} \quad (2.13)
\]
Expressions (2.12) and (2.13) may be used to compute the current and voltage of the ground wire at any distance, \(x\), from the source station. When implemented on a digital computer, they require very little computational time, and are numerically stable throughout the entire length of the transmission line. On the other hand, due to the initial assumptions made, the expressions cannot be used for short transmission line calculations when \(d\) is less than 5 km [12], and span to span changes in line parameters and tower-footing impedances cannot be introduced.

2.3 **VARYING LINE PARAMETERS**

In this section, the methods suggested by Sebo (1969) and Dawalibi (1980) will be discussed. For these methods, the phase conductor impedance, ground wire impedance, mutual impedance between the phase conductor and ground wire, tower-footing impedance and ground return impedance in each span of the network are allowed to vary along the power line. This is very important since in the real world these parameters do change from span to span due to the constraints as imposed by right-of-way, environmental and soil conditions. It is expected that the varying line parameter approach will provide a more accurate result compared to the constant line parameter approach. In fact, in a more recent
publication [12], Dawalibi has shown that when the fault is at the second tower structure from the source station, the constant line parameter approach may cause an error as high as 33%. Furthermore, regardless of the fault location, the constant line parameter approach yields a faulted structure current value lower than that predicted by the varying line parameter approach.

2.3.1 Sebo's Methods

2.3.1.1 Matrix Approach

Figure 2.2 Transmission Line with Ground Return Path
Figure 2.2 represents the equivalent circuit of \( n \) spans of a power transmission line. Each span of the network consists of a circuit model as shown in Figure 2.3. Here \( Z_{pk} \), \( Z_{ck} \), and \( Z_{mk} \) represent the \( k \)th span impedance parameters and may be computed from Carson's impedance equation. Since Carson's equation includes the impedance of the ground return path \( (Z_{gk}) \), the actual self and mutual impedances may then be calculated by subtracting \( Z_{gk} \) from their corresponding impedances in Carson's equation.

From Figure 2.3, two loop equations around the phase conductor and ground wire, each via the ground return path, may be written. An additional node equation can be obtained from the node of the \( k \)th tower-footing impedance \( (R_{tk}) \) and ground wire impedance. Expressing the three equations in a
matrix form, an $M_k$ matrix of dimension 4 by 4 as given below is obtained.

\[
\begin{bmatrix}
V_{p_{k+1}} \\
V_{c_{k+1}} \\
I_p \\
I_{c_{k+1}}
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & Z_{pk} & -Z_{mk} \\
0 & 1 & Z_{mk} & -Z_{ck} \\
0 & 0 & 1 & 0 \\
0 & -\frac{1}{R_{tk}} & \frac{Z_{mk}}{R_{tk}} & 1+\frac{Z_{ck}}{R_{tk}}
\end{bmatrix}
\begin{bmatrix}
V_{pk} \\
V_{ck} \\
I_p \\
I_{ck}
\end{bmatrix}
\]  

(2.14)

or $X_{k+1} = M_k X_k$

where $X_k$ and $X_{k+1}$ are 4 by 1 matrices.

The product of $M_k$ matrices from $k = 1$ to $k = n - 1$ yields a chain equation which relates the boundary conditions at the fault location, $X_1$, and at the source side of $(n-1)$th span, $X_n$. This equation is

\[
X_n = M_{n-1} \cdots M_1 X_1
\]

(2.15)

The matrices $X_n$ and $X_1$ may be expressed as

\[
X_n = \begin{bmatrix}
V_{pn} \\
V_{cn} \\
I_p \\
I_{cn}
\end{bmatrix}
= \begin{bmatrix}
V_{pn} \\
R_{tn-1} (I_{cn-1} - I_{cn}) \\
I_p \\
I_{cn}
\end{bmatrix}
\]

(2.16)
where $I_p$ represents the fault current in the phase conductor, and is assigned a value of $1.0 + j0.0$ per-unit. $V_{pk}$'s and $V_{ck}$'s are the phase conductor and ground wire voltages, respectively, and $I_{ck}$'s are the ground wire currents. $Z_{FL}$ includes the resultant impedance of the faulty tower and the impedance of downstream ladder network, if necessary. The unknowns in equations (2.16), and (2.17) are $V_{pn}$, $I_{cn}$, $I_{cn-1}$, and $I_{c1}$, but there are only three independent equations in expressions (2.15)-(2.17). The fourth one is needed from the a-b-c-d loop of Figure 2.2. This equation is

$$I_p(Z_{mn} + R_{FP}) - I_{cn}(Z_{cn} + R_{tn-1} + R_{FP}) + I_{cn-1}R_{tn-1} = 0 \quad (2.18)$$

where $R_{FP}$ is the source station ground impedance.

When equation (2.15) is solved, all the values of $V_{pk}$, $V_{ck}$, and $I_{ck}$ in the $X_k$ matrix may then be obtained using the relationship

$$X_k = M_{k-1}X_{k-1} \quad (2.19)$$
Here $X_{k-1}$ is obtained from $X_{k-2}$, and initially $X_1$ is known by solving equation (2.15). The process is repeated until all the $X_k$'s in the network are evaluated. Obviously, accumulated round-off errors cannot be avoided since the present $X_k$ values depend on the previous $X_{k-1}$ values which already have some round-off errors imbedded in them. The situation becomes very critical in the mid-section of a long transmission line in which the ground wire current in the neighboring spans are about the same. It has been a well established fact in numerical methods implemented on a digital computer that when two floating-point numbers are approximately equal, subtraction of these numbers usually leads to a loss of significant figures in the end result [23]. This is actually happening in the computation of tower currents around the mid-section of the network. Moreover, the tower current which has already been distorted is used further in the next span calculation in expression (2.14).

An additional source of round-off errors arises in the multiplication process of expression (2.15). To understand this, an eigenvalue analysis of the 4x4 chain matrix representation is carried out. For the purpose of this analysis, all the 4x4 matrices are assumed to be the same, that is

$$M_1 = M_2 \ldots M_{n-1} = M$$  \hspace{1cm} (2.20)

Substitute equation (2.20) into equation (2.15):

$$X_n = M^{n-1}X_1$$  \hspace{1cm} (2.21)
It can be shown that
\[ M = P \Lambda P^{-1} \]  
(2.22)
where \( P \) is an eigenvector matrix and \( \Lambda \) is a diagonal eigenvalue matrix [24]. Substitute equation (2.22) into equation (2.21):
\[ x_n = P \Lambda^{n-1} P^{-1} x_1 \]  
(2.23)
Here,
\[ \Lambda^{n-1} = \begin{bmatrix} 
\lambda_1^{n-1} & 0 & 0 & 0 \\
0 & \lambda_2^{n-1} & 0 & 0 \\
0 & 0 & \lambda_3^{n-1} & 0 \\
0 & 0 & 0 & \lambda_4^{n-1} 
\end{bmatrix} \]  
(2.24)

It is clear from the above equation that when a long transmission line is considered, \( n \) tends to become very large. If \( \lambda \)'s are smaller than 1, \( \lambda^{n-1} \)'s approach zero. If \( \lambda \)'s are greater than 1, \( \lambda^{n-1} \)'s approach infinity. Since the solution of expression (2.21) is a function of \( \lambda^{n-1} \)'s, round-off errors could be very severe when \( n \) is large.

In summary, the matrix approach provides a very convenient way of representing the transmission line network as a chain matrix equation. However, it is only good for short transmission lines with less than 30 spans for computations since round-off errors may not be avoided in the process of matrix manipulations [8].
2.3.1.2 Driving Point Impedance Approach

Figure 2.4 shows a circuit model for a transmission line energized by two source stations. It should be noted that this approach is equally good for transmission lines with one source station. The intention here is to show the general concept in the case of two source stations so that this will not be repeated in the proposed method in Chapter 3.

A line to ground fault is applied to tower structure number one. The mutual impedance between the phase conductor and the ground wire in Figure 2.4 may be transformed into the equivalent circuit as in Figure 2.5.
Figure 2.5 Power Network with Self-Impedances Only

The circuit in Figure 2.5 consists exclusively of self-impedances and is ready for star network reduction. Starting from the left source station, each span of the network is reduced to an equivalent star network. It is found that three delta-wye transformations are required for every span of the network (for details, see Chapter 4). The process is repeated until finally a resultant star network is obtained at the fault location. In a similar manner, an equivalent star is found for the right-side network.
Figure 2.6 Resultant Star Network at the Fault Location

At the fault location, there are four unknowns, $I_{PA}$, $I_{PB}$, $I_{CA}$, and $I_{CB}$ (for definition of these four variables, see list of principal symbols on page ix), to be solved for (Figure 2.6), therefore, four independent equations are needed. These equations are obtained from the nodes $O_p$, and $O_c$. Each node provides two equations, one voltage and one current equation. These equations are

\[
\begin{align*}
V_p - V_p &= 0 \\
I_p + I_p &= 1 \\
V_c - V_c &= 0 \\
I_c + I_c &= 1 
\end{align*}
\]

(2.25)

where

\[
\begin{align*}
V_p &= -Z_p I_p - Z_g (I_p - I_c) \\
V_p &= -Z_p I_p - Z_g (I_p - I_c) \\
V_c &= -Z_c I_c - Z_c (I_p - I_c) \\
V_c &= -Z_c I_c - Z_c (I_p - I_c) 
\end{align*}
\]

(2.26)
\[ V_{CB} = -Z_{CB}I_{CB} - Z_{CB}(I_{PB} - I_{CB}) \]

Round-off errors in the six-terminal driving point impedance method are improved since the star network reduction technique does not cause any noticeable numerical instability during the computation process. Sebo used this method in 1966 for a long transmission line energized by one and two source stations and the results from his computer program were within ±15% from those of field tests. On the other hand, the method requires a substantial amount of computations due to the delta-wye transformations. Later (in Chapter 3), the proposed four-terminal driving point impedance method which basically adopts the same principle will be introduced. It can be shown that the proposed method requires less arithmetic operations and, therefore, may be used to speed up the computations.

2.3.2 Dawalibi's Methods

The techniques for ground current computations suggested by Dawalibi [12] are the single-sided and the double-sided elimination methods. In both these methods, \( n+1 \) loop equations are needed. Here \( n \) is the number of spans of the network considered.
Figure 2.7 shows the equivalent circuit of a transmission line. Based on this figure, the n+1 loop equations are:

**phase current loop**

\[
\begin{align*}
\sum_{i=1}^{n} \left[ (Z_{pi} + Z_{ci} - 2Z_{mi}) + Z_n \right] I_p = 0
end{align*}
\]

\[ (2.27) \]

**n loops of grounding network**

**loop I_1**

\[ -(Z_{c1} - Z_{m1}) I_p - R_{t2} I_2 + (R_{t1} + Z_{c1} + R_{t2}) I_1 = 0 \]

\[ (2.28) \]

**loop I_k, k = 2, 3, ..., n-1**
\[-(Z_{ck} - Z_{mk})I_p - R_{tk+1}I_{k+1} + (R_{tk} + Z_{ck} + R_{tk+1})I_k - R_{tk}I_{k-1} = 0 \] (2.29)

loop \(I_n\)

\[-(Z_{cn} - Z_{mn})I_p + (R_{tn} + Z_{cn} + R_{tn+1})I_n - R_{tn}I_{n-1} = 0 \] (2.30)

Here \(R_{tn+1} = R_{fp}\), the source station grounding impedance.

2.3.2.1 Single-Sided Elimination Method

Consider loop \(I_{k-1}\) in Figure 2.7. Its loop equation may be obtained from expression (2.29) if \(k\) in expression (2.29) is replaced by \(k-1\), that is

\[
I_k = -\frac{R_{tk-1}I_{k-1}}{R_{tk}} + \left(\frac{R_{tk-1} + Z_{ck-1} + R_{tk}}{R_{tk}}\right)I_{k-1}
\]

\[
-\frac{(Z_{ck-1} - Z_{mk-1})}{R_{tk}}I_p
\]

where \(k = 3, 4, ..., n\).

Adding equation (2.28) to expression (2.31), a set of \(n-1\) equations may be obtained. These are,

\[
I_2 = 0 + B_2I_1 + C_2I_p
\]

\[
I_3 = A_3I_1 + B_3I_2 + C_3I_p
\]

\[
I_4 = A_4I_2 + B_4I_3 + C_4I_p
\]

\[
\vdots
\]

\[
I_n = A_nI_{n-2} + B_nI_{n-1} + C_nI_p
\] (2.32)
where

\[ A_k = \begin{cases} \frac{R_{tk-1}}{R_{tk}} & \text{for } k = 3, 4, \ldots, n \\ 0 & \text{for } k = 2 \end{cases} \]  

(2.33)

\[ B_k = \frac{R_{tk-1} + Z_{ck-1} + R_{tk}}{R_{tk}} \quad \text{for } k = 2, 3, \ldots, n \]

\[ C_k = \frac{Z_{ck-1} - Z_{mk-1}}{R_{tk}} \]

and \( A_k, B_k, \) and \( C_k \) are the coefficients associated with the loop equations (2.32) in the grounding network for \( k = 2 \) to \( k = n \).

The \( n-1 \) equations in (2.32) may be expressed in terms of \( I_1 \) and \( I_p \) only. This requires substituting the first equation into the second equation of (2.32) to eliminate \( I_2 \). Next, \( I_2 \) and \( I_3 \) in the third equation may be replaced by the first and second equations which after the substitution have only \( I_1 \) and \( I_p \). The process is repeated for all \( I_k \)'s starting from \( k = 3 \) to \( k = n \). When the elimination is completed, expression (2.32) may be written as

\[ I_k = f_k(I_1, I_p) \quad \text{for } k = 2, 3, \ldots, n \]  

(2.34)

Substitute expression (2.34) into equation (2.27):

\[ E = f_p(I_1, I_p) \]  

(2.35)
From equation (2.30), it is clear that \( I_n \) is a function of \( I_{n-1} \) and \( I_p \), that is
\[
I_n = f(I_{n-1}, I_p) \tag{2.36}
\]
Replace \( I_{n-1} \) in equation (2.36) by \( I_{n-1} = f_{n-1}(I_1, I_p) \) in expression (2.34):
\[
I_n = f(I_1, I_p) \tag{2.37}
\]
Combining \( I_n = f_n(I_1, I_p) \) in expression (2.34) with \( I_n = f(I_1, I_p) \) in expression (2.37), the following expression is obtained:
\[
f(I_1, I_p) = f_n(I_1, I_p) \tag{2.38}
\]

The unknowns \( I_1 \) and \( I_p \) may now be evaluated from expressions (2.35) and (2.38). Once the unknowns are solved, the rest of the loop currents may readily be computed using expression (2.34).

At this stage, it is clear that \( I_k \) may also be written in terms of \( I_{k+1} \), \( I_{k+2} \), and \( I_p \) by replacing \( k \) by \( k+1 \) in expression (2.29). If the elimination of \( I_{k+1} \) and \( I_{k+2} \) is carried out in the order from \( k = n-2 \) to \( k = 1 \), a set of equations which are functions of \( I_n \) and \( I_p \) only may be obtained.

In both these cases, and no matter what the order of elimination is, it is found that \( B_k \) is always greater than one as can be seen in expression (2.33). This may cause substantial round-off errors since \( B_k \)'s multiplied themselves many times in the elimination process of expression (2.32).
Obviously, the product of \( B_k' \)'s yields a number which grows rapidly and in no time the computer is running out of significant bit representation of this number. In a recent publication [12], using an example, Dawalibi has shown that this is in fact the case. To get around this, he then proposed a second method -- the double-sided elimination method.

2.3.2.2 Double-Sided Elimination Method

In this method, \( I_k \) in the \( k \)th current loop is expressed as

\[
I_k = A_k I_{k-1} + B_k I_{k+1} + C_k I_p \quad \text{for} \quad k = 1, 2, \ldots, n
\]  

(2.39)

where

\[
A_k = \frac{R_{tk}}{T_k} \quad \text{for} \quad k = 2, 3, \ldots, n
\]

\[
= 0 \quad \text{for} \quad k = 1
\]

\[
B_k = \frac{R_{tk+1}}{T_k} \quad \text{for} \quad k = 1, 2, \ldots, n-1
\]

\[
= 0 \quad \text{for} \quad k = n
\]

\[
C_k = \frac{(Z_{ck} - Z_{mk})}{R_{tk}} \quad \text{for} \quad k = 1, 2, \ldots, n, \text{ and}
\]

\[
T_k = R_{tk} + Z_{ck} + R_{tk+1} \quad \text{for} \quad k = 1, 2, \ldots, n
\]

(2.40)

Since the \( I_k \) current is a function of the two neighboring loop currents, \( I_{k+1} \) and \( I_{k-1} \), and to eliminate them requires substitution starting from the two end loops (\( I_n \) and \( I_1 \) loops) and proceeds towards the \( I_k \) loop. Consequently,
two-pass elimination is needed to carry out both the forward and the backward substitutions. The results are

\[ I_1 = f_1(I_n, I_p) \]
\[ I_k = f_k(I_1, I_n, I_p) \quad \text{for } k = 2, 3, \ldots, n-1 \]  
(2.41)
\[ I_n = f_n(I_1, I_p) \]

Substitute expression (2.41) into equation (2.27):

\[ E = f_p(I_1, I_n, I_p) \]  
(2.42)

By making use of the first and last equations in expression (2.41), it is possible to express \(I_1\) and \(I_n\) as a function of \(I_p\) only. This implies that expression (2.42) may be further reduced to

\[ E = f_p(I_p) \]  
(2.43)

Once \(I_p\) is known when (2.43) is solved, the rest of the ground loop current may readily be found using expression (2.41).

Since \(A_k\), \(B_k\), and \(C_k\) in expression (2.40) are always smaller than one, round-off errors may be minimized. However, as a result of both forward and backward eliminations, this method does require more computation time when compared to the single-sided elimination method.
3.1 GENERAL REVIEW

Five different methods of computing fault current distribution in transmission line grounding systems have been reviewed in Chapter 2. These are the closed form method proposed by DeSieno, Sebo's matrix and six terminal driving point impedance approaches, and Dawalibi's single-sided and double-sided elimination methods. Among these methods, De-Sieno's method can only be used for long transmission line calculations due to the constraints in the initial assumptions made. Sebo's matrix approach and Dawalibi's single-sided elimination method are good only for short transmission line calculations. Some suitable techniques need to be sought so that these methods may be modified and applied to the entire length of a long transmission line.

Sebo's six terminal driving point impedance approach and Dawalibi's double-sided elimination method may be used for any length of transmission lines. No numerical instabilities have been reported so far. They have been well-tested
and proved to be useful for ground current calculations. Unlike DeSieno's method, these methods have very little constraints, and they allow varying parameters to be introduced.

The possibilities of improving the matrix approach or the single-sided elimination method will not be sought. The question of obtaining a closed form solution applicable to any length of transmission lines still remains as an unknown and will not be discussed here. However, it is necessary to look further into Sebo's six terminal driving point impedance approach. A method which basically adopts the same principle will be introduced. Hopefully, this method will speed up the computation process while still maintaining the accuracy of the simulation results. A detailed comparison of the number of arithmetic operations needed in the proposed and existing methods will be presented in Chapter 4.

The accuracy of the proposed method will be verified in Chapter 6 by comparing the simulation results of the proposed computer algorithm with those obtained from a recent EPRI research project in this area [11,12]. The project was directed to solve transmission grounding problems. Four computer programs were developed in the course of the project. One of them allows the computation of fault current
distribution in ground wires. This computer program adopted Dawalibi's double-sided elimination method, and a comparison of this method and the proposed method may be carried out in terms of various parameters of interest. The advantages and disadvantages, if any inherent in these two methods will also be discussed in Chapter 6.

3.2 BASIC MODEL

In Section 2.3, two different transmission line models were used for ground wire current calculations. For the purpose of this discussion, they are reproduced in Figure 3.1. The model in Figure 3.1a has six terminals, three on each side for neighboring span connections, while that in Figure 3.1b has only four terminals, two on each side. It is clear from Figure 3.1 that both models have the same tower-footing impedance. The six terminal model differs from the four terminal model in the representation of phase conductor impedance, ground wire impedance, and mutual impedance between the phase conductor and ground wire. These impedances do not include \( Z_{gk} \). In addition, the ground return path is being modelled by \( Z_{gk} \) impedance in the six terminal model representation whereas it is omitted in the four terminal model.
Figure 3.1 Six Terminal Versus Four Terminal Models
At this stage, it will be shown that these two models are equivalent in terms of voltages and currents. First, assume that both models have the same $I_p$ and $I_{ck+1}$ currents. Two loop equations may be written for each model in Figure 3.1, one taken around the phase conductor loop and the other around the ground wire loop. These equations are:

**Phase Conductor Loop**

**Six Terminal Model**

$$V_{pk+1} = V_{pk} + (Z_{pk} - Z_{gk})I_p - (Z_{mk} - Z_{gk})I_{ck+1} + Z_{gk}(I_p - I_{ck+1})$$

$$= V_{pk} + Z_{pk}I_p - Z_{mk}I_{ck+1}$$

**(3.1)**

**Four Terminal Model**

$$V_{pk+1} = V_{pk} + Z_{pk}I_p - Z_{mk}I_{ck+1}$$

**(3.2)**

**Ground Wire Loop**

**Six Terminal Model**

$$V_{ck+1} = V_{ck} - (Z_{ck} - Z_{gk})I_{ck+1} + (Z_{mk} - Z_{gk})I_p + Z_{gk}(I_p - I_{c+1})$$

$$= V_{ck} - Z_{ck}I_{ck+1} + Z_{mk}I_p$$

**(3.3)**

**Four Terminal Model**

$$V_{ck+1} = V_{ck} - Z_{ck}I_{ck+1} + Z_{mk}I_p$$

**(3.4)**

It could be seen from the above that equation (3.1) is the same as equation (3.2), and equation (3.3) is the same...
as equation (3.4). Therefore, the transmission line models in Figure 3.1 are equivalent in terms of the voltages.

If the voltages for any span of the model in Figure 3.1a are the same as the corresponding voltages in the model of Figure 3.1b, and if both models have the same boundary conditions at the fault location and at the source station, the corresponding currents in the phase conductor and ground wire in both models would also be the same. This verifies the initial assumption that both models have the same \( I_p \) and \( I_{ck+1} \) currents. Therefore, the two models are indeed equivalent in terms of voltages and currents since both models do have the same boundary conditions, a necessary assumption.

It is clear from the above analysis that the four terminal model is just as good as the six terminal model. It appears that all the voltages and currents may be calculated from the four terminal model with less computational time since the equivalent model is much simpler.

Though the four terminal model does not have a ground return impedance, \( Z_{gk} \), its voltage drop in the ground return path may still be calculated. This is done by assuming that the ground return path in the four terminal model has the same current as the corresponding one in the six terminal
model. This assumption is logical since both models represent the same physical grounding system. Consequently, the voltage drop in the ground return path of the kth span in both cases would be the same. As a result, the voltage drop in the kth span of the four terminal model may be computed exactly the same way as in the six terminal model. This voltage drop, when expressed mathematically, is equal to $Z_{gk}(I_p-I_{ck+1})$.

The proposed method uses the four terminal model and it can be seen from the following matrix derivations that due to the characteristics of the driving point impedance matrix, a further simplification and thus a further reduction in the computational time is still possible.

3.3 DERIVATIONS

Figure 3.2 Transmission Line with Injected Fault Current
Figure 3.2 shows n spans of a transmission line with the equivalent impedance of an external system, $Z_n$, at the source station and a one per-unit fault current injected into the fault location. Starting from the source station, a matrix equation relating voltages and currents may be written:

$$
\begin{bmatrix}
V_{p(n+1)} \\
V_{c(n+1)}
\end{bmatrix} =
\begin{bmatrix}
-(Z_n + R_{FP}) & R_{FP} \\
-R_{FP} & R_{FP}
\end{bmatrix}
\begin{bmatrix}
I_p \\
I_{c(n+1)}
\end{bmatrix}
$$

$$
\begin{bmatrix}
Z_{11(n+1)} & Z_{12(n+1)} \\
Z_{21(n+1)} & Z_{22(n+1)}
\end{bmatrix}
\begin{bmatrix}
I_p \\
I_{c(n+1)}
\end{bmatrix}
$$

where $Z_{12(n+1)} = -Z_{21(n+1)}$

Here the 2x2 matrix is referred to as the driving point impedance matrix at the source station or at the (n+1)th span of the transmission line. Moving one span to the right from the source station, the voltage matrix equation at span n in terms of the voltages and currents of the source station may be written. This is

$$
\begin{bmatrix}
V_{p(n)} \\
V_{c(n)}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{p(n+1)} \\
V_{c(n+1)}
\end{bmatrix} +
\begin{bmatrix}
-Z_{pn} & Z_{mn} \\
-Z_{mn} & Z_{cn}
\end{bmatrix}
\begin{bmatrix}
I_p \\
I_{c(n+1)}
\end{bmatrix}
$$

(3.6)
Substitute equation (3.5) into equation (3.6):

\[
\begin{bmatrix}
V_{pn} \\
V_{cn} \\
0
\end{bmatrix} =
\begin{bmatrix}
Z_{1n+1} - Z_{pn} & Z_{12n+1} + Z_{mn} & \]
\begin{bmatrix}
I_{p} \\
I_{cn} \\
0
\end{bmatrix}
\]

\[
= \begin{bmatrix}
Z_{21n+1} - Z_{mn} & Z_{22n+1} + Z_{cn}
\end{bmatrix}
\begin{bmatrix}
I_{p} \\
I_{cn+1}
\end{bmatrix}
\]

(3.7)

Equation (3.7) expresses the voltages in terms of ground wire current \( I_{cn+1} \). If \( I_{cn} \) current is needed instead of \( I_{cn+1} \) in equation (3.7), an additional current equation obtainable from the node of \( V_{cn} \) in Figure 3.2 may be used. This equation is

\[
I_{cn} = I_{cn+1} + \frac{V_{cn}}{R_{tn}}
\]

(3.8)

By substituting \( V_{cn} \) from equation (3.7) into equation (3.8),

\[
I_{cn} = I_{cn+1} + \frac{(Z_{21n+1} - Z_{mn})I_{p} + (Z_{22n+1} + Z_{cn})I_{cn+1}}{R_{tn}}
\]

or

\[
I_{cn} = \frac{(Z_{21n+1} - Z_{mn})}{R_{tn}}I_{p} + \left(1 + \frac{Z_{22n+1} + Z_{cn}}{R_{tn}}\right)I_{cn+1}
\]

(3.9)

Incorporating equation (3.9) into equation (3.7), an expanded 3x3 matrix equation is obtained:

\[
\begin{bmatrix}
V_{pn} \\
V_{cn} \\
0
\end{bmatrix} =
\begin{bmatrix}
Z_{1n+1} - Z_{pn} & 0 & Z_{12n+1} + Z_{mn} \\
Z_{21n+1} - Z_{mn} & 0 & Z_{22n+1} + Z_{cn} \\
\frac{Z_{21n+1} - Z_{mn}}{R_{tn}} & -1 & 1 + \frac{Z_{22n+1} + Z_{cn}}{R_{tn}}
\end{bmatrix}
\begin{bmatrix}
I_{p} \\
I_{cn} \\
I_{cn+1}
\end{bmatrix}
\]

(3.10)
Equation (3.10) is of the form
\[
\begin{bmatrix}
V_1 \\
0
\end{bmatrix} =
\begin{bmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
\]  
\tag{3.11}

having a null matrix on the left-hand side of the equation. If the inverse of $M_{22}$ exists (in this case, the non-zero matrix element $(3,3)$ in equation (3.10)), a further simplification in equation (3.10) may be carried out using
\[
\begin{bmatrix}
V_1 \\
0
\end{bmatrix} =
\begin{bmatrix}
M_{11} - M_{12}(M_{22})^{-1}M_{21}
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
\]  
\tag{3.12}

The result is a matrix equation as shown in equation (3.13). The calculation of the driving point impedance matrix in equation (3.13) may be carried out in a proper order so that the computational time may be minimized.
\[
\begin{align*}
V_{pn} & = \left[ z_{1n+1} - z_{pn} \right] - \left[ \frac{z_{2n+1} - z_{mn}}{R_{tn}} \right] \left[ \frac{z_{1n+1} + z_{mn}}{1 + \frac{z_{2n+1} + z_{cn}}{R_{tn}}} \right] \\
V_{cn} & = \left[ z_{2n+1} - z_{mn} \right] - \left[ \frac{z_{2n+1} - z_{mn}}{R_{tn}} \right] \left[ \frac{z_{2n+1} + z_{cn}}{1 + \frac{z_{2n+1} + z_{cn}}{R_{tn}}} \right]
\end{align*}
\]

(3.13)

\[
\begin{bmatrix}
V_{pn} \\
V_{cn}
\end{bmatrix}
\begin{bmatrix}
1_{p} \\
1_{cn}
\end{bmatrix}
\]
Figure 3.3 Suggested Sequence of Computation

This sequence of calculation is:

1. Compute and store \([1+(Z_{22n+1}+Z_{cn})/R_{tn}]\), the denominator of \(Z_{22n}\).
2. Compute \([Z_{22n+1}+Z_{cn}]\), the numerator of \(Z_{22n}\), and divide this by the value in step 1 to obtain \(Z_{22n}\).
3. Compute \([Z_{12n+1}+Z_{mn}]\), the numerator of \(Z_{12n}\), and store the result.
4. Divide the value in step 3 by the value in step 1 to get \(Z_{12n}\), and store the result.
5. Divide the value in step 3 by the value \(R_{tn}\).
6. Multiply the result in step 5 by the value in step 4.
7. Add the resultant value in step 6 to \( Z_{11n+1} - Z_{mn} \) to obtain \( Z_{11n} \).

It should be noted from Figure 3.3 that
\[-[Z_{21n+1} - Z_{mn}] = [Z_{12n+1} + Z_{mn}] \]
since \( Z_{12n+1} = -Z_{21n+1} \) in expression (3.5). Furthermore, the long expression of \( Z_{21n} \) in Figure 3.3 may be deduced to \(-Z_{12n}\) if a proper manipulation is carried out. As a result, there is no need to compute
\[-[Z_{21n+1} - Z_{mn}] \] and \(-Z_{21n}\).

In the same manner, the driving point impedance matrices for the rest of the spans of the transmission line may be derived. They are found to possess matrix characteristics similar to the one at span \( n \). This makes the reduction in the computational time possible for every span of the transmission line.

To understand the characteristics of the driving point impedances during the computational process, the curves of \( Z_{11k}, Z_{12k}, Z_{21k}, \) and \( Z_{22k} \) for values of \( k \) form 1 to 200 are plotted. The values of line parameters used in the calculations of these curves are included in Appendix B. From the curves in Figure 3.4, it is clear that values of \( Z_{12k}, Z_{21k}, \) and \( Z_{22k} \) remain relatively constant after a substantial distance away from the source station. This situation arises only when the fault location is very far away from the
source station. The absolute values of $Z_{11k}$ increase as $k$ decreases mainly because as the distance from the source station increases, the self-impedance of the phase conductor increases. This increase is being limited by the finite self-impedance of the entire length of the phase conductor.

It should be noted from Figure 3.4 that the phase angles $Z_{11k}$ and $Z_{21k}$ are in the third quadrant of an X-Y plane. This is the result of the negative sign introduced in the matrix equation (3.5) due to the direction of $I_p$ current. As can be seen from equation (3.5) the initial values of $Z_{12k}$, $Z_{21k}$ and $Z_{22k}$ are determined by $R_{FP}$. This value has a significant effect on the nature of curves $Z_{12k}$, $Z_{21k}$ and $Z_{22k}$ when $k$ is close to 200 (source station). It is found that the absolute values of these three curves near the source station could be decreasing instead of increasing when $k$ decreases for different values of $R_{FP}$. For example, for $R_{FP} = 10$ ohms the curves have a decreasing trend at the station location, as opposed to $R_{FP} = 0.1$ ohm, when they have an increasing trend as it can be seen in Figure 3.4.

Based on these four curves in Figure 3.4, one may then conclude that the driving point impedances are considerably stable for all values of $k$. This is very important since the numerical stability of the end results depends very much on the stability of the driving point impedances. Conse-
quently, the more stable the curves are, the less round-off errors in the end results exist.

Figure 3.4 Curves of Driving Point Impedances
3.4 **BOUNDARY CONDITIONS**

![Diagram](image)

**Figure 3.5 Fault Fed by One Source Station**

At the fault location, a fault current of 1.0 per-unit is assumed. Because of this assumption, \( I_p = I_{c1} = 1.0 \text{ per-unit} \). Knowing these two values, the rest of the currents in each span of the transmission line may then be solved (see the following section).

The above is valid only when the fault current is fed by one source station with a ladder network connected at the fault location if necessary. References 4, 5, and 8 have treated the calculations of ladder networks in depth. The results of the computer simulation will be presented in Chapter 6.

When the fault current is fed by two source stations, the resultant network at the fault location after the span by span network deduction is shown in Figure 3.6.
Based on the equivalent circuit in Figure 3.6, the four unknowns, $I_{pA}$, $I_{pB}$, $I_{c1A}$, and $I_{c1B}$, may then be solved for. The equations used are very similar to those in equation (2.25) in Sebo's second method. Subsequent current computations will be much simpler since the equivalent circuit in Figure 3.6 is simpler than the one in Figure 2.6.

3.5 **KTH SPAN CURRENT**

In Section 2.3.1.1, one realized that the computation of the kth span current cannot be obtained from the (k-1)th span current since the round-off errors could be very severe. To get around this, the following method is proposed which basically adopts the same fundamental concept as used...
in the Dawalibi's elimination method \([7,12]\). In both methods, the equation used in the \(k\)th span ground wire current computation may be expressed as 
\[
I_{ck} = f(I_{c1}, I_p)
\]
or
\[
I_{ck} = E_k I_{c1} + F_k I_p
\]
assuming that the currents \(I_{c1}\) and \(I_p\) have already been evaluated in the previous section. The question then is to derive a general expression to evaluate the factors, \(E_k\), and \(F_k\) at the \(k\)th span.

Consider a simple case in which the fault current is fed by one source station and there is no ladder network connected to the fault location as in Figure 3.7.

![Figure 3.7 Transmission Line Fed by One Source Station](image)

Starting from span 1 in the above figure,
\[ I_{c2} = I_{c1} - \frac{V_{c1}}{R_{t1}} \]
\[ = (1 - \frac{Z_{211}}{R_{t1}})I_{c1} - \frac{Z_{211}I_p}{R_{t1}} \]  
(3.15)
\[ = E_2I_{c1} + F_2I_p \]

Similarly, at span 2,
\[ I_{c3} = (1 - \frac{Z_{222}}{R_{t2}})I_{c2} - \frac{Z_{212}I_p}{R_{t2}} \]  
(3.16)

Substituting \( I_{c2} \) from (3.15) into (3.16),
\[ I_{c3} = [(1 - \frac{Z_{222}}{R_{t2}})E_2]I_{c1} \]
\[ + [(1 - \frac{Z_{222}}{R_{t2}})F_2 - \frac{Z_{212}}{R_{t2}}]I_p \]
\[ = E_3I_{c1} + F_3I_p \]  
(3.17)

In general, the ground wire current at span \( k \) in (3.14) has
\[ E_k = (1 - \frac{Z_{22k-1}}{R_{tk-1}})E_{k-1} \]  
(3.18)
\[ F_k = (1 - \frac{Z_{22k-1}}{R_{tk-1}})F_{k-1} - \frac{Z_{21k-1}}{R_{tk-1}} \]  
(3.19)

Figure 3.8 shows the current coefficients, \( E_k \) and \( F_k \), of the corresponding impedance curves in Figure 3.4. \( E_k \) is the
current coefficient of $I_{c1}$ (see equation 3.14). Its value is the greatest near the fault location. As $k$ increases, this value decays rapidly and approaches zero at the source station. The contribution of phase current $I_p$ to the ground wire current $I_{ck}$ may be examined by its current coefficient $F_k$ in equation (3.14). Near the fault location, the value of $F_k$ is the least and it increases as $k$ increases. For intermediate values of $k$, $F_k$ approaches a constant value. Near the source station ($k = 200$), $F_k$ increases slightly as may be seen in Figure 3.4. This small increase in $F_k$ explains mathematically the end-effect current at the source station.

In the computations of expressions (3.18) and (3.19), two storage locations for each span of the transmission line need to be reserved so that values of $(1-Z_{2k-1}/R_{tk-1})$ and $(Z_{21k-1}/R_{tk-1})$ stored during span by span driving point impedance calculations (see Section 3.3) may then be retrieved. This method, obviously, minimizes the round-off errors at the expense of computer memory space. In actual system computations, the transmission line system under study is usually less than 200 spans. Assuming double precision computations (16 bytes for each complex number represented in the computer), the memory space requirement would be $2 \times 16 \times 200$ bytes. This is somewhat around 6 kilobytes and
Figure 3.8 Curves of Current Coefficients
is considered small when the OSU Amdahl 470 is used for the above calculations. Although the above general equations (3.18), and (3.19) are derived only for fault currents supplied from one source station without ladder network connected to the fault location, they may readily be used for any case studies as long as the boundary conditions at the fault location are properly taken care of.

In summary, the general equations for driving point impedance and ground wire current computations have been obtained. The number of arithmetic operations appears to be small due to the inherent characteristics of the driving point impedance matrix. The following chapter will compute the actual number of arithmetic operations needed in each span of the line and will compare this number to the values obtained from the five existing methods.
Chapter IV
COMPARISON OF VARIOUS METHODS

4.1 INTRODUCTION

In this chapter, the computational speed and storage requirements for each of the methods discussed in Chapters 2 and 3 will be compared in terms of the number of arithmetic operations and computer memories. To ensure a meaningful analysis, it is important that the comparison be made on the same basis and computational environment. The existing methods as described by their corresponding published papers [5,6,7] and as interpreted in Chapter 2 will be monitored and analyzed closely, but some minor deviations from the original intentions of their authors may not be avoided due to lack of sufficient information in their papers.

At the end of this chapter, a table which summarizes the computational speed, storage requirements, round-off errors, and other imposed constraints in each of these methods will be presented. It is hoped that this table will provide the readers with a clear picture of the advantages and disadvantages if any associated with these techniques.
4.2 SPEED AND STORAGE REQUIREMENTS

The following conditions are stated to ensure a uniform way of comparison.

1) A transmission line fed by one source station and with no ladder network beyond the fault location is considered for simplication purposes.

2) The magnitude of the current in the phase conductor for a line-to-ground fault is assumed to be one per-unit and the calculation of the actual fault current is not required.

3) Comparisons made are based on the following aspects:
   - number of arithmetic operations for each span
   - computer memory requirements.

4) Some computer memories are needed for the storage of input data and for the temporary storage of intermediate values during the arithmetic manipulations. These, however, will not be included in the actual storage requirements for the retrieval of intermediate results used in the computation of ground wire currents. An example of data retrieval is described in Section 3.5.

5) Some additional arithmetic manipulations are expected in solving the final expression incorporating the two boundary conditions at the source station and at the fault location. These are not included in the counting of per
span arithmetic operations since they are done only once for the entire length of the line.

4.2.1 DeSieno's Method

The closed form expression (2.11) is used for the calculation of ground wire currents. The only term that is varied in expression (2.11) is \( \cosh(\alpha x) \). Assuming that a good \( \cosh \) routine is used, the computation of ground wire current may be very fast.

No memory space is needed since no intermediate results need to be stored and retrieved for the calculation of ground wire currents.

4.2.2 Sebo's Matrix Method

The 4x4 \( M_k \) matrix in expression (2.14) is used. Before matrix \( M_{k+1} \) may be multiplied by matrix \( M_k \), it is necessary that all the elements in the last row of \( M_k \)'s be evaluated first. For each \( M_k \) matrix, 1 addition and 3 divisions are needed. The calculation of ground wire current requires the multiplication of the last row of \( M_{k+1} \) matrix by every column of \( M_k \) matrix as shown symbolically in Figure 4.1. This does not include the calculations of phase conductor voltage and ground wire voltage.
The number of arithmetic operations needed for the above matrix multiplication depends only on the multiplication of non-zero matrix elements. Furthermore, a matrix element multiplied by the value one requires zero arithmetic operation since its value does not change. The total number of arithmetic operations required for the calculation of each span of the line is shown below the dashed line in Figure 4.1.
Once the $I_{cl}$ current is solved via expression (2.15), the calculation of next span current is given by

$$I_{ck+1} = I_{ck} - \frac{V_{ck} + I_{ck}Z_{ck} - I_{p}Z_{mk}}{R_{tk}}$$

(4.1)

where $V_{ck} = (I_{ck-1} - I_{ck})R_{tk-1}$. Since $I_{p} = 1.0$ per-unit, expression (4.1) may be written as:

$$I_{ck+1} = I_{ck} - \frac{(I_{ck-1} - I_{ck})R_{tk-1} + I_{ck}Z_{ck} - Z_{mk}}{R_{tk}}$$

(4.2)

Equation (4.2) requires 1 addition, 3 subtractions, 2 multiplications, and 1 division. Adding these values to the number of arithmetic operations in Figure 4.1, one has 6 additions, 3 subtractions, 7 multiplications, and 4 divisions for the calculation of ground wire current.

Since the ground wire current at any span is computed using the current value in its neighboring span, no storage space is needed.

4.2.3 Sebo's Driving Point Impedance Method

Figure 4.2 (extracted from Sebo's Ph.D. dissertation) [25] explains why three delta-wye transformations are needed for the reduction of each span of the network, and how the actual reduction is carried out.
Figure 4.2 Network Reduction in Sebo's Second Method (+ indicated means an addition)
Given three delta elements $Z_{AB}$, $Z_{BC}$ and $Z_{CA}$, any wye element in Figure 4.3 may be computed using the following equations:

$$Z_{OA} = \frac{Z_{AB}Z_{CA}}{Z_S}$$

$$Z_{OB} = \frac{Z_{AB}Z_{BC}}{Z_S}$$

$$Z_{OC} = \frac{Z_{BC}Z_{CA}}{Z_S}$$

where $Z_S = Z_{AB} + Z_{BC} + Z_{CA}$

$Z_S$ which requires 2 additions needs to be computed only once, and for each wye element in equation (4.3), 1 multi-
plication and 1 division are needed. Therefore, the total number of arithmetic operations for the manipulation of equation (4.3) is 2 additions, 3 multiplications, and 3 divisions. Since three delta-wye transformations are needed for the reduction of each span of the network, the number of operations is simply three times the previous value. In addition to that, 8 more additions are still needed in Figure 4.2 for adding up all the series impedances.

The computation of ground wire current is carried out by the current division technique in Figure 4.4.

\[
\begin{align*}
I_p &= 1 \text{ P.U.} \\
I_{ck} &= \frac{Z_{gAk}}{Z_{cAk}+Z_{gAk}} \\
I_{gk} &= \frac{Z_{PAk}}{Z_{cAk}}
\end{align*}
\]

Figure 4.4 Current Division in Ground Wire and Ground Path

This requires 1 addition and 1 division. Summing up the number of arithmetic operations, one has 15 additions, 9 multiplications, and 10 divisions.
During the star network network reduction, values of $Z_{gA_k}$ and $Z_{cA_k}$ need to be stored so that they may be retrieved for the computation of ground wire currents. Therefore, two memory storage locations are needed for every span of the line.

4.2.4 Dawalibi's Single-Sided Elimination Method

Expression (2.32) is used to carry out the loop current substitution and elimination until the final form of expression (2.34) is reached. Before this is done, it is necessary to compute $A_k$, $B_k$, and $C_k$ coefficients in expression (2.33). The number of arithmetic operations needed to compute expression (2.33) is 2 additions, 1 subtraction, and 3 divisions. To examine the number of operations during the substitution and elimination process, an expanded form of expression (2.34) is derived. This is

$$I_k = (A_k G_{k-2} + B_k G_{k-1}) I_1 + (A_k H_{k-2} + B_k H_{k-1} + C_k) I_p$$

$$= G_k I_1 + H_k I_p$$

(4.4)

where $G_k$ and $H_k$ denote the current coefficients after the substitution and elimination have been carried out for the loop current $I_k$. From expression (4.4), it is now clear that 3 additions and 4 multiplications are needed to obtain coefficients $G_k$ and $H_k$. 
Once the loop current \( I_1 \) is solved via expression (2.38), the ground wire current may be computed using

\[
I_{ck} = I_p - I_k = -G_k I_1 + (1 - H_k) I_p
\]

which requires 1 addition, 1 subtraction, and 2 multiplications. Summing up, the number of arithmetic operations is 6 additions, 2 subtractions, 6 multiplications, and 3 divisions.

Expression (4.4) requires two memory storage locations so that \( G_k \) and \( H_k \) may be retrieved and used in expression (4.5).

4.2.5 Dawalibi's Double-Sided Elimination Method

Expression (2.40) is used to compute the current coefficients needed in equation (2.39). This requires 2 additions, 1 subtraction, and 3 divisions. Expression (2.41) is obtained via two-pass elimination. An expanded form of expression (2.41) showing each pass of elimination is as follows:

\[
I_k = \frac{A_k}{1 - B_k P_{k+1}} I_{k-1} + \frac{B_k Q_k + 1}{1 - B_k P_{k+1}} I_n + \frac{B_k R_k + 1 + C_k}{1 - B_k P_{k+1}} I_p
\]

\[
= P_k I_{k-1}^I + Q_k I_n + R_k I_p
\]

\[
I_k = P_k P_{k-1} I_1 + (P_k Q_{k-1} + Q_k) I_n + (P_k R_{k-1} + R_k) I_p
\]

\[
= S_k I_1 + T_k I_n + U_k I_p
\]

(4.6)
where $P_k$, $Q_k$ and $R_k$ denote the current coefficients after
the first pass elimination, and $S_k$, $T_k$ and $U_k$ are the cur­
rent coefficients after the second pass elimination. The
above two expressions require 3 additions, 1 subtraction, 6
multiplications, and 3 divisions so that their current coef­
ficients may be computed.

When expression (2.41) is solved, the loop currents $I_l$
and $I_n$ are found. The ground wire current may then be com­
puted using

$$I_{ck} = I_p - I_k = -S_k I_l - T_k I_n + (1 - U_k)I_p$$

(4.8)

which requires 1 addition, 2 subtractions, and 3 multiplica­
tions. The total number of arithmetic operations then be­
comes 6 additions, 4 subtractions, 9 multiplications, and 6
divisions.

Three memory storage locations are required for retrieval
of values of $S_k$, $T_k$, and $U_k$ in expression (4.8).

4.2.6 Proposed Method

To compute the ground wire current, only the lower half
of the matrix in Figure 3.3 is required. If the first four
steps suggested in Figure 3.3 are traced, the number of ar­
ithmetic operations needed is 4 additions and 3 divisions.
It should be noted that $Z_{21n}$ is computed from steps 3 and 4
in Figure 3.3 since $Z_{12n} = -Z_{21n}$. 
The calculation of the current coefficients $E_k$ and $F_k$ in equations (3.18) and (3.19) requires 2 subtractions, 2 multiplications, and 2 divisions. These numbers are small because both expressions share the same common factor $(1 - Z_{22k-1}/R_{tk-1})$. When the ground wire current is computed in expression (3.14), 1 addition and 2 multiplications are needed. Summing up the number of arithmetic operations for the computation of ground wire current, one obtains 5 additions, 2 subtractions, 4 multiplications and 5 divisions.

4.3 TABULATED RESULTS

Summarizing the number of arithmetic operations, the memory requirements for each method discussed in this chapter, the round-off errors and constraints imposed on each method discussed in Chapters 2 and 3, one obtains the table as shown on the following page.

While every effort is made to present a fair and meaningful comparison, the values given under the column "operations per span" still cannot be treated as minimum. Some deviations might still exist and could only be determined by the authors of these methods.
<table>
<thead>
<tr>
<th>Methods</th>
<th>Operations per span</th>
<th>Storage per span</th>
<th>Round-off errors</th>
<th>Applications (limitations, if any)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform distributed method</td>
<td>very little</td>
<td>Nil</td>
<td>No</td>
<td>Limited to long transmission lines with constant line parameters</td>
</tr>
<tr>
<td>(DeSieno)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 x 4 matrix method</td>
<td>+ 6</td>
<td>Nil</td>
<td>Yes</td>
<td>All cases</td>
</tr>
<tr>
<td>(Sebo)</td>
<td>- 3</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>x 7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>÷ 4</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>6-terminal driving-point imp.</td>
<td>+ 13</td>
<td>2</td>
<td>No</td>
<td>All cases</td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
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<td></td>
<td>x 9</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>÷ 10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-Sided elimination method</td>
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<td>Yes</td>
<td>All cases</td>
</tr>
<tr>
<td>(Dawalibi)</td>
<td>- 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>x 6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>÷ 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double-sided elimination</td>
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<td>3</td>
<td>No</td>
<td>All cases</td>
</tr>
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<td></td>
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<tr>
<td></td>
<td>x 9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>÷ 6</td>
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<td></td>
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</tr>
<tr>
<td>4-terminal driving-point</td>
<td>+ 5</td>
<td>2</td>
<td>No</td>
<td>All cases</td>
</tr>
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<td>- 2</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>x 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>÷ 5</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 4.1 Comparison of Various Methods
Chapter V
CASE STUDIES

5.1 INTRODUCTION

The method developed in Chapter 3 in its present form can be used for calculations of ground wire currents - for different phase conductor arrangements, different ground wire and tower structure configurations - for different ground wire material, tower-footing impedances, and soil resistivities - for the change of the distance between the source station and fault location - in a ground wire ladder network extended beyond the location of a fault - in the studies of end-effect phenomena of the ground wire and ground systems.

These studies may be introduced in a computer program by the change of one or more impedance parameters as appeared in the equivalent circuit of Figure 3.1b. Further use of the computer program requires some modifications so that it may be applied for other case studies. Among the
The studies which will be discussed are the distribution of ground wire current in
- a multi-circuit transmission line system
- an open ground wire system
- a steel ground wire system using an iterative approach.

5.2 MULTI-CIRCUIT TRANSMISSION LINE

The term 'multi-circuit' implies that there are at least two circuits of a three-phase conductor system in a power transmission network. In a more general application, one could also consider the ground wire system as a separate circuit in the power transmission network. Depending on the number of uninsulated ground wires on the tower structures, the number of circuits in the ground wire system may also be more than one.

With these changes introduced, the problem then becomes solving a transmission line system which has \( m \) phase conductors and \( j \) ground wires. Equation (3.13) has been derived mainly for use in a single-circuit system. To incorporate the studies of multi-circuit system into the equations, the following expanded form is obtained.
The matrix characteristics of equation (5.1) are very similar to those of equation (3.13). Each of the matrix elements in the upper triangle of the $Z_k$ matrix is either equal to or $-1$ times the corresponding element in the lower triangular matrix. As a result of that, not all the elements in the full matrix need to be calculated. Only the matrix elements in the upper triangular matrix are computed. For $n^2$ matrix elements, the number of computed elements is $\lfloor (n^2 - n)/2 \rfloor + n$. Subtracting this value from $n^2$ is the number of matrix elements not computed. Based on these calculations, the following table may then be constructed.
Table 5.1 reveals that as the number of circuits in the study system increases, the computational time also increases. However, this increase has been reduced somewhat due to the saving in the computational time of the lower triangular matrix. The last column in the above table gives the actual number of matrix elements not computed. This number approaches one half the nxn value of the full matrix and becomes a major source for saving in the computational time as n becomes large.

Although the above discussion is confined to an equivalent phase conductor and/or an equivalent ground wire in each circuit of a multi-circuit system, it may readily be expanded to the studies of multi-circuit and multi-conductor systems. This allows the representation of each three-phase conductor and/or the representation of each ground wire as opposed to the use of equivalent conductor concept. It
should be pointed out that equation (5.1) may still be used because it makes no difference to the computer whether the conductor considered is of equivalent or individual representation. For convenience reasons, it might be advisable to alter the subscript notations so that they may be interpreted properly.

Once the $Z_k$ matrix is formed, impedance matrix deduction may then be carried out starting from the source station until the impedance matrix at the fault location is obtained. A current source of one per-unit is then inserted between the faulty phase conductor and the ground wire at the fault location. Solving the boundary conditions at the fault location determines not only the current value of the faulty phase conductor but also the current value in all the ground wires and the sound phase conductors.

5.3 OPEN GROUND WIRE

Figure 5.1 shows a power transmission line with ground wire shielding for only a portion of the line, e.g., for 4-5 miles (24-30 spans) from the source station. The idea of leaving a portion of the phase conductors unshielded by a ground wire has been suggested by a few utility companies mainly because in case of lightning strokes, the propagating
waves attenuate themselves before reaching the source station due to some long distance from the station. The fault current might possibly be handled by the phase conductor alone without causing any damage to the conductor. It appears that this type of ground wire system will reduce the cost of construction due to the smaller length of ground wires used. Whether or not this may be applied to any existing systems will have to be justified from the protection point of view.

Starting from span q and advancing towards the source station, a set of voltage equations may be written for the ground wire system.

At span q,
\[ V_{cq} = -R_{tq} I_{cq} + 0 I_p \]
\[ = Z_{21q} I_{cq} + Z_{22q} I_p \]

At span \( q + 1 \),
\[ V_{cq+1} = \frac{Z_{22q} - Z_{cq}}{1 - (Z_{22q} - Z_{cq})/R_{tq}} I_{cq+1} + \frac{Z_{21q} + Z_{mq}}{1 - (Z_{22q} - Z_{cq})/R_{tq}} I_p \]
\[ = Z_{21q+1} I_{cq+1} + Z_{22q+1} I_p \]  
(5.3)

In general, the above equation may be used for any span \( k \) from \( k = q + 1 \) to \( k = n + 1 \) by replacing \( q + 1 \) by \( k \).

The current \( I_{cn+1} \) at span \( n + 1 \) or at the source station is equal to the phase current of 1.0 per-unit. This allows the voltage of the grounding tower at the source station to be evaluated. Once the voltage at the source station is known, the computation of ground wire current for span \( n \) may then be carried out using the following equation.

\[ I_{cn} = (1 + \frac{Z_{21n+1} + Z_{22n+1}}{R_{fp}}) I_p \]
\[ = F_n I_p \]  
(5.4)

In a similar manner, \( I_{cn-1} \) may be computed using

\[ I_{cn-1} = (F_n + \frac{Z_{21n} + Z_{22n} F_n}{R_{tn}}) I_p \]
\[ = F_{n-1} I_p \]  
(5.5)
If \( n - 1 \) in the above is replaced by \( k \), equation (5.5) may be applied to any span \( k \) for \( k = q + 1 \) to \( k = n \). It is important that all the ground wire currents be expressed as the coefficients of the phase current so that round-off errors in the mid-section of the ground wire may be minimized.

Once the current coefficients are known, the driving-point impedance looking into the fault location may be obtained. This is needed for solving the phase current in the case of a fault fed by two source stations since the phase current value is not known until the driving-point impedance at the fault location is solved.

5.4 **ITERATIVE APPROACH FOR STEEL GROUND WIRE**

Unlike ACSR ground wires, the resistance and reactance of steel ground wires change as a function of current. To determine the correct impedance characteristics of a steel ground wire, it is first necessary to determine the magnitude of the current which would flow in the wire for a given load. Then determine if the calculated ground wire current matches the impedance characteristics of the steel ground wire. In general, this is an iterative procedure.

Before the iterative procedure may be carried out, curves of steel ground wires must be prepared. The impedance data
provided by the manufacturer together with their corresponding currents are usually discrete as may seen in Table 3.3.11 on page 82 of Reference [10]. To obtain a continuous and a smooth curve, interpolation of the given data points might be needed. Once this is done, any ground wire current computed during the iteration process may then be mapped to its impedance value. Reference [26] describes the use of the IMSL cubic interpolation routine.

The use of an iterative method for steel ground wires is essential in the neighborhood of fault location where the change of span to span current can be as much as 100 percent especially when the fault location is close to the source station. Uncorrected impedance values for steel ground wires may lead to incorrect computed current values in the ground wire and ground systems.

In summary, the driving-point impedance method that has been developed may be used for various case studies in addition to the base case studies. Three case studies have been described in this chapter and their simulation results will be presented in the following chapter.
Chapter VI
RESULTS

6.1 INTRODUCTION

A Fortran computer program based on the four terminal driving point impedance method has been written for general purposes and various case studies. The program has the capabilities of reading transmission line parameters as inputs, and outputs plots of ground wire currents on a line-printer. Curves of tower currents and/or tower voltages may also be plotted when necessary. Details of I/O control words are described in Appendix C.

An optional plotter-plot of high resolution may be generated on the OSU Versatec plotter [27]. This requires simulation results to be stored first on the disk so that they may be read as input data into a plotting routine which then generates the requested plotter-plot. A listing of the plotting program and its JCL are also included in Appendix C.
The test program which computes the ground wire current can take in data from at most 4 transmission lines. Each transmission line consists of 1 or 2 equivalent phase conductors and 1 equivalent ground wire with at most 200 spans per line. If a situation arises where it is necessary to go beyond the upper limits, the related dimension statements will have to be modified and their associated parameters reinitialized. The whole program will then need to be compiled and linked again. A listing of the source program and the steps in obtaining its load module data set are described in Appendix C.

Before the test program was used for any case studies, the accuracy of the computed results from the computer was checked by comparison to those from hand calculations. Simple systems with short length transmission lines have been calculated by both the computer and hand calculations and their results agreed. Long transmission lines are difficult to compute by hand. It was then decided to use an EPRI program [11] for comparison purposes. The EPRI program uses Dawalibi's double-sided elimination method and performs about the same work as the test program. The main difference between the two programs is that the test program computes all the currents in per-unit values whereas the EPRI program has these values in actual amperes.
The EPRI program is available at OSU in the form of a magnetic tape. Some JCL statements written by EPRI's Electric Power Software Center [28] were not compatible with the OSU computer systems. Appendix D describes how the modifications were carried out and how the program was used for various studies. Some additional JCL statements are also included in Appendix D for interested readers who might wish to use the program for some other studies in the future.

The following section describes the comparison between the EPRI and the test program. Results of case studies follow immediately after the comparison.

6.2 COMPARISON OF EPRI AND TEST PROGRAMS

Both the EPRI and the test program are written in Fortran language. They are compiled and linked using the same OSU cataloged procedure. Comparison is made only at the execution stage. Certain interesting parameters such as CPU time, I/O operations, cost per run, and memory requirements for a typical study are tabulated in Table 6.1:

<table>
<thead>
<tr>
<th></th>
<th>CPU TIME</th>
<th>I/O RECORD DISK</th>
<th>COST DOLLAR</th>
<th>MEMORY VIRTUAL SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPRI</td>
<td>3.41s</td>
<td>1189 97</td>
<td>1.90</td>
<td>152K 204K</td>
</tr>
<tr>
<td>TEST</td>
<td>0.21s</td>
<td>220 169</td>
<td>0.76</td>
<td>116K 200K</td>
</tr>
</tbody>
</table>

Table 6.1 Cost and Memory Comparison
The cost per run at OSU in this case is determined by the CPU time and the number of arithmetic operations. The memory requirements for the whole program are not charged at OSU. Interpretation of the above table is not attempted mainly because it is uncertain whether the additional CPU time needed in the EPRI program is due to the additional arithmetic operations it performs for the preparation of its lengthy output. Since both programs do not have the same computational environment, the results of comparison might not be conclusive.

Table 6.2 lists the ground wire currents computed by both programs. The line parameters for these studies may be found in Appendix B. The fault is located at a distance of 32 spans from the left source station and 134 spans from the right source station as shown in Figure 6.1.
Total Fault Current = 25416.513 amps.

<table>
<thead>
<tr>
<th>Span No.</th>
<th>Left Side</th>
<th>Right Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14680.393</td>
<td>13324.536</td>
</tr>
<tr>
<td>2</td>
<td>13324.536</td>
<td>12130.007</td>
</tr>
<tr>
<td>3</td>
<td>12130.007</td>
<td>11613.800</td>
</tr>
<tr>
<td>15</td>
<td>6837.246</td>
<td>6834.128</td>
</tr>
<tr>
<td>16</td>
<td>6834.128</td>
<td>6847.343</td>
</tr>
<tr>
<td>17</td>
<td>6847.343</td>
<td>6850.000</td>
</tr>
<tr>
<td>30</td>
<td>7352.083</td>
<td>7413.000</td>
</tr>
<tr>
<td>31</td>
<td>7413.000</td>
<td>7470.000</td>
</tr>
<tr>
<td>32</td>
<td>7470.000</td>
<td>7532.000</td>
</tr>
</tbody>
</table>

Table 6.2 Comparison of Ground Wire Currents

Only certain values near the source stations, fault locations and mid-sections of the lines are compared. The results from both programs are agreeable up to their third significant digit.
6.3 GROUND WIRE MATERIAL

Two plots are generated for comparison of the use of ACSR and steel ground wires respectively. Here the steel ground wire is not corrected for its impedance as the current changes. Similarly, the impedance of the ACSR ground wire is also not corrected as the temperature changes.

Results from the two plots in Figures 6.1 and 6.2 reveal that a higher steel wire impedance is the main cause for less ground wire current. The end-effect phenomenon using ACSR ground wires is more pronounced due to the smaller impedance. In the case of steel ground wires, the length of the end-effect section is shorter because of the larger impedance. Similar results were obtained by Sebo in Reference [6].

6.4 VARYING TOWER-FOOTING IMPEDANCE

Four tests are conducted to study the effect of varying tower-footing impedances on the distribution of ground wire current. These are:

Right Side Section

Case 1: $R_{t2B} = 1$ ohm at span 2 to the right of the fault location and the rest remains the same as in the base case of Figure 6.1 (see Appendix B).
Result: Figure 6.3 (the insert of Figure 6.3 shows the change in $R_{t2B}$ from 10 ohms to 1 ohm).

Case 2: $R_{t67B} = 1$ ohm at span 67 to the right of the fault location and the rest remains the same as in the base case of Figure 6.1 (see Appendix B).

Result: Figure 6.4 (the insert of Figure 6.4 shows the change in $R_{t67B}$ from 10 ohms to 1 ohm).

Case 3: $R_{t133B} = 1$ ohm at span 133 to the right of the fault location and the rest remains the same as in the base case of Figure 6.1 (see Appendix B).

Result: Figure 6.5 (the insert of Figure 6.5 shows the change in $R_{t133B}$ from 10 ohms to 1 ohm).

Left Side Section

Case 4: $R_{t16A} = 1$ ohm at span 16 to the left of the fault location and the rest remains the same as in the base case of Figure 6.1 (see Appendix B).

Result: Figure 6.6 (the insert of Figure 6.6 shows the change in $R_{t16A}$ from 10 ohms to 1 ohm).

Figure 6.3 indicates that when $R_{t2B}$ in the right side section is changed from 10 ohms to 1 ohm, the per-unit values of ground wire currents near the fault location also change. The currents at the source station and at the middle of the right side section show practically no change in magnitude. If, however, the change is introduced in $R_{t133B}$
at the right side section, the end-effect currents at the right source station will be affected as shown in Figure 6.5. When $R_{t67B}$ is changed at the middle of the right side section, the current distribution remains the same (Figure 6.4). Similar conclusions were obtained by Dawalibi in Reference [12].

It should be pointed out: that the result in Case 3 is only true when the fault occurs at a considerably long distance away from the source station and any change of $R_t$ at the middle of the section will not affect the distribution of ground wire current in that section of the line. However, when the line is short as in the left side section in Figure 6.6, the current at the middle is disturbed when $R_{t16A}$ is changed.

Generally, the distribution of ground wire current is affected by the tower-footing impedance. Decrease in $R_t$ increases the actual magnitude of the fault current and provides an easier path for the fault current to enter the soil.
6.5 **SOIL RESISTIVITIES**

As the soil resistivity increases, the reactance components of $Z_p$, $Z_m$, and $Z_c$ parameters increase (see Carson's equations in Appendix A). The result of this increase causes the per-unit ground wire current to increase (Figures 6.7 and 6.8), although the actual current might be decreasing due to the increase of the Thevenin impedance looking into the fault location.

Comparing Figures 6.7 and 6.8, it is easy to see that the length of the end-effect section is practically unaffected by the change in soil resistivities.

6.6 **OPEN GROUND WIRE**

Figure 6.9 is the result of the simulation of a sample open ground wire system. The ground wire current for the short section on the left shows a sharp increase all the way from the first span of the ground wire to the left source station. For the section on the right that is longer, a constant current distribution in the at the middle of the section is found. Compared to Figure 6.1, the distribution of ground wire current for the line is now quite different. The ground wire sections close to the source stations for an open ground wire system carry currents larger than in the case of continuous ground wire.
6.7 **ITERATION METHOD IN STEEL GROUND WIRE**

Two tests are conducted, one with iteration in the steel wire and the other with no iteration. For the latter, the ground wire current distribution depends very much on the ground wire impedance chosen initially. In Figure 6.10, the left side line has its ground wire impedance 20% higher than the final converged impedance, its average ground wire current at the middle of the section is 17% less than its actual per-unit value in Figure 6.11. For a long line, the iteration approach has no significant effect on the current distribution, although the actual fault current might be affected.

6.8 **MULTI-CIRCUIT TRANSMISSION LINE**

In this case, a double-circuit transmission line with one and two source stations, respectively, is examined. The ground wire current is influenced not only by the phase current in the faulty circuit but also by the phase current in the sound circuit. A constant current distribution may also be seen at the middle of the section when the line is long. When the line is short, the constant current does not appear as may be seen in Figure 6.12. With one source station as in Figure 6.13, the ladder network on the right side of the
fault has its ground wire current decreasing to zero towards the rightmost tower. No end-effect phenomena may be seen near the rightmost sections. This could be due to the fact that no mutual interactions are present between the ground wire and the phase conductors.

6.9 **Comparison of Computed and Measured Values**

Figure 6.14 shows the distribution of ground wire current for both computed and measured values. The measured values are obtained from field tests conducted in 1963 [3]. The computed values are obtained from the computer program developed for this dissertation employing the proposed method. Values of line parameters and tower-footing impedances as inputs of the computer program are listed in Appendix B.

The fault current is supplied by a source station located 132 spans away from the fault. The network beyond the fault has no source station, therefore, the ground wire current beyond the fault decays to zero in less than 20 spans. Only 64 spans of the line beyond the fault are represented.

From Figure 6.14, the maximum absolute errors between the measured and computed ground wire currents are found to be 0.0543 per-unit and 0.0632 per-unit for the source line and non-source line respectively. The main reason for these de-
viations is due to the inaccuracies in the measurement of the tower-footing impedances which in turn affect the computed ground wire currents. Other reasons which accounted for the errors are listed in Reference [5].

Based on the information given by Figure 6.14, it could be seen that the greatest derivations occur in the immediate neighborhood of the fault location. Since the magnitude of the ground wire current close to the fault location is sensitive to the change of the tower-footing impedance near the fault location (see Figure 6.3 and 6.1), it is believed that if the tower-footing impedances close to the fault location can be measured more accurately, the errors in the computation of the ground wire current may then be minimized.

In summary, this chapter has investigated some of the possible applications and uses of a newly developed computer program. Each of the case studies is illustrated with an example which could represent the type of problem possibly encountered in the real world. The results of the simulation agree not only with those from hand calculations but also with those obtained from the EPRI program.
Figure 6.1 Distribution of Ground Wire Current; Material: ACSR Conductor
Figure 6.2 Distribution of Ground Wire Current; Material: Steel Conductor
Figure 6.3 Distribution of Ground Wire Current When \( R_{t2B} = 1 \text{ Ohm} \)
Figure 6.4 Distribution of Ground Wire Current
When $R_{t678} = 1$ Ohm
Figure 6.5 Distribution of Ground Wire Current
When $R_{t133B} = 1$ Ohm
Figure 6.6 Distribution of Ground Wire Current When $R_{c16A} = 1$ Ohm
Figure 6.7 Distribution of Ground Wire Current
When Soil Resistivity = 100 ohm-m
Figure 6.8 Distribution of Ground Wire Current
When Soil Resistivity = 1000 ohm-m
Figure 6.9 Distribution of Ground Wire Current in Open Ground Wire System
Figure 6.10  Distribution of Ground Wire Current; Material: Steel Wire - No Iteration
Figure 6.11 Distribution of Ground Wire Current; Material: Steel Wire - with Iteration
Figure 6.12 Distribution of Ground Wire Current in Double-Circuit Transmission Line, Two Source Stations
Figure 6.13 Distribution of Ground Wire Current in
Double-Circuit Transmission Line,
One Source Station
Figure 6.14  Deviations between Computed and Measured Values
Chapter VII
CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

7.1 GENERAL

In this dissertation, the four terminal driving point impedance method suitable for ground wire current computations has been proposed. A review of pertinent literature is discussed in Chapters 1 and 2. Chapter 3 shows the step by step derivation of the proposed method and explains why a further simplification in the impedance matrix is possible. In Chapter 4, the actual number of arithmetic operations for each of the 6 methods is computed and tabulated for comparison purposes. Chapter 5 discusses some special case studies that can be solved by the proposed method. Their results are presented in Chapter 6.

7.2 CONCLUSIONS

Specific conclusions of this work may be summarized as follows
1) Round-off errors in the ground wire current computation can be minimized by expressing the current in terms of
the current at the first span of the network. It has been found that if a span current is expressed in terms of its neighboring span current, its round-off errors are amplified in the process of span by span multiplication and, very soon, the span current will be completely distorted.

2) Typical driving point impedances and current coefficients in the proposed method are stable according to their curve behaviors shown in Chapter 3. This is the main reason why the computation of ground wire currents was successful with more than 200 spans without any numerical instability.

3) The method can be used not only for single circuit computations but also for multi-circuit and multi-conductor calculations. In the latter, the equivalent conductor concept is not used and each conductor in the circuit is represented by the corresponding row in the driving point impedance matrix.

4) Computer memories are needed for the storage of intermediate results since the ground wire current cannot be computed at the same time the driving point impedance is computed. Basically, a two-pass calculation cannot be avoided and memories are needed to minimize the round-off errors.
5) An iterative method for the impedance of the steel ground wire is useful only when the fault location is close to the source station and where the end-effect ground wire currents need to be determined more accurately.

6) The concept gained in the derivation of the four terminal driving point impedance method can be applied in the study of the open ground wire system. This is useful in deriving the driving point impedances and the current coefficients for the open ground wire system.

7) Soil resistivities, tower-footing impedances, and line impedances have a significant effect on the per-unit ground wire current distribution when the line is short. As the length of the line increases, these effects are less significant.

The major contribution of this work is the development of the computer-oriented driving point impedance method. It has been shown that this method has the least computational time and a reasonable memory requirement when compared to some methods proposed and described earlier.
7.3 FUTURE WORK

The following are suggested for future work related to the computation of ground wire currents:

1) Some of the ideas gained for overhead line zero sequence current distribution may be applied in the study of underground cables. The method developed in this dissertation is suitable only for the approximate underground cable model. A more rigorous treatment of the method is needed if a more accurate solution is sought.

2) The method may be modified for the computation of ground wire currents under impulse conditions. The frequency range to be examined would be extended to about 1 MHz.

3) Since the number of arithmetic operations for this method is reasonably small and since the method is stable numerically, the use of a microprocessor for ground wire computations may be considered.

A microprocessor usually has a small memory bank and each number in the microprocessor has a fewer bit representation. Its execution time is limited by its clock frequency and memory access time. Therefore, to use the method for a microprocessor, further modifications in the method are still needed so that the program becomes shorter and round-off errors are properly controlled.
APPENDIX A

Carson's Equations

Zero Sequence Impedances:

\[ Z_S = r + 0.00477f + j0.01397f \log\left(\frac{2160\sqrt{\rho/f}}{\text{GMR}}\right) \text{ ohms/mile} \]

\[ Z_m = 0.00477f + j0.01397f \log\left(\frac{2160\sqrt{\rho/f}}{\text{GMD}}\right) \text{ ohms/mile} \]  

(A.1)

where

- \( Z_S \) = self impedance
- \( Z_m \) = mutual impedance between two groups of conductors
- \( r \) = \( r_c \) or \( r_p \), resistance of the conductor, ohms
- \( f \) = frequency, Hz
- \( \rho \) = soil resistivity, ohm-meters
- \( \text{GMR} \) = geometric mean radius for the group of the phase conductors or ground wires, feet
- \( \text{GMD} \) = geometric mean distance between two groups of conductors, feet
APPENDIX B
Test Data

Towers:

--- Diagram of towers and conductors ---

Single Circuit

Conductors:

Single Circuit

Phase conductor - Bluebird
ACSR 84/19, \( GMR_p = 0.0588 \text{ ft, } r_p = 0.0505 \text{ ohms/mile, } \)
Diameter = 1.762 inches = 2156 MCM

Ground conductor - Drake
ACSR 26/7, \( GMR_c = 0.0375 \text{ ft, } r_c = 0.1190 \text{ ohms/mile, } \)
Diameter = 1.108 inches = 795 MCM
Ground conductor - 3/8 inch EHS steel

\[ G_{MR_c} = 3.90 \times 10^{-8} \text{ ft}, \quad r_c = 7.83 \text{ ohms/mile}, \]

Diameter = 0.360 inches

**Double Circuit**

Phase conductor

Circuit 1: Bluebird

(see previous page)

Circuit 2: Kiwi

ACSR 72/7, \( G_{MR_p} = 0.0570 \text{ ft}, \quad r_p = 0.0511 \text{ ohm/mile}, \)

Diameter = 1.735 inches = 2167 MCM

Ground conductor - Drake (see previous page)

Tower Spacing: 6 towers/mile

Test Data (ohm/mile):

<table>
<thead>
<tr>
<th>Single Circuit</th>
<th>10 ohm-m</th>
<th>100 ohm-m</th>
<th>1000 ohm-m</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_p )</td>
<td>0.05612+j0.35790</td>
<td>0.05612+j0.42775</td>
<td>0.05612+j0.49761</td>
</tr>
<tr>
<td>( Z_m )</td>
<td>0.04770+j0.21130</td>
<td>0.04770+j0.28115</td>
<td>0.04770+j0.35101</td>
</tr>
<tr>
<td>( Z_{ACSR} )</td>
<td>0.10720+j0.61068</td>
<td>0.10720+j0.68053</td>
<td>0.10720+j0.75038</td>
</tr>
<tr>
<td>( Z_{Steel} )</td>
<td>3.9627 + j1.4465</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Double Circuit

<table>
<thead>
<tr>
<th></th>
<th>10 ohm-m</th>
<th>100 ohm-m</th>
<th>1000 ohm-m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit 1:</td>
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</tr>
<tr>
<td>$Z_p$</td>
<td></td>
<td>0.05612+j0.42210</td>
<td></td>
</tr>
<tr>
<td>Circuit 2:</td>
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<tr>
<td>$Z_p$</td>
<td></td>
<td>0.05622+j0.42273</td>
<td></td>
</tr>
<tr>
<td>$Z_{mp-p}$</td>
<td></td>
<td>0.04770+j0.26839</td>
<td></td>
</tr>
<tr>
<td>$Z_{mp-c}$</td>
<td></td>
<td>0.04770+j0.27432</td>
<td></td>
</tr>
<tr>
<td>$Z_c$</td>
<td></td>
<td>0.10720+j0.68053</td>
<td></td>
</tr>
</tbody>
</table>

Tower and Station Ground Impedance (ohm):

$3R_{FPA} = 0.1 + j0.0$

$3R_{FPB} = 0.2 + j0.0$

$3R_t = 10. + j0.0$
Test Program:

Input Data Cards (for explanation, see Appendix C)

Figure 3.4, Figure 3.9:

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
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<td>1000000</td>
<td>000000</td>
<td>005612</td>
<td>035790</td>
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</tr>
<tr>
<td>2</td>
<td></td>
<td>000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>999</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1, Table 6.2, Figure 6.1:

|   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| 1 | 33 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 2 |   | 000000 |   |   |   |   |   |   |   |
| 10 | 135 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 999 | 1 |   |   |   |   |   |   |   |   |

Figure 6.2:

|   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| 1 | 33 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 396270 | 144650 |
| 2 |   | 000000 |   |   |   |   |   |   |   |
| 10 | 135 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 396270 | 144650 |
| 999 | 1 |   |   |   |   |   |   |   |   |

Figure 6.3:

|   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| 1 | 33 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 2 |   | 000000 |   |   |   |   |   |   |   |
| 10 | 135 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 999 | 1 |   |   |   |   |   |   |   |   |

Figure 6.4:

|   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| 1 | 33 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 2 |   | 000000 |   |   |   |   |   |   |   |
| 10 | 135 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 999 | 1 |   |   |   |   |   |   |   |   |

Figure 6.5:

|   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| 1 | 33 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 2 |   | 000000 |   |   |   |   |   |   |   |
| 10 | 135 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 999 | 1 |   |   |   |   |   |   |   |   |

Figure 6.6:

|   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| 1 | 16 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 16 | 17 | 000000 |   |   |   |   |   |   |   |
| 10 | 135 | 1000000 | 000000 | 005612 | 035790 | 004770 | 021130 | 010720 | 061068 |
| 999 | 1 |   |   |   |   |   |   |   |   |
| Figure 5.7 | 1000000 000000 005612 035790 004770 021130 010720 061068 | 1 |
| 2 | 1000000 000000 005612 035790 004770 021130 010720 061068 | 1 |
| 10 | 000000 020000 | |
| 999 | 1 |

| Figure 5.8 | 1000000 000000 005612 042775 004770 028115 010720 068053 | 1 |
| 2 | 1000000 000000 005612 042775 004770 028115 010720 068053 | 1 |
| 10 | 000000 020000 | |
| 999 | 1 |

| Figure 5.9 | 1000000 000000 005612 043751 004770 035101 010720 075038 | 1 |
| 2 | 1000000 000000 005612 043751 004770 035101 010720 075038 | 1 |
| 10 | 000000 020000 | |
| 999 | 1 |

| Figure 5.10 | 1500000 006612 042775 004770 021130 010720 380000 150000 | 1 |
| 1 | 1500000 006612 042775 004770 021130 010720 380000 150000 | 1 |
| 1 | 010000 | |
| 999 | 1 |

| Figure 5.11 | 1000000 006612 042775 004770 021130 340000 130000 | 1 |
| 1 | 1000000 006612 042775 004770 021130 340000 130000 | 1 |
| 2 | 010000 | |
| 2 | 027432 004770 027432 | |
| 1 | 26339 1 2 | |
| 1 | 010000 | |
| 999 | 1 |

| Figure 5.12 | 1000000 0095612 042219 004770 027132 010720 053053 | 1 |
| 7 | 000000 0095612 042219 004770 027132 010720 053053 | 1 |
| 1 | 0095622 042273 004770 027132 010720 053053 | 1 |
| 1 | 020000 | |
| 9 | 020000 | |
EPRI Program:
Input Data Cards (for explanation, see Reference [12])

TEST FILE (APPENDIX B)
SINGLE CIRCUIT
NO RING

EX1
N
Y
Y
Y
Y
N
Y
N
N
N
345
Y
T1, 0.1, 0.0, 0.0
31
Y
T2, 0.2, 0.0, 0.0
133
0.33672, 2.1474
A1, GW, 0.2862, 1.2678
END
0.6432, 3.66408
10.00
A1, 0.0, 0.0
END
Y
880.
1, 31, 10, 0
END
880.
Y
880.
1, 133, 10, 0
END
880.
APPENDIX C

Source Program, Control Words, and JCL

Control Words:

Columns 1-3, equal to 0 or blank: Line data
less than 0: Line with no source station
greater than 0: Line fed by source station
equal to 999: End of input data

Columns 5-7, from tower or
number of plots (1,2,3) if columns 1-3 = 999
if plot = 1, Ic versus span no.
if plot = 2, Ic and Vc versus span no.
if plot = 3, Ic, Vc and It versus span no.

Columns 9-11, to tower
The above has format I3

Columns 13-28, Rt or RFp

Columns 29-44, Zp

Columns 45-60, Zm

Columns 61-76, Zc

The above has format 2G8.5 for complex number

Column 78, type of ground wire
equal to 1: ACSR
equal to 2: steel
equal to 9: open ground wire
Column 80, number of circuits
equal to 1 or blank: 1 circuit
equal to 2: 2 circuits

The above has format II

An Example (Figure 6.9):

---

<table>
<thead>
<tr>
<th>Line no.</th>
<th>Tower no. (to)</th>
<th>Tower no. (from)</th>
<th>Rt</th>
<th>I_p</th>
<th>Im</th>
<th>Z_C</th>
<th>ALSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>12</td>
<td>100000</td>
<td>000000</td>
<td>005612</td>
<td>035790</td>
<td>004770</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>12</td>
<td>100000</td>
<td>000000</td>
<td>005612</td>
<td>035790</td>
<td>004770</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>1</td>
<td>100000</td>
<td>000000</td>
<td>005612</td>
<td>035790</td>
<td>004770</td>
</tr>
<tr>
<td>15</td>
<td>135</td>
<td>1</td>
<td>100000</td>
<td>000000</td>
<td>005612</td>
<td>035790</td>
<td>004770</td>
</tr>
<tr>
<td>10</td>
<td>999</td>
<td>1</td>
<td>020000</td>
<td>000000</td>
<td>RFP</td>
<td>I_m</td>
<td>Z_C</td>
</tr>
</tbody>
</table>

---

Number of plots

End of input data
Source Program and Its JCL for Obtaining A Load Module Data Set:

// JOB
// REGION=SIZK, MSGCLASS=X, TIME=(0,05), NOTIFY=TS1336, MSGLEVEL=(1,1)
// JOBPARM LINES=8000, DISKIO=1362, SERVICE=DEFER
// EXEC FORTQCL
// SYSPRINT DD SYSOUT=X
// FORT SYSIN DD

LOGICAL * FIRST, OPEN, CONVOK, DCKT
INTEGER DCKTYN(4)
INTEGER TYPE(4,5), TYPE2(5), TOSPALN(4), LOPROW(4)
INTEGER ALINE(4), WORKB(8), IMSAV(4), LCTSL(4), SUPN(4)
INTEGER RPTSP(10), L1NE(4), MRLINE(4), SPAN(4), LSTRMN(4), SSEQ(4)
INTEGER CONTROL, FROM, TO, SUPPLY, RPTCT, TOSAV, RCT, SPANCRT, RCTSAV, 52
INTEGER YES, NO
REAL AIST(200,4), ARN(4,5), RN(4,5), RNX(4,5)
REAL CRN(4,4,3), CXN(4,4,3), CRN1(4,4,3), XVI(5), XVII(5)
REAL*8 DFLOAT, DSUP, COABS, AITOW, AVG, AIG, AIGDIFF, DREAL, DIMAG
REAL*8 OPI, DIPR1, AIGSAV

C * * * * * * * * * * * * * *
INITIALIZATION
C
C  LCT: NUMBER OF TRANSMISSION LINES
C  RCT: STORAGE ROW COUNT
C  LADCT: NUMBER OF NON-SOURCE LINES
C  SUPPLY: NUMBER OF SOURCE LINES

DCKT=.FALSE.
ICKTS=0
FIRST=.TRUE.
OPEN=.FALSE.
LCT=0
RCT=0
RCTSAV=0
LADCT=0
SUPPLY=0
TOL*=1.D-5
LST=0
CONVOK=.FALSE.

*********
READ INPUT
*********

INPUT LINE AND TOWER PARAMETERS
WRITE(6, 445)
WRITE(6, 460)
WRITE(6, 460)
WRITE(6, 460)
WRITE(6, 462)
WRITE(6, 463)
FORMAT(3(1X, IX ), 8(G8.5), 2(1X, II))
READ(5, 1) CONTRL, FROM, TO, ZTOW, ZPHA, ZMUT, ZGRD, ITYPE, ICKT
FORMAT(‘ ’, ’40X,2(Z(10.4,1X),2X, ZG10.4, 2X, 11,3X, 11)
IF(CONTRL.EQ.999) GO TO 135
IF(.NOT.FIRST) GO TO 10
IF(FROM.NE.1) CALL ERROR(1)
LCT = LCT + 1
TOSPN(LCT) = 0
IF(LCT.GT.4) CALL ERROR(5)
ZTOW(LCT) = ZTOW
FIRST = .FALSE.
ITYSAV = ITYPE
IF(ICKT.EQ.1) ICKTS = 2
TOSAV = 1
IF(CONTRL.NE.0) GO TO 100
RCT = RCT + 1
IF(ITYPE.NE.9) GO TO 18
WRITE(6, 17) CONTRL, FROM, TO, ZTOW, ZPHA, ITYPE, ICKT
FORMAT(‘ ’, ’40X,2(Z(10.4,1X),2(ZG10.4,1X),64X,11,3X, 11)
IF(ITYPE.NE.ITYSAV) CALL ERROR(11)
TOSPN(LCT) = TO - 1
LORW(LCT) = RCT
OPEN = .TRUE.
GO TO 19
WRITE(6, 9) CONTRL, FROM, TO, ZTOW, ZPHA, ZMUT, ZGRD, ITYPE, ICKT
ITYSAV = ITYPE
IF(RPTSP(RCT).LE.0).OR.(TO.LE.0).OR.(FROM.LE.0))
CALL ERROR(1)
IF(FROM.NE.TOSAV) CALL ERROR(1)
S(RCT, 1) = ZPHA
S(RCT, 2) = ZMUT
S(RCT, 3) = ZGRD
S(RCT, 4) = ZTOW
TOSAV = TO
IF(ICKT.NE.1) GO TO 25
IF(ICKT.NE.2) CALL ERROR(20)
READ(5, 1) CONTRL, FROM, TO, ZTOW, ZPHA, ZMUT, ZLTL, ITYPE, ICKT
IF(ICKT.NE.2) CALL ERROR(19)
S(RCT, 5) = ZPHA
S(RCT, 5) = ZMUT
S(RCT, 7) = ZLTL
DOCK = .TRUE.
WRITE(5, 8) ZPHA, ZMUT, ZLTL, ITYPE, ICKT
GO TO 5
ICKTS = 0
GO TO 5
C
100 IF(CONTROL.LT.0) LADCT=LADCT+1
1 WRITE(6,101) CONTROL,ZTOW,ZPHA,ITYPE,ICKT
101 FORMAT(' ',2X,13,14X,2(2G10.4,4X),64X,11,3X,11)
1 IF(CONTROL.LT.0.OR.ICKT.NE.2) WRITE(6,10199)
1 CONTROL,ZTOW,ITYPE,ICKT
10199 FORMAT(' ',2X,13,14X,2G10.4,4X,11,3X,11)
1 IF(CONTROL.LT.0.AND.ICKT.NE.2) WRITE(6,10199)
1 LINE(LCT)=CONTROL
1 ALINE(LCT)=ABS(LINE(LCT))
1 IF(TOSPAN(LCT).EQ.0) GO TO 102
1 IF(TOSPAN(LCT).EQ.TOSAV) CALL ERROR(14)
1 IF(CONTROL.LT.0) CALL ERROR(15)
1 IF(T0SPAN(LCT).EQ.0) GO TO 102
1 IF(T0SPAN(LCT).EQ.TOSAV) CALL ERROR(14)
1 IF(ICKT.NE.2) GO TO 102
1 DCKTYN(LCT)*YES
1 DCKTYN(LCT)*NO
1 ICKT=0
1 IF(ICKT.NE.1) GO TO 110
1 DO 103 JK=1,5
1 TYPE(LCT,JK)=TYPE1(JK)
1 CONTINUE
1 GO TO 5
1 STEEL=STEEL+1
1 LCTSTL(STEEL)=LCT
1 READ(5,112) ITYPE,(ARN(LCT,IJ),RN(LCT,IJ),IJ=1,5)
1 FORMAT(6X,A1,2X,10G7.4)
1 CALL RCHECK(ITYPE,ARN,LCT)
1 READ(5,112) ITYPE,(AXN(LCT,IJ),XN(LCT,IJ),IJ=1,5)
1 CALL XCHECK(ITYPE,AXN,LCT)
1 DO 120 JK=1,5
1 TYPE(LCT,JK)=TYPE2(JK)
1 ARNI(JK)=ARN(LCT,JK)
1 AXNI(JK)=AXN(LCT,JK)
1 RN(JK)=RN(LCT,JK)
1 XN(JK)=XN(LCT,JK)
1 CONTINUE
1 CALL ICSCCU(ARN1,RN1,1,CRN1,4,IER)
1 CALL ICSCCU(AXN1,XN1,1,CXN1,4,IER)
1 DO 123 IL2=1,4
1 DO 122 IL3=1,3
1 CRN(LCT,IL2,IL3)=CRN1(IL2,IL3)
1 CXN(LCT,IL2,IL3)=CXN1(IL2,IL3)
1 CONTINUE
1 CONTINUE
1 GO TO 5
1 FORMAT(' ',3X,'CONTROL',10X,'PLOTS')
1 FORMAT(' ',4X,'WORD',10X,'PER LINE')
1 FORMAT(' ',3X,'999',14X,11)
1 WRITE(6,125)
1 WRITE(6,126)
1 WRITE(6,128) FROM
SUPPLY=LCT-LADCT

******************************************************************************
CHECK FOR POSSIBLE ERRORS IN INPUT DATA CARDS
******************************************************************************

IF( (IPLOT.LT.1) .OR. (IPLOT.GT.3) ) CALL ERROR(10)
IF(RCT.NE.RCTSAV) CALL ERROR(2)
IF(LC1.EQ.1) GO TO 145
DO 140 J=2,LCT
   IF(COABS(ZTOW1(J)).NE.COABS(ZTOW1(J))) CALL ERROR(3)
140 CONTINUE
M=LCT+1
DO 143 I=1,M
   K=I+1
   DO 142 J=K,LCT
      IF(ALINE(I).EQ.ALINE(J)) CALL ERROR(7)
142 CONTINUE
143 CONTINUE
145 IF(SUPPLY.EQ.0) CALL ERROR(4)

******************************************************************************
EQUIVALENT IMPEDANCES CALCULATIONS VIA
BACKWARD PATH (TOWARDS FAULT LOCATION)
RESULTS ARE STORED IN ZSTORE ARRAY
******************************************************************************

SSEQ: TRANSMISSION LINES ORDERING ARRAY, SUPPLY LINES FIRST THEN
       FOLLOWED BY LADDER NETWORK
SUPN: INVERSE OF SSEQ

145  K=0
     J=SUPPLY
     DO 148 I=1,LCT
        IF(LINE(I).LT.0) GO TO 147
        K=K+1
        SSEQ(K)=I
        SUPN(I)=K
     GO TO 149
147  J=J+1
     SSEQ(J)=I
148 CONTINUE
WRITE(6,149) SUPPLY, (LINE(SSEQ(I)) , I=1,SUPPLY)
IF(DCKT) WRITE(6,192) (DCKTYN(I), I=1,SUPPLY)
WRITE(6,150) (SPAN(SSEQ(I)) , I=1,SUPPLY)
IF(OPEN) WRITE(6,190) (TOPAN(I) , I=1,SUPPLY)
WRITE(6,138) ( (TYPE(SSEQ(I),J) , J=1,5) , I=1,SUPPLY)
149 FORMAT(' - TOTAL NUMBER OF SOURCE LINES = ',13,1X,'LINE NUMBERS ARE: ',1X,4110)
150 FORMAT(' - TOTAL NUMBER OF SPANS IN EACH LINE: ',24X,4110)

ZFL: EQUIVALENT IMPEDANCE AT FAULT LOCATION WHICH INCLUDES BOTH FAULTY
      TOWER IMPEDANCE AND POSSIBLE LADDER NETWORK IMPEDANCES (EQUALLY
      DISTRIBUTED AMONG ALL SOURCE LINES)

ZFL=ZTOW1(J1)
IF(LADCT.EQ.0) GO TO 250
I) LADDER NETWORK IMPEDANCES CALCULATIONS

C  ISCSUPPLY +  1
WRITE (6, 189) LAOCT, (ALINE (SSEQ (I) ), I = 1, LCT)
WRITE(6, 150) (SPAN (SSEQ (I) ), I = 1, LCT)
WRITE (6, 108) ((TYPE (SSEQ (I), J), J = 1, 5), I = 1, LCT)
DO 180 IJ = 1, LCT
   LC = SSEQ (IJ)
   Z22 = RFP (LC)
   I = LSTRO (LC)
   LST = RLINE (LC)
   M1 = LC + 1
   DO 180 J = 1, LST
      RPTCT = RPTSP (IJ)
      IF (J .NE. LST) GO TO 154
      RPTCT = RPTCT - 1
      IF (RPTCT .EQ. 0) GO TO 157
   DO 155 K = 1, RPTCT
      Z21 = S (IJ, 3) + Z22
      Z22 = S (IJ, 4) * Z21 / (S (IJ, 4) + Z21)
      S (L, M1) = Z21
   L = L - 1
   CONTINUE
157 I = I - 1
157 CONTINUE
ZZ1 = S (IL, 3) + Z22
ZSTORE(LC1) = Z21
ZFL = ZFL * Z21 / (ZFL * Z21)
DO 252 IL = 1, ISTEEL
   LC1 = LCST (IL)
   WRITE (6, 135) ALINE (LC1), ARN (LC1, IJ), RN (LC1, IJ), IJ = 1, 5
   WRITE (6, 136) ALINE (LC1), AXN (LC1, IJ), YN (LC1, IJ), IJ = 1, 5
252 CONTINUE
C C PRINT STEEL CONDUCTOR PARAMETERS
C 250 IF (ISTEEL .EQ. 0) GO TO 253
WRITE (6, 132)
WRITE (6, 193)
WRITE (6, 184)
WRITE (6, 414)
DO 252 IL = 1, ISTEEL
   LC1 = LCST (IL)
   WRITE (6, 135) ALINE (LC1), ARN (LC1, IJ), RN (LC1, IJ), IJ = 1, 5
   WRITE (6, 136) ALINE (LC1), AXN (LC1, IJ), YN (LC1, IJ), IJ = 1, 5
252 CONTINUE
C C II) SOURCE LINE IMPEDANCES CALCULATIONS
C 253 DSUP = DFLOAT (SUPPLY)
   ZFL = DSUP * ZFL
   DO 400 IJ = 1, SUPPLY

C C

C
LC=SSQ(I,J)
1=STROW(LC)
IF(TOSPAN(LC).EQ.0) GO TO 278
M2=LC+2
M1=M2-1
IST=LOPROW(LC)+1
LST=1-LOPROW(LC)
Z21=0.00
Z22=5(IST,4)
IM=1
DO 270 J=1,LST
RPTCT=RPTSP(IST)-1
IF(RPTCT.EQ.0) GO TO 266
DO 260 K=1,RPTCT
Z22=Z22+5(IST,3)
Z21=Z21-5(IST,2)
Z12=1.00-Z22/5(IST,4)
Z22=Z21/Z12
Z22=Z22/12
SZ(IM,M1)=Z21
SZ(IM,M2)=Z22
IM=IM+1
260 CONTINUE
265 IF(J.EQ.LST) GO TO 270
Z22=Z22+5(IST,3)
Z21=Z21-5(IST,2)
Z12=1.00-Z22/5(IST,4)
Z22=Z21/Z12
Z22=Z22/12
SZ(IM,M1)=Z21
SZ(IM,M2)=Z22
IM=IM+1
270 CONTINUE
Z22=Z22+5(IST,3)
Z21=Z21-5(IST,2)
Z12=1.00-Z22/RFPLC
Z22=Z22/12
Z22=Z22/12
E=Z22-E/RFPLC
Z11=EN(LC)-E1
IMSAV(LC)=IM
SZ(IM,M1)=IG
Z11=Z11+5(IST,1)-5(IST,2)*IG
DO 276 J=1,LST
RPTCT=RPTSP(IST)
IF(J.EQ.1) GO TO 272
RPTCT=RPTCT-1
IF(RPTCT.EQ.0) GO TO 275
DO 274 K=1,RPTCT
M=K-1
IG=5*(SZ(IM,M1)+SZ(IM,M2)*IG)/5(IST,4)
SZ(IM,M1)=IG
Z11=Z11+5(IST,1)-5(IST,2)*IG
274 CONTINUE
275 IST=IST-1
276 CONTINUE
LST=4WLINE(LC)-LST
DO 277 J=1,LST
ISPAN=DFLOAT(RPTSP(I))
Z1=Z1+ISPAN*S(I)
IST=IST-1
CONTINUE
AZ1(I,J,1)=Z1
AZ1(I,J,2)=0.00
AZ1(I,J,3)=0.00
AZ1(I,J,4)=ZFL
GO TO 400

IF(DCKTYN(LC).EQ.YES) GO TO 41310
M2=LC+2
M1=M2-1
Z11=RFP(LC)+ZN(LC)
Z21=RFP(LC)
Z12=Z21
Z22=Z21
LST=RKLINE(LC)
ISPAN=SPAN(LC)
DO 390 J=1,LST
RPTCT=RPTSP(I)
IF(J.NE.LST) GO TO 280
RPTCT=RPTCT-1
IF(RPTCT.EQ.0) GO TO 300
290 CONTINUE
I=1-1
CONTINUE
M=1+1
A1=-(Z21+S(M,2))/ZFL
B1=(S(M,3)-Z32)/ZFL+1.00
AZ1(I,J,2)=(Z12-S(M,2))/B1
AZ1(I,J,1)=(ZII+S(M,1))-A1*AZ1(I,J,2)
AZ1(I,J,3)=AZ1(I,J,2)
AZ1(I,J,4)=(Z22-S(M,3))/B1
GO TO 400

41310 CONTINUE
M3=LC+3
M2=M3-1
M1=M2-1
Z11=RFP(LC)+ZN(LC)
Z21=RFP(LC)+ZN(LC)
Z13=RFP(LC)
Z23=RFP(LC)+ZN(LC)
Z31=RFP(LC)
Z33=RFP(LC)
Z31=-Z13
ISPAN=SPAN(LC)
DO 41315 J=1,LST
RPTCT=RPTSP(I)
IF(J.NE.LST) GO TO 41312
RPTCT=RPTCT-1
41312  IF(RPTCT.EQ.0) GO TO 41314
GO 41311 K=1,RPTCT
A1=1.0+(S(I,3)-Z33)/S(I,4)
B1=(Z23-S(I,6))/S(I,4)
Z33=(Z33-S(I,1))/A1
Z23=(Z23-S(I,6))/A1
Z12=Z12-(Z1,7)+Z13
Z11=Z11+(Z1,1)+(Z13+(Z31+S(I,2))/S(I,4))
Z31=Z13
SZ(ISPAN,M1)=Z31/S(I,4)
SZ(ISPAN,M2)=Z23/S(I,4)
SZ(ISPAN,M3)=1.0+Z33/S(I,4)
ISPAN=ISPAN-1
CONTINUE

41311  CONTINUE
41314  I=I-1
41315  CONTINUE
M=I+1
A1=1.0+(S(M,3)-Z33)/ZFL
B1=(Z23-S(M,6))/ZFL
AZ2(IJ,9)=(Z33-S(M,3))/A1
AZ2(IJ,6)=(Z23-S(M,6))/A1
AZ2(IJ,5)+(Z22-S(M,5)-B1*AZ2(IJ,6)
AZ2(IJ,3)=(Z13-S(M,2))/A1
AZ2(IJ,2)=(Z12-S(M,7)-B1*AZ2(IJ,3)
AZ2(IJ,1)=(Z11-S(M,1)+AZ2(IJ,3)+(Z31+S(M,2))/ZFL
AZ2(IJ,4)=AZ2(IJ,2)
AZ2(IJ,7)=AZ2(IJ,3)
AZ2(IJ,8)=AZ2(IJ,6)
CONTINUE
WRITE(6,414)
IF(DCKT) GO TO 41350
IF(SUPPLY.EQ.0) GO TO 42199
DO 404 IJ=2,SUPPLY
IM1=0
IJ1=IJ-1
IJ=IJ+1
IL=I2-1
DO 403 IL=I1,12
IM=IM+1
MZ=IM+2
AZ1(IL,IM)+AZ1(IJ1,IM1)
AZ1(IL,IM2)+AZ1(IJ1,IM1)
CONTINUE
CONTINUE
CONTINUE
IF(SUPPLY.NE.2) GO TO 405
CONTINUE
402  CONTINUE
404  CONTINUE
405  CONTINUE
GO TO 409
409  IF(SUPPLY.EQ.2) GO TO 405
I1=1
DO 408 IJ=3,SUPPLY
IL=IL+1
407  CONTINUE
CONTINUE
GO TO 409
AZ(IL,IM)=0.00
AZ(IL*1,IM)=1.00
CONTINUE
CONTINUE
CONTINUE
CONTINUE
CONTINUE
DO 412 IL=1,12
DO 411 IM=1,12
II=IL+IM
IF(II/2*2.EQ.IK)GO TO 410
AZ(IL,IM)=0.00
GO TO 411
AZ(IL,IM)=1.00
CONTINUE
CONTINUE
CONTINUE
GO TO 41510
41350 IF(SUPPLY.EQ.0)GO TO 41390
DO 41355 IJ=2,SUPPLY
IM1=0
IJ=IJ-1
II=II-2
DO 41354 IL=1,12
IM=IM+1
II=II+2
IM1=IM1+1
IM2=IM2+3
AZ(IL,IM)=AZZ(IJ,IM1)
CONTINUE
CONTINUE
CONTINUE
S2=SUPPLY*3
CALL CMINV(AZ, S2, DET, LWORK, HWORK)
DO 41375 IJ=1,SUPPLY
IL2=IL3-1
IL3=IJ+3
IL4=IL2-1
LC=LC+2(IJ)
IPHA(LC)+AZ(IL1,IL2)*AZ(IL1,IL3)
IPHALC)+AZ(IL2,IL3)*AZ(IL2,IL3)
IGRLC)+AZ(IL3,IL3)*AZ(IL3,IL3)
IP1=IPHALC)
DIPM=DIWAG(IP)
DIPR=DREAL(IP)
DIPM1=DIWAG(IP1)
DIPR=DREAL(IP1)
IF(DIPM.GT.0.00)WRITE(6,41377)LINE(LC),DIPR,DIPM
IF(DIPM.LE.0.00)WRITE(6,41378)LINE(LC),IP
IF(DIPM1.GT.0.00)WRITE(6,41379)LINE(LC),DIPR1,DIPM1
IF(DIPM1.LE.0.00)WRITE(6,41380)LINE(LC),IP1
CONTINUE

41377 FORMAT('O' 'ZERO SEQUENCE CURRENT IN SOURCE LINE', 14, 3X,
  + 'G1.4,' + 'G9.4,' (CIRCUIT 1))

41380 FORMAT('O', 'ZERO SEQUENCE CURRENT IN SOURCE LINE', 14, 3X,
  + 'G1.4,' + 'G9.4,' (CIRCUIT 2))

WRITE(6, 415)
VGLFTW = AZ2(SUPPLY, 7) * IPHA(LC) + AZ2(SUPPLY, 8) * IPHA1(LC) +
  AZ2(SUPPLY, 9) * IGRD(LC) - VGFLTW

IFLTON = VGFLTW/ZFL
AVGF T W = CDABS(VGFLTW)

41395 CONTINUE
WRITE(6, 436) VPMVG1
GO TO 467

41390 LC = SSEQ(I)
A1 = AZ2(1, 1) - AZ2(1, 4)
B1 = AZ2(1, 2) - AZ2(1, 5)
C1 = AZ2(1, 6) - AZ2(1, 3)
D1 = A1 - B1
IPHA(LC) = (C1 - D1) / D1
IPHA1(LC) = (A1 - C1) / D1
VGFLTW = AZ2(1, 7) * IPHA(LC) + AZ2(1, 8) * IPHA1(LC) +
  AZ2(1, 9) * IGRD(LC) - VGFLTW
ZSTORE(LC) = TOTAL/IPHA(LC)
ZSTRE1(LC) = TOTAL/IPHA1(LC)

AVGF T W = VGFLTW/ZFL

IFLTON = VGFLTW/ZFL
AVGF T W = CDABS(VGFLTW)

41395 CONTINUE
WRITE(6, 436) VPMVG1
GO TO 467

41390 LC = SSEQ(I)
A1 = AZ2(1, 1) - AZ2(1, 4)
B1 = AZ2(1, 2) - AZ2(1, 5)
C1 = AZ2(1, 6) - AZ2(1, 3)
D1 = A1 - B1
IPHA(LC) = (C1 - D1) / D1
IPHA1(LC) = (A1 - C1) / D1
VGFLTW = AZ2(1, 7) * IPHA(LC) + AZ2(1, 8) * IPHA1(LC) +
  AZ2(1, 9) * IGRD(LC) - VGFLTW
ZSTORE(LC) = TOTAL/IPHA(LC)
ZSTRE1(LC) = TOTAL/IPHA1(LC)

AVGF T W = VGFLTW/ZFL

IFLTON = VGFLTW/ZFL
AVGF T W = CDABS(VGFLTW)

41395 CONTINUE
WRITE(6, 436) VPMVG1
GO TO 467

41390 LC = SSEQ(I)
A1 = AZ2(1, 1) - AZ2(1, 4)
B1 = AZ2(1, 2) - AZ2(1, 5)
C1 = AZ2(1, 6) - AZ2(1, 3)
D1 = A1 - B1
IPHA(LC) = (C1 - D1) / D1
IPHA1(LC) = (A1 - C1) / D1
VGFLTW = AZ2(1, 7) * IPHA(LC) + AZ2(1, 8) * IPHA1(LC) +
  AZ2(1, 9) * IGRD(LC) - VGFLTW
ZSTORE(LC) = TOTAL/IPHA(LC)
ZSTRE1(LC) = TOTAL/IPHA1(LC)

AVGF T W = VGFLTW/ZFL

IFLTON = VGFLTW/ZFL
AVGF T W = CDABS(VGFLTW)

41395 CONTINUE
WRITE(6, 436) VPMVG1
GO TO 467
WRITE(6, 414)
DIPM = -DIMAG(ZSTORE(LC))
DIPR = DREAL(ZSTORE(LC))
DIPM1 = -DIMAG(ZSTORE1(LC))
DIPR1 = DREAL(ZSTORE1(LC))
IF(DIPM, LE, 0.00) WRITE(6, 43201) LINE(LC), ZSTORE(LC)
IF(DIPM, GT, 0.00) WRITE(6, 43202) LINE(LC), ZSTORE1(LC)
IF(DIPM1, LE, 0.00) WRITE(6, 43203) LINE(LC), DIPR1, DIPM1
DIPM = -DIMAG(ZTOTAL)
DIPR = DREAL(ZTOTAL)
IF(DIPM, GT, 0.00) WRITE(6, 43204) LINE(LC), DIPR, DIPM
GO TO 467
C
C *****************************************************
C BOUNDARY VALUES AT FAULT LOCATION
C *****************************************************
C
414 FORMAT(' ')
415 FORMAT('O', 'ASSUMED ZERO SEQUENCE CURRENT FOR THE SYSTEM = ',
1, ' 1.000 + J.0')
41510 S2 = SUPPLY*2
C
C STORE AZ MATRIX IN AZS FOR FUTURE USE
C
IF(ISTEEL, EQ, 0) GO TO 418
DO 417 IK = 1, S2
   DO 416 IJ = 1, S2
      AZS(IK, IJ) = AZ(IK, IJ)
   CONTINUE
CONTINUE
CALL CMINV(AZ, S2, 3, OET, LW ORX, MW ORX)
IF(ISTEEL, EQ, 0) GO TO 463
DO 4672 IL = 1, ISTEEL
   LCl » LCTSTL(IL)
   M2 = S2*2
   M1 = M2 - 1
   IF(SUPPLY, EQ, 1) GO TO 4570
   [J] = SUPN(LCl)
   IL2 = [J]*2
   IL1 = IL2 - 1
   IK1 = S2 - 1
   [PHA(LCl)] = AZ([L1, IK1] + [L1, S2])
   [GRD(LCl)] = AZ([L2, IK1] + [L2, S2])
   [GRD(LCl)] = [GRD(LCl)] - (AZ([J, 3]* [PHA(LCl)] + AZ([J, 4]*
1, [GRD(LCl)])) / ZFL
   GO TO 4579
   [PHA(LCl)] = 1.00
   [GRD(LCl)] = (AZ([J, 3] + AZ([J, 4]) / ZFL + 1.00
4575 AIST = AZL + 1, LCl) + COSB(1 + DGD[LCl])
   ISPAN = SPAN(LCl)
   DO 4671 J = 2, ISPAN
      IG55Z(J, M1) = AZPH(LCl) - AZ(J, M2) + [GRD(LCl)]
      AIST(J, LCl) = COSB(IG55Z(J, M1) - AZ(J, M2))
      AZ(J, M1) = 5Z(J, M1) + 5Z(J + M1) + 5Z(J, M3) - 5Z(J + M3)
      AZ(J, M2) = 5Z(J, M2) + 5Z(J + M2)
4571 CONTINUE
4672 CONTINUE
C FIND NEW IMPEDANCE FOR STEEL CONDUCTOR DUE TO CURRENT
C CHANGE IN STEEL CONDUCTOR
C
4673 DO 4678 I=1, NSTEEL
   LC=LCTSTL(I)
   IJ=SPAN(LC)
   M2=LC+2
   M1=M2+1
   I=LSTWGLC)
   ZII=REPLC)+ZN(LC)
   Z21=REP(LC)
   Z12=-Z21
   Z22=-Z22
   LST=RULNE(LC)
   ISPAN=SPAN(LC)
   DO 4677 J=1,LST
      RPTCT=RPTSP(J)
      IF(J.LE.LST) GO TO 4674
      RPTCT=RPTCT-1
      IF(RPTCT.EQ.0) GO TO 4676
   4674 DO 4675 X=1,RPTCT
      AMP=AIISTL(ISPAN,LC)
      CALL EVUZ(ZI, AMP, ARN, AXN, RN, CXN, CNX, LC, 5, 4, 3)
      WRITE(6, 49999) ISPAN, AMP, ZI
        FORMAT(' ', 15, G14.4, 2X, 2G12.4)
   49999 A1=-(Z21+S(M,2))Z1
   B1=(Z1-Z22)/Z1
   ZII=(ZII+S(I,1)-A1*Z12
   Z12=-Z12
   Z22=(Z22-Z12)/B1
   ZZ(S(ISPAN,M1)=Z21/S(I,4)
   Z2(S(ISPAN,M2)=1.00+Z22/S(I,4)
   ISPAN=ISPAN+1
   4675 CONTINUE
4676 I=I+1
4677 CONTINUE
M=(I+1
   AMP=AIISTL(ISPAN,LC)
   CALL EVUZ(ZI, AMP, ARN, AXN, RN, CXN, CNX, LC, 5, 4, 3)
   WRITE(6, 49999) ISPAN, AMP, ZI
   A1=-(Z21+S(M,2))/ZFL
   B1=(Z1-Z22)/ZFL
   AZ1(I,J)=Z12-S(M,2))
   AZ1(I,J)=Z12-S(M,2))
   AZ1(I,J)=Z12-S(M,2))
   4679 CONTINUE
4679 IF(SUPPLY.EQ.1) GO TO 46792
4679 DO 46799 I=1, NSTEEL
4679 LC=LCTSTL(I)
4679 IJ=SPAN(LC)
4679 M1=I+1
4679 IF(IJ.EQ.1) GO TO 4673
4679 IF(IJ.EQ.4) GO TO 46799
4679 K1=I+1
4679 K2=I+2
4679 DO 46793 I=1,1K2
4679 DO 46793 Z=1K1,1K2
4679 DO 46793 M=1M1+1
IM2=I+1 2*2
AZ(S(I,J),IM2)=AZ1(I,J,IM1)
IF(IJ.LT.SUPPLY) AZ(S(I+2,J,IM1)=AZ1(I,J,IM1)
CONTINUE
CONTINUE
GO TO 46780
46785 I=1,2
DO 46784 I=1,2
IM1=I+1
AZ(S(I,J,IM1)=AZ1(I,J,IM1)
CONTINUE
CONTINUE
GO TO 46789
46786 IJ=5,5
J=7,8
IM1=I+1
AZ(S(I,J,IM1)=AZ1(I,J,IM1)
CONTINUE
CONTINUE
CONTINUE
C
C DUPLICATE A COPY OF AZS FOR STORAGE
C
DO 46790 I=1,8
DO 46791 J=1,8
AZS(I,J)=AZ1(I,J)
CONTINUE
CONTINUE
CALL CMINV(AZ, S2, 3, OET, LW ORK, M W  ORK)
IF ( CONVOK) 30 T O 46793
CONVOK=.TRUE.
C
C FIND NEW GROUND DUE TO CHANGE OF GROUND WIRE IMPEDANCE
C
DO 46796 IL=1,ISTEEL
LC1=LCTSL(I,3)
IF(SUPPLY.EQ.1) GO TO 46793
I=1,8
IL2=I+2
IL1=I+1
IK1=J+1
I=R(3I)+AZ(I,J,3)+AZ(I,J,4)*I(3I)
IGRD(I)=AZ(I,J,3)+AZ(I,J,4)*I(3I)
GO TO 46794
46793 IPHA(I)=IPHA(I)+1.0
IGRD(I)=AZ(I,J,3)+AZ(I,J,4)*I(3I)
46794 46795 M2=LCL+2
M1=M2+1
AIG=DA8S(IGRD(I))
IF(DABS(AIG).LT.TOL) CONVOK=.FALSE.
AISTL(I,LC1)+AIG
SPAN=SPAN(LC1)
DO 46799 J=2,ISPAN
IG=SZ(I,3)*IPHA(I)+SZ(J,M2)*IGRD(I)
AIG=DSABS(IG)
IF(DABS(AISTL(I,LC1)-AIG).LT.TOL) CONVOK=.FALSE.
AISTL(I,LC1)=AIG
SZ(J+1,M1)+SZ(J+1,M1)+SZ(J,M1)+SZ(J+1,M2)
S2(J+1,M2) = S2(J+1,M2) * S2(J,M2)

GO TO 4673

CONTINUE

GO TO 46795

CONTINUE

C PHASE CURRENT AND GROUND WIRE CURRENT AT THE FAULT LOCATION. HERE THE
C GROUND WIRE CURRENT IS FICTITIOUS. IT IS EQUAL TO THE FIRST SPAN GROUND
C WIRE CURRENT MINUS THE ZFL CURRENT

IF(SUPPLY.EQ.1) GO TO 424

DO 419 IJ = 1, SUPPLY
   ILZ = IJ * 2
   IL = ILZ - 1
   I2 = SUPPLY * 2
   I1 = I2 - 1
   LC = SSEQ(IJ)
   IPHA(LC) = AZ(IL1, I1J + 1) + AZ(IL2, I2) - AZ(IL1, I2)
   IGRD(LC) = AZ(IL2, I1) + AZ(IL2, I2)
   IP = IPHA(LC)
   DIPM = DIMAG(IP)
   DIPR = DREAL(IP)
   IF (DIPM.GT.0.0) WRITE(6,422) LINE(LC), DIPR, DIPM
   IF (IPM.LE.0.0) WRITE(6,423) LINE(LC)
   WRITE(6,421)

CONTINUE

IF(SUPPLY.EQ.1) GO TO 424

DO 419 IJ = 1, SUPPLY
   ILZ = IJ * 2
   IL = ILZ - 1
   I2 = SUPPLY * 2
   I1 = I2 - 1
   LC = SSEQ(IJ)
   IPHA(LC) = 1.00
   IFLTOW = VGFLTW / ZTOW(1)
   AVGFTW = CDABS(VGFLTW)
   GO TO 425

VGFLTW = AZ1(SUPPLY, 3) + AZ1(SUPPLY, 4) + GRO(LC)
VPMVG = AZ1(SUPPLY, 1) + AZ1(SUPPLY, 2) - VGFLTW
IFLTOW = VGFLTW / ZTOW(1)
AVGFTW = CDABS(VGFLTW)
GO TO 425

LC = SSEQ(1)
VGFLTW = AZ1(1, 1) + AZ1(1, 2) - VGFLTW
IFLTOW = VGFLTW / ZTOW(1)
AVGFTW = CDABS(VGFLTW)
GO TO 425

ZERO SEQUENCE CURRENT IN NON-SOURCE PHASE LINE

IF(LAQCT.EQ.0) GO TO 428
WRITE(6,414)
DO 427 I=1,LCT
   LC=SEQ(I)
   WRITE(6,426) ALINE(LC)
426   FORMAT('0','ZERO SEQUENCE CURRENT IN NON-SOURCE LINE',I4,'=','0')
   CONTINUE
C
C SOURCE LINE EQUIVALENT IMPEDANCE
C
WRITE(6,414)
   IF(SUPPLY.NE.1) GO TO 429
   ZTOTAL=ZSTORE(SEQ(1))
   I=I+1
   CONTINUE
429   IF(TSPAN(LC).NE.0) GO TO 430
   IGRID(LC)=IGRID(L)+VGFLTW/ZFL
   WRITE(6,431) LINE(LC),ZSTORE(LC)
431   FORMAT('0','ZERO SEQUENCE IMPEDANCE FOR SOURCE LINE ','I3,
      1 IX.=',G11.4,'+J ' G9.4, (CIRCUIT 1)')
43201   FORMAT('0','ZERO SEQUENCE IMPEDANCE FOR SOURCE LINE ','I3,
      1 IX.=',G11.4,'+J ',G9.4, (CIRCUIT 2)')
43203   FORMAT('0','ZERO SEQUENCE IMPEDANCE FOR SOURCE LINE ','I3,
      1 IX.=',G11.4,'-J ',G9.4, (CIRCUIT 1)')
43204   FORMAT('0','ZERO SEQUENCE IMPEDANCE FOR SOURCE LINE ','I3,
      1 IX.=',G11.4,'-J ',G9.4, (CIRCUIT 2)')
   CONTINUE
   ZTOTAL=ZSTORE(SEQ(1))
   I=I+1
   CONTINUE
433   IF(LADCT.EQ.0) GO TO 467
   DO 433 I=1,LCT
      LC=SEQ(I)
      WRITE(6,434) ALINE(LC),ZSTORE(LC)
433   CONTINUE
434   FORMAT('0','ZERO SEQUENCE IMPEDANCE FOR LADDER NETWORK OF NON-SOURCE LINE ','I3,
      1 IX.=',G11.4,'+J ',G9.4)
   WRITE(6,436) ZTOTAL
435   IF(LADCT.EQ.0) GO TO 467
   OUT=TOTAL
   FORMAT('0','TOTAL ZERO SEQUENCE IMPEDANCE FOR THE SYSTEM = ','
5   IX.=',G11.4,'+J ',G9.4)
   WRITE(6,436) OUT
43605   FORMAT('0','TOTAL ZERO SEQUENCE IMPEDANCE FOR THE SYSTEM = ','
      1 IX.=',G11.4,'-J ',G9.4)
C
C NON-SOURCE LINE EQUIVALENT IMPEDANCE
C
   IF(LADCT.EQ.0) GO TO 467
   WRITE(6,414)
   DO 439 I=1,LCT
      LC=SEQ(I)
      WRITE(6,434) ALINE(LC),ZSTORE(LC)
439   CONTINUE
   WRITE(6,420)
C
C CALCULATIONS OF GROUND WIRE CURRENT IN THE FIRST SPAN OF LADDER NETWORK
C
   DO 440 I=1,LCT
      LC=SEQ(I)
      IPHA(LC)=VGFLTW/ZSTORE(LC)
440   CONTINUE
129

1 FORMAT('*,T16,'STUDY OF ZERO SEQUENCE CURRENT DISTRIBUTION IN T
TRANSMISSION LINES, GROUND WIRES AND TOWER STRUCTURES')

1 **--------------------------------------------------------------------------------**

1 FORMAT(' ', 'CONTROL', '2X,'FROM', '3X,'TO', '8X,'TOWER', '15X,'ZPHASE', '14X,'ZM(L-G)', '14X,'ZGROUND', '14X,'ZM(L-L)', '7X,'WIRE', '1X,'CKT')

1 FORMAT(' ', 'CONTROL', '2X,'TOWER', '1X), '2X,4('REAL', '6X,'IMAG', '5X,'NO NO')/

** SPAN BY SPAN CURRENT DISTRIBUTION CALCULATIONS **
** VIA FORWARD PATH (AWAY FROM FAULT LOCATION) **

CALL PLTITL(IPLT)
00 690 1*I,LST
M2=M2+1
SPANCT=1
LST=RWLINE(I)
IF (LST .GT. 0) GO TO 500

CALL PLOT(LIST(1),A11)
1 FORMAT(' ', 'NON-SOURCE LINE', '13,6X,'ZPHASE = ', '5A1)
WRITE(6,473) IIK
IG=IPHA(I)
AIG=CDABS(IG)
call plot(spanct,aig,avgftw,aifltw)
call plot(spanct,avg,aig)
00 480 J=I,LST
PCT=I+1
IF (J .NE. 1) GO TO 475
RPTCT=RPTCT-1
IF (RPTCT.EQ.0) GO TO 478

CALL PLOT(SPANCT,AVG,AIG,AITOW)
CONTINUE
475 CONTINUE
478 I=I+1
480 CONTINUE

CALL PLOT(SPANCT,AVG,AITOW)
GO TO 683

** SOURCE LINE CURRENT DISTRIBUTION **
C 503 WRITE(6,502) IP=IPHA(1) AIP=CDABS(IPHA(1)) IF(CKTN(1).EQ.NO) GO TO 503 AIP=CDABS(IPHA(1)) WRITE(6,507) LINE(I),AIP,AIP1,(TYPE(I,J),J=1,5) GO TO 505 503 WRITE(6,504) LINE(I),AIP,(TYPE(I,J),J=1,5) 504 FORMAT(" 'SOURCE LINE ',13,6X,' 'PHASE = ',G11.4, 1,12X,' 'TYPE OF GROUND WIRE: ',5A1) 505 WRITE(6,506) LIMIT(LIMIT),AIP,(TYPE(I,J),J=1,5) 506 FORMAT(" 'SOURCE LINE ',13,6X,' 'PHASE = ',G11.4, 1,3X, 1,12X,' 'TYPE OF GROUND WIRE: ',5A1) IF(TOSPAN(I).EQ.O) GO TO 550 507 FORMAT(1." ',13,6X,' 'PHASE = ',G11.4, 1,3X, 1,12X,' 'TYPE OF GROUND WIRE: ',5A1) 509 CONTINUE 509 FORMAT(1.13,6X,' 'PHASE = ',G11.4, 1,3X, 1,12X,' 'TYPE OF GROUND WIRE: ',5A1) 520 CONTINUE
GO TO 600
IF(DCKTYN(I).EQ.YE5) GO TO 56790
IIK=SPAN(I)
WRITE(9,10997) IIK

FORMAT(14)
IG=IGRD(I)
AIG=COABS(IGRD(I))
CALL PLTIST(AIG,AVGFTW,AILFTW)
CALL PLOT(SPANC, AIG,AVGFTW,AILFTW)
ISPAN=SPAN(I)-1
IFRPT=1
RPTCT=RIPTSP(IST)
DO 590 J=2,ISPAN1
   IF(RIPT.NE.RPTCT) GO TO 560
   IST=IST+1
   RPTCT=RIPTSP(IST)
   IRTPT=0
560   IRTPT=IRTPT+1
   IGSAV=IG
   IG=SZ(J,M1)*PHA(I)+SZ(J,M2)*IGRD(I)
   ITOW=IG-IGSAV
   AIG=COABS(IG)
   AITOW=COABS(ITOW)
   AVG=COABS(S(J,4))*AITOW
   CALL PLOT(J,AIG,AVG,AITOW)
   SZ(J+1,M1)=SZ(J+1,M1)+SZ(J,M1)*SZ(J+1,M2)
   SZ(J+1,M2)=SZ(J+1,M2)+SZ(J,M2)
   CONTINUE
   IF(IRTPT.NE.RPTCT) GO TO 592
   IST=IST+1
590   IGSAV=IG
      ISPAN=SPAN(I)
      IG=SZ(ISPAN,M1)*PHA(I)+SZ(ISPAN,M2)*IGRD(I)
      ITOW=IG-IGSAV
      AIG=COABS(IG)
      AITOW=COABS(ITOW)
      AVG=COABS(S(J,4))*AITOW
      CALL PLOT(ISPAN,AIG,AVG,AITOW)
      GO TO 680

M3=I*3
M2=M3-1
M1=M2-1
IIK=SPAN(I)
WRITE(8,10997) IIK
IG=IGRD(I)
AIG=COABS(IGRD(I))
CALL PLTIST(AIG,AVGFTW,AILFTW)
CALL PLOT(SPANC, AIG,AVGFTW,AILFTW)
ISPAN=SPAN(I)-1
IRPT=1
RPTCT=RIPTSP(IST)
DO 59011 J=2,ISPAN1
   IF(RIPT.NE.RPTCT) GO TO 56011
     IST=IST+1
   RPTCT=RIPTSP(IST)
   IRTPT=0
56011  IRTPT=IRTPT+1
   IGSAV=IG
   IG=SZ(J,M1)*PHA(I)+SZ(J,M2)*PHA1(I)+SZ(J,M3)*IGRD(I)
   ITOW=IG-IGSAV
   GO TO 680
AIG = CDABS(IG)
AITOW = CDABS(ITOW)
AVG = CDABS(S(IST,4))*AITOW
CALL PLOT(J, AIG, AVG, AITOW)
SZ(J+1,M1) = SZ(J+1,M1) + SZ(J,M1)
SZ(J+1,M2) = SZ(J+1,M2) + SZ(J,M2)
SZ(J+1,M3) = SZ(J+1,M3) + SZ(J,M3)

59011 CONTINUE
IF(IRPT .NE. RPTCT) GO TO 59211
IST = IST + 1
59211 IGSAV = IG
ISPAN = SPAN(I)
IG = S(ISPAN, M1)*IPHA(I) + S(ISPAN, M2)*IPHA1(I) + S(ISPAN, M3)*IGRD(I)
ITOW = IG - IGSAV
AIG = CDABS(IG)
AITOW = CDABS(ITOW)
AVG = CDABS(S(IST, 4))*AITOW
CALL PLOT(ISPAN, AIG, AVG, AITOW)
ITOW = IPHA(LC) + IPHA1(LC) - IG
GO TO 683

C
C TERMINATING STATION VOLTAGE AND CURRENT CALCULATIONS
C
680 ITOW = IPHA(I) - IG
683 AITOW = CDABS(ITOW)
VG = ITOW*RFP(I)
AVG = CDABS(VG)
WRITE(6, 685) AITOW, AVG
685 FORMAT('0', 79X, 'TERMINATING STATION: ',2(311.4, 2X))
690 CONTINUE
STOP
END

SUBROUTINE RCHECK(I TYPE, AMP, LCT)
REAL*8 AMP(4,5), A1
DATA IR, IX, ' R ', ' X '/
IF(I TYPE .NE. IX) CALL ERROR(16)
A1 = AMP(LCT, I)
DO 20 I = 2, 5
IF(A1 .GE. AMP(LCT, I)) CALL ERROR(18)
A1 = AMP(LCT, I)
20 CONTINUE
RETURN
END

ENTRY XCHECK(I TYPE, AMP, LCT)
IF(I TYPE .NE. IX) CALL ERROR(17)
A1 = AMP(LCT, I)
DO 20 I = 2, 5
IF(A1 .GE. AMP(LCT, I)) CALL ERROR(18)
A1 = AMP(LCT, I)
20 CONTINUE
RETURN
END

SUBROUTINE CMINV(A, N, N1, D, L, M)
C THE STANDARD GAUSS-JORDAN METHOD IS USED TO INVERT A COMPLEX
C MATRIX IN THIS SUBROUTINE
C N = ACTUAL SIZE OF THE MATRIX TO BE INVERTED
C N1 = ORDER OF THE MATRIX
C A = THE INPUT AND OUTPUT MATRIX
C  L,M=WOR.VECTOR OF LENGTH N1
C  COMPLEX*16 A(N1,N1),BEGA,HOLD,D
C  DIMENSION L(N1),M(N1)
D= (1.DO,0.DO)
DO 80 K=1,N
L(K)=K
M(K)=K
BEGA=A(K,K)
DO 20 J=K,N
DO 20 I=K,N
IF(CDABS(BEGA)-CDABS(A(I,J)))15,19,19
BIGA=A(I,J)
L(K)=I
M(K)=J
CONTINUE
DO 20 CONTINUE
J=L(K)
IF(J<K)35,35,25
CONTINUE
DO 30 I=1,N
HOLD=A(K,I)
A(K,I)=A(J,I)
30 A(J,I)=HOLD
I=M(K)
IF(I<K)38,38,35
CONTINUE
DO 40 J=1,N
HOLD=A(J,K)
A(J,I)=A(J,I)
40 A(J,I)=HOLD
CONTINUE
IF(CDABS(BEGA))48,46,48
CONTINUE
D= (0.DO,0.DO)
RETURN
CONTINUE
DO 55 I=1,N
IF(I<K)50,55,50
A(I,K)=A(I,K)/(-BEGA)
CONTINUE
DO 65 I=1,N
DO 65 J=1,N
IF(I<K)60,64,60
IF(J<K)62,64,62
A(I,J)=A(I,K)*A(K,J)+A(I,J)
CONTINUE
D=D*BEGA
A(K,K)=1.DO/BEGA
CONTINUE
CONTINUE
CONTINUE
K=N
CONTINUE
I=L(K)
IF(I<K)108,108,105
CONTINUE
DO 110 J=1,N
HOLD=A(J,K)
A(J,K)=A(J,1)
110 A(J,1)=HOLD
120 J=K
125 CONTINUE
DO 130 J=1,N
HOLD=A(K,1)
130 A(K,1)=A(J,1)
GO TO 100
150 RETURN
END

SUBROUTINE ERROR(I)
20 IF (I.EQ.1) WRITE(6,20)
FORMAT(**** ERROR IN TOWER NUMBER ****)
IF (I.EQ.2) WRITE(6,30)
30 FORMAT (**** MISSING END LINE DATA CARD ****)
IF (I.EQ.3) WRITE(6,40)
40 FORMAT(**** INCONSISTENT FAULT TOWER IMPEDANCES ****)
IF (I.EQ.4) WRITE(6,50)
50 FORMAT(**** SYSTEM HAS NO FEEDING SOURCE ****)
IF (I.EQ.5) WRITE(6,60)
60 FORMAT(**** MORE THAN FOUR TRANSMISSION LINES PROCESSED -----
1 TO PROCEED, CHANGE THE DIMENSION STATEMENT IN THE PROGRAM ****)
IF (I.EQ.6) WRITE(6,70)
70 FORMAT(**** IGROUND GREATER THAN IGROUND MAX DETECTED ****)
IF (I.EQ.7) WRITE(6,80)
80 FORMAT(**** SAME LINE NUMBER REPEATED ****)
IF (I.EQ.8) WRITE(6,90)
90 FORMAT(**** ITOWER GREATER THAN ITOWER MAX DETECTED ****)
IF (I.EQ.9) WRITE(6,100)
100 FORMAT(**** VTOWER GREATER THAN VTOWER MAX DETECTED ****)
IF (I.EQ.10) WRITE(6,110)
110 FORMAT (**** ILLEGAL PLOT CONTROL WORD ****)
IF (I.EQ.11) WRITE(6,120)
120 FORMAT (**** ILLEGAL GROUND WIRE TYPE NUMBER ****)
IF (I.EQ.12) WRITE(6,130)
130 FORMAT(**** GROUND WIRE CURRENT OUT OF INTERPOLATION ****)
1 FORMAT (**** UPPER LIMIT ****)
IF (I.EQ.13) WRITE(6,140)
140 FORMAT(**** GROUND WIRE CURRENT OUT OF INTERPOLATION ****)
1 FORMAT (**** LOWER LIMIT ****)
IF (I.EQ.14) WRITE(6,150)
150 FORMAT (**** LINE HAS NO GROUND WIRE ****)
IF (I.EQ.15) WRITE(6,160)
160 FORMAT (**** NON-SOURCE LINE WITH NO GROUND WIRE CONNECTED TO FAULT LOCATION ****)
IF (I.EQ.16) WRITE(6,170)
170 FORMAT (**** EXPECTED I PARAMETERS FOR STEEL GROUND WIRES, 'BUT NOT FOUND.****)
IF (I.EQ.17) WRITE(6,180)
180 FORMAT (**** EXPECTED X PARAMETERS FOR STEEL GROUND WIRES, 'BUT NOT FOUND.****)
IF (I.EQ.18) WRITE(6,190)
190 FORMAT (**** PARAMETERS FOR STEEL GROUND WIRES NOT IN PROPER ASCENDING ORDER ****)
IF (I.EQ.19) WRITE(6,200)
200 FORMAT (**** EXPECTED LINE PARAMETERS FOR CIRCUIT NO. 2, 'BUT NOT FOUND.****)
IF (I.EQ.20) WRITE(6,210)
SUBROUTINE EVU2(ZI, AMP, ARN, AXN, CRN, CXN, LCT, N5, N4, N3)
REAL*8 AMP, RR, RX, 0
REAL*8 ARN(N4,N5), AXN(N4,N5), CRN(N4,N4,N3), CXN(N4,N4,N3)
COMPLEX*16 ZI

C MAX(ARN) AND MAX(AXN) ASSUMED TO BE EQUAL

IF(AMP.GT.ARN(LCT,5)) CALL ERROR(12)
IF(AMP.LT.ARN(LCT,1)) CALL ERROR(13)
J = 5
IF(AMP.GE.ARN(LCT,J)) GO TO 200
GO TO 10
200 D'AMP-ARN(LCT,J)  
RR'((CRN(LCT,J,3)*D+CRN(LCT,J,2))*D+CRN(LCT,J,1))*D+RN(LCT,J)
J = 5
300 J = J - 1
IF(AMP.GE.AXN(LCT,J)) GO TO 400
GO TO 300
400 D'AMP-AXN(LCT,J)  
RX'((CXN(LCT,J,3)*D+CXN(LCT,J,3))*D+CRN(LCT,J,1))*D+XN(LCT,J)
ZI = CMPLX(RR,RX)
RETURN

SUBROUTINE PLTITL(ITEST)
INTEGER XA(79), SPANCT, ITEST
REAL*8 AIG, AVG, AITOW, AIGREF, AVGREF, AITREF
RETURN
ENTRY PLTIST(AIGREF,AVGREF,AITREF)
ICNT = 9
WRITE(6,10)
10 FORMAT(-,6X,'MIN',75X,'MAX')
IF(ITEST.EQ.1) GO TO 150
WRITE(6,20) AIGREF
20 FORMAT(-,7X,'0',3IX,'IGROUND = ''**''',29X,G11.4)
WRITE(6,30) AVGREF
30 FORMAT(-,7X,'0',3IX,'VTOWER = ''**''',29X,G11.4)
IF(ITEST.NE.3) GO TO 45
WRITE(6,40) AITREF
40 FORMAT(-,7X,'0',3IX,'ITOWER = ''**''',29X,G11.4)
WRITE(6,50) AIGREF
50 FORMAT(-,7X,'SPAN',87X,'IGROUND',6X,'VTOWER',7X,'ITOWER')
55 FORMAT(-,7X,'SPAN',6X,'VERSUS',6X,'SPAN',19X,G11.4)
WRITE(6,60) AITREF
60 FORMAT(-,7X,'SPAN',6X,'VERSUS',6X,'SPAN',19X,G11.4)
WRITE(6,70) AIGREF
70 FORMAT(-,7X,'SPAN',77X,'ITOWER')
ENTRY PLOT(SPANCT,AIG,AVG,AITOW)
RATIO=SNGL(AIG/AIGREF)
RETURN
IF (AIG.GT.AIGREF) CALL ERROR(6)
I=INT(RATIO*73.+1.5)
RATI0=SNGL(AIG)
SPAN2=SPANCT*I.0
WRITE(6,19971) SPAN2,RATI0
FORMAT(2E15.6)
IF (TEST.EQ.1) GO TO 600
N=1
IA(I)=ISYM1
CNT=1
IF (CNT.NE.10) GO TO 200
CNT=0
DO 185 L=1,6
DO 182 M=1,12
N=N+1
IA(N)=ISYM
182 CONTINUE
N=N+1
IA(N)=ISYM1
185 CONTINUE
GO TO 250
DO 200 L=1,6
DO 220 M=1,12
N=N+1
IA(N)=ISYM3
220 CONTINUE
N=N+1
IA(N)=ISYM1
230 CONTINUE
IA(I)=ISYM3
IF (TEST.NE.1) GO TO 300
RATIO=SNGL(AITOW/AITREF)
IF (AITOW.GT.AITREF) CALL ERROR(8)
I=INT(RATIO*73.+1.5)
IA(I)=ISYM3
300 RATIO=SNGL(AVG/AVGREF)
IF (AVG.GT.AVGREF) CALL ERROR(9)
I=INT(RATIO*73.+1.5)
IA(I)=ISYM2
WRITE(6,55) SPANCT,IA,AIG,AVG,AITOW
RETURN
500 IF (I.EQ.1) GO TO 650
IF (I.EQ.79) GO TO 660
J=I-1
M=I+1
WRITE(6,55) SPANCT,(ISYMI,L=J),ISYM1,(ISYMB,L=M,79),AIG,
1 AVG,AITOW
RETURN
550 WRITE(6,55) SPANCT,ISYM1,(ISYMB,I=2,79),AIG,AVG,AITOW
RETURN
650 WRITE(6,55) SPANCT,(ISYMM,L=1,78),ISYM1,AIG,AVG,AITOW
RETURN
END
* /
/*LKED.SYSLMOD DD DSN=TS1336.MYPROG.LOAD(TST1),DISP=(NEW,CATLG),
* UNIT=USERDA
*/
Typical JCL for Computation of Ground Wire Current:

```
// JOB
// **JOBPARM LINES=1000,DISKIO=1362
// EXEC PGM=TEST1,REGION=192K
// STEPLIB DD DSN=TS1336.MYPROG.LOAD,DISP=SHR
// FTOBFO01 DD SYSOUT=Y,DSN=(RECEM=YA,RECL=137,BLKSIZE=141,BUFNO=1)
// FTOBFO01 DD DSN=TS1851.PLOT1.DATA,DISP=SHR
// FTOBFO01 DD *

INPUT DATA CARDS
```

Plotting Routine and its JCL for Job Submittal:

```
// JOB
// **JOBPARM LINES=1000
// EXEC PLOT
// GO.FT0BFO01 DD DSN=TS1851.PLOT1.DATA,DISP=SHR
// GO.SOURCE DD *

REAL*4 SPAN(400),IGRD(400)
CALL PLOTS(0,0,0)
ICT=0
10 READ(8,100) ISPAN1
100 FORMAT(14)
   IF(ICT.NE.0) GO TO 300
   DO 200 1=1,ISPAN1
      READ(8,150) SPAN1,GRD
      K=ISPAN1-(1-1)
      SPAN(K)=K*1.0
      IGRD(K)=GRD
      WRITE(6,150) SPAN(K),IGRD(K)
   150 FORMAT(2E15.6)
   CONTINUE
   ICT=ICT+1
   ISPAN2=ISPAN1
   GO TO 10
300 ISPAN=ISPAN2+ISPAN1
   DO 400 1=1,ISPAN1
      READ(8,150) SPAN1,GRD
      K=ISPAN2+(1-1)
      SPAN(K)=K*1.0
      IGRD(K)=GRD
      WRITE(6,150) SPAN(K),IGRD(K)
   400 CONTINUE
   N1=ISPAN+1
   N2=ISPAN+2
   CALL SCALE(ISPAN,7,ISPAN,1)
   CALL SCALE(IGRD,8,ISPAN,1)
   CALL PLOT(5.5,-3)
   CALL AXIS(.0,.0,'SPAN',-.4.75,.0,SPAN(N1),SPAN(N2))
   CALL AXIS(.0,.0,'PER-UNIT GROUND WIRE CURRENT',+28,8,.90.,
   IGRD(N1),IGRD(N2))
   CALL LINE(SPA N,IGRD,ISPAN,1,-1.75)
   CALL NEWPEN(2)
```
CALL SYMBOL(1.8..14,'STEEL GROUND WIRE - TWO SUPPLIES', 1.0,32)  
CALL PLOT(0.,0.,999)  
STOP  
END
APPENDIX D

EPRI Program for Use at OSU

Tape Information (see Reference 29):

Name: EP0994
Track: 9
Density: 1600 bpi
Conversion: EBCDIC
Files: 15
Code: GATL Version-1
Hardware: IBM
Date: March 30, 1983
Create a Load Module Data Set:

```csh
// JOB
// JOBPARM LINES=8000, DISKIO=1362
// SETUP UNIT=TAPE9, ID=(EP0994, L260, READ)
// EXEC FORTOCL, PARM='MAP, XREF, GOSTMT, AUTO DBL (DBLPAD)'
// FOR T SYSLIN DD NAME=CYL, (5,5), RLSE
// FOR T SYSLIN DD DS N=GATL.PATH S, DISP=OLD, UNIT=TAPE9,
// VOL IN, RETAIN, SER=EP0994), LABEL=(6, NL),
// OCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
// LKED. SYSLMOD DD DS N=TS1336.EPRIPROG.LOAD (TEST1), DISP=(NEW, CATLG),
// UNIT=USERO
```

JCL for Case Studies:

```csh
// JOB
// JOBPARM LINES=3000, DISKIO=3362
// EXEC PGM=TEST1, REGION=192K
// STEPLIB DD DS N=TS1336.EPRIPROG.LOAD, DISP=SHR
// FT05F001 DD SYSOUT=A, DCB=(RECFM=VA, LRECL=137, BLKSIZE=141, BUFNO=1)
// FT05F001 DD UNIT=SYSOA, SPACE=(CYL, (1,1), RLSE)
// FT05F301 DD *
```

INPUT DATA CARDS

Copy EPRI Tape to Backup Tape:

```csh
// JOB
// SETUP UNIT=TAPE9, ID=(EP0994, L260, READ)
// SETUP UNIT=TAPE9, ID=(G001, L256, WRITE)
// JOBPARM TAPE9=1000
// COPY TAPE EXEC TCUP, INSER=EP0994, INLBL=NL,
// PARM=NEWTAPE, OUTSER=G001, OUTLBL=NL
```

Print Source Program and Data Set from Tape:

```csh
// JOB
// SETUP UNIT=TAPE9, ID=(G001, L256, READ)
// JOBPARM LINES=5000, TAPE1=1000
// COPY EXEC PGM=JMLCOPY
// SYS PRT DD SYSOUT=A
// SYSSUT2 DD DS N=GATL.PATH S, DISP=OLD, UNIT=TAPE9,
// LABEL=(6, NL), VOL=SER=G001, OCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
// SYSSUT2 DD SYSOUT=A
```
JCL toUnload Tape, Compile Source, and Execute Samples:

```plaintext
// JOB
/*SETUP UNIT=TAPE9, ID=(EP0994, L260, READ)
// EXEC PGM=IEBGENER
//SYSIN DD DUMMY
//SYSPRINT DD SYSOUT=* 
//SYSUT1 DD DSN=JCL, DISP=OLD, UNIT=TAPE9, VOL=(, RETAIN, SER=EP0994),
//LABEL=(2, NL), DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
//SYSUT2 DD DSN=TS1338.JCL, DISP=(, CATLG, DELETE), UNIT=USERDA,
//VOL=SER=IRCC71, SPACE=(TRK,(5, 1)),
//DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
*/
```

Load PDS from Tape:

```plaintext
// JOB
/*SETUP UNIT=TAPE9, ID=(EP0994, L260, READ)
/**
/** LOAD GATL.LOADLIB FROM TAPE
/**
/**STEPO001 EXEC PGM=IEBCOPY
//SYSIN DD DUMMY
//SYSPRINT DD SYSOUT=A 
//SYSUT1 DD DSN=GATL.LOADLIB, DISP=OLD,
//UNIT=TAPE9, VOL=(, RETAIN, SER=EP0994),
//LABEL=(7, NL),
//DCB=(RECFM=VS, LRECL=6248, BLKSIZE=6252)
//SYSUT2 DD DSN=TS1338.GATL.LOADLIB, DISP=(, CATLG, DELETE),
//UNIT=USERDA, VOL=SER=IRCC71,
//SPACE=(TRK,(35, 10, 1), RLSE)
//SYSUT3 DD UNIT=SYSDA, SPACE=(CYL,(1, 1), RLSE)
//SYSUT4 DD UNIT=SYSDA, SPACE=(CYL,(1, 1), RLSE)
*/
```
LIST OF REFERENCES


Electric Power Research Institute, Project No. 1494-2, 1982.


