MicroTran®

mtLine™ & fdData™
Reference Manual

Microtran Power System Analysis Corporation
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USING THE PROGRAMS

I. Introduction

mtLine

The program mtLine™ calculates the parameters of an overhead transmission line based on the conductor characteristics and the geometrical tower configuration. The program can accept any combination of line circuits, phase conductors, and ground wires up to a total of 100 conductors and 50 phases.

Bundled conductors can be specified as individual subconductors or by describing the bundle arrangement.

The program can output the line's series impedance or shunt admittance matrices directly in phase quantities or in modal coordinates with the corresponding transformation matrices.

For transients analysis, mtLine can calculate in modal coordinates the line's characteristic impedance, travelling time and velocity of propagation. This information can then be used in the transients program MicroTran® for the constant-parameters line model. For the frequency dependent line model, the companion program fdData™ should be used.

For steady-state solutions, the program can produce n-nominal circuits. This approximate representation is valid for "short lines" (e.g., $l < \frac{10,000}{f}$, for the length in km and the frequency in Hz). Short-line sections can be cascaded to simulate longer lines. The π-nominal model should not be used for transient simulations.

The general structure of the input data file for mtLine in shown in Table 111.1.

fd Data

The program fdData™ produces the frequency dependent line model (FDL) for the transients program MicroTran®.

The required input data for fdData is basically the same as for mtline, that is, the conductor characteristics and the geometrical tower configuration. fdData can accept a total of 37 conductors and 37 phases.

The structure of the input file for fdData in shown in Table 111.2. The main difference with respect to the input file for mtLine is the addition of the `MODEL` card (item [la] in Table 111.2) placed between the `TITLE` and `UNITS` cards. Also, optional cards can be added at the end of the data deck (item [5] in Table 111.2) for finer control of the model synthesis procedure and output listing options. Another difference with respect to mtLine is that only "reactance type 4" (tubular model for skin effect) is recognized in the `CONDUCTORS` card.

fdData will produce a "punch" file which contains the parameters for the frequency dependent line `model`. This file can be read directly by the transients program MicroTran (MT) for an accurate modelling of the transmission line over a wide range of frequencies in transient studies.

II. Running mtLine and fdData

mtLine

The file names needed by mtLine are:

Input File	(e.g., `case1.dat`)
Output File	(e.g., `case1.out`)

Additionally a "Punch File" may be needed if punched output is requested in the FREQUENCY card of the input data case. The file names may be passed to the program by running the program in prompt mode or in command-line mode.

PROMPT MODE:

To run mtLine in prompt mode type

```
> MTLINE
```

The user will then be prompted for the names of the input and output files. Directory path names can be included.

After entering the name of the input file, the program prompts for the name of the output file. A default file name is suggested. If the name of the input file is, for example, "`case1.dat`", the name "`case1.out`" is suggested for the output file. Press the [return] key to accept the suggested default name or type in a different name.

Typing "con" as the name of the output file directs the output to the screen ("console").

Accidental overwriting of existing files can be prevented by using the switch "`-o`" when running the program. For example, entering

```
> MTLINE -o
```

instead of just "`MTLINE`" will prompt the user before overwriting an already existing output file.

COMMAND-LINE MODE:

File names can be specified directly in the command line, thus by-passing the prompts for the file names. For example, entering

```
> MTLINE case1.dat, hiland.out, hiland.pun
```

will create the file "`hiland.out`" for the output listing and the file "`hiland.pun`" if a punch-file request has been specified in the `FREQUENCY` card.

The files names in the command line must be separated by at least one space or by commas. The maximum length of the command line is 64 characters. Directory paths can be included.

In command-line mode, only the name of the input file is required. If any of the other file names is omitted, a default file name is assumed. For example, entering

```
> MTLINE  case1.dat
```

will read the input data from the file "`case1.dat`" and will create the files "`case1.out`" for the output listing, and "`case1.pun`" for punched output.

As indicated above for the prompt mode option, the switch "`-o`" can be included in the command line to prevent overwriting of existing files. For example, entering

```
> MTLINE  case1.dat, hiland.out -o
```

will prevent the overwriting of an already existing "`hiland.out`" output file.

When invoking mtLine in prompt mode there is no prompting for the name of the punch file. If punch file output is requested in the `FREQUENCY` card, the name of the punch file is internally generated, taking the root name of the input file and adding the extension "`.pun`". For example, if the input file name is "`case1.dat`", the program will assign the name "`case1.pun`" to the punch file. If a different name is desired for the punch file, the command-line option should be used.

In case of multiple punch file requests within the same data file (for example, for stacked data cases or for multiple frequency cards), the program will internally generate successive file names for the punch files. These files will be named "`hhmmss.pun`", where "`hh:mm:ss`" is the time of the day in 24-hour notation when the file opening request is processed.

fd Data

The file names needed by fdData are:

Input File	(e.g., `case1 . dat`)
Output File	(e.g., case1 `. out`)
Punch File	(e.g., `case1.pun`)

As in the case of mtLine, fdData can be run both in prompt mode and in command-line mode.

PROMPT MODE:

To run fdData in prompt mode, type

```
>   FDDATA
```

The program will prompt for the required file names. Press `[return]` to accept the suggested file names, or type in the desired names. Typing “con” directs the output to the screen. !*command* enters a DOS command. Overwriting of existing names can be prevented using the switch “`-o`” at the command line.

COMMAND-LINE MODE:

Specifying the file names directly in the *command* line by-passes the program prompts. For example,

```
>   FDDATA case1.dat, hiland.out, hiland.pun
```

`specifies "case1 . dat"` as the input file, “`hiland.`out” as the output listing file, and `"hi 1 and. pun"` as the punch file for the frequency dependent line model. If only the input file name is given, e.g.,

```
>   FDDATA casel.dat
```

default names are internally generated for the output file `("case1 . out")` and for the punch file `("case1 .pun”)`. Adding the switch “`-o`” to the command line will prevent overwriting of existing file names.

III. Input Formats

mtLine

The format for an mtLine data input file is shown in Table 111.1. The detailed description of the different items is given in the corresponding section of this manual.

The `TITLE` card contains any comment between columns 1 and 80. The first four columns may not be blank.

The `UNITS` card indicates whether the units are S.I. metric or British.

The `CONDUCTOR` cards specify the type and geometry of the line conductors. The total number of conductors (phase conductors plus ground wires) cannot exceed 100. (Note: An N-subconductor bundle counts as N conductors.)

A `MARKER` card (`&END` or blank line) is used to indicate the end of the `CONDUCTOR` cards.

The `FREQUENCY` cards are used to indicate the frequencies at which the line parameters are calculated and to request output options. There may be any number of `FREQUENCY` cards.

A `MARKER` card (`&END` or blank line) is used to indicate the end of the `FREQUENCY` cards. At this point, another data case can be added, beginning with the new `TITLE` card.

A `MARKER` card (`&END` or blank line) is needed to indicate that there are no additional data cases.

(Note: The end of the data file will have two `MARKER` cards, one to indicate the end of the `FREQUENCY` cards and one to indicate that this is the last data case.)

fd Data

The format of the fdData input file is shown in Table 111.2.

The main difference with the mtLine input file is the insertion of an extra card, the `MODEL` card.

fdData accepts only one `FREQUENCY` card and there can be only one data case per file. As a result, there is no need for `MARKERS` after the `FREQUENCY` card and to terminate the data cases.

Optional request cards (`. KEYWORD` cards) can be added after the `FREQUENCY` card to fine tune the model's synthesis process.

The line-model file produced by fdData is used by MicroTran for the frequency dependent line model.

Table III.1 mtLine Input File

Item	*Description*	*# Cards*
[1]	TITLE	1
[2]	UNITS	1
[3]	CONDUCTORS	N
marker	&END or blank line	1
[4]	FREQUENCY	1 or more
marker	&END or blank line	1
marker	&END or blank line	1

Table III.2 fdData Input File

Item	*Description*	*# Cards*
[1]	TITLE	1
[1a]	***MODEL***	***1***
[2]	UNITS	1
[3]	CONDUCTORS	N
marker	&END or blank line	1
[4]	FREQUENCY	1 or more
[5]	***.KEYWORD*** *(optional)*	***any***

PROGRAMS DESCRIPTION

1. Evaluation of the Line Parameters

The solution technique used by mtLine™ [1,2] and fdData™ to calculate the line parameters is completely general and can handle any number of circuits (e.g., double-circuit lines), any bundle arrangement, and any number of ground wires. To explain the method, the example of a single-circuit line with twin bundle conductors and two ground wires, as shown in Fig. 1.1, will be used. Conductors 1 and 2 are bundled into phase *a* , conductors 3 and 4 into phase *b* and conductors 5 and 6 into phase *c* . Conductors 7 and 8 are the ground wires.

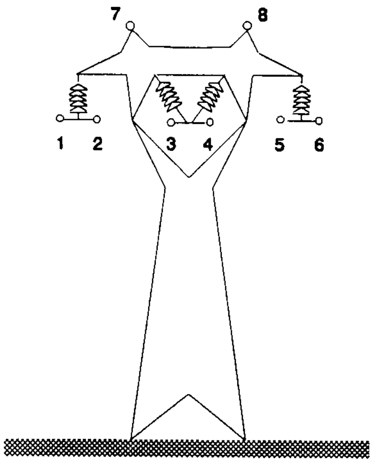


Figure 1.1 Tower configuration

1.1. Series Impedance

The series impedances of the eight conductors are described in the form[1] of an 8 × 8 impedance matrix [Z]. Its diagonal element Z_{ii} is the series self impedance per unit of length of conductor i with ground serving as the return path, and its off-diagonal element Z_{ik} is the series mutual impedance per unit of length between conductors i and k . The matrix is symmetric, $Z_{ik} = Z_{ki}$. The values of the matrix elements are computed with Carson's formula [3],

---

[1] In the program output, these are the matrices "for the system of physical conductors" (each physically existing conductor is represented in them).

$$Z_{ii} = (R_i + \Delta R_{ii}) + j\left(2\omega 10^{-4} \ln \frac{2h_i}{GMR_i} + \Delta X_{ii}\right), \text{ in } \Omega/\text{km} \quad (1.1)$$

$$Z_{ik} = Z_{ki} = \Delta R_{ik} + j\left(2\omega 10^{-4} \ln \frac{D_{ik}}{d_{ik}} + \Delta X_{ik}\right), \text{ in } \Omega/\text{km} \quad (1.2)$$

with

R_i = resistance of conductor i (in Ω/km),

h_i = average height above ground of conductor i (in meters),

D_{ik} = distance between conductor i and the image of conductor k (in meters) (see Fig. 1.2),

d_{ik} = direct distance between conductors i and k (in meters),

GMR_i = geometric mean radius of conductor i (in meters),

ω = angular frequency,

ΔR, ΔX = Carson's correction terms which account for ground return effects.

(D_{ik}, d_{ik}, and GMR_i are in the same units, for example, all in meters.)

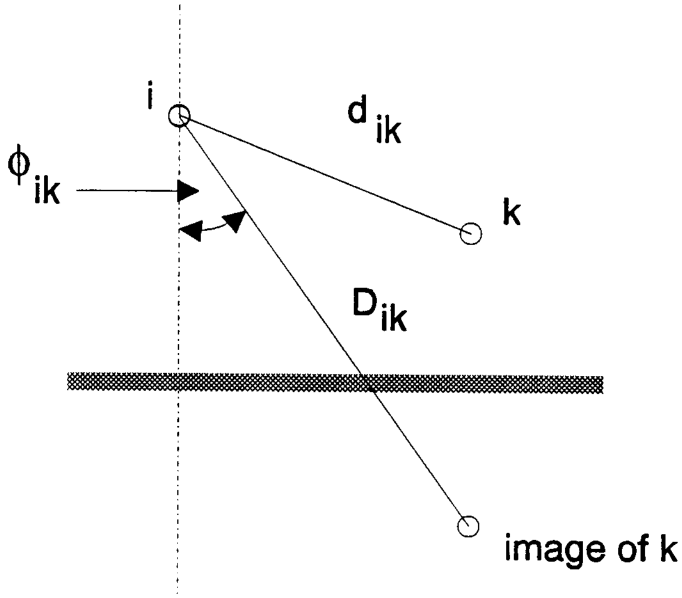


Figure 1.2 Distances between conductors i and k.

The steady-state equations for voltage drop per unit of length along the eight conductors can then be written as

$$-\begin{bmatrix} dV_1/dx \\ dV_2/dx \\ \vdots \\ dV_8/dx \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{18} \\ Z_{21} & Z_{22} & \cdots & Z_{28} \\ \vdots & \vdots & \vdots & \vdots \\ Z_{81} & Z_{82} & \cdots & Z_{88} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_8 \end{bmatrix}. \tag{1.3}$$

1.2. Shunt Capacitance

The capacitances between the eight conductors and ground are described in the form[2] of an 8 × 8 capacitance matrix [C]. Its diagonal element C_{ii} is the sum of the shunt capacitances per unit of length from conductor i to all other conductors as well as to ground; its off-diagonal element C_{ik} is the negative value of the shunt capacitance per unit of length between conductors i *and* k . Again, [C] is symmetric, $C_{ik} = C_{ki}$. The capacitance matrix cannot be computed directly. Instead, the matrix [P] of Maxwell's potential coefficients is first formed (see footnote), and [C] is then found by matrix inversion,

$$[C] = [P]^{-1}. \tag{1.4}$$

The elements of [P] are computed from the tower geometry. If $r << h$, with r being the radius of the conductor, then

$$P_{ii} = 18 \cdot 10^6 \cdot \ln\frac{2h_i}{r_i}, \text{ in km/F,} \tag{1.5a}$$

$$P_{ik} = P_{ki} = 18 \cdot 10^6 \cdot \ln\frac{D_{ik}}{d_{ik}}, \text{ in km/F.} \tag{1.5b}$$

The exact value of the factor in Eq. 1.5 is $2c^2 \cdot 10^{-4}$, with c being the velocity of light in air in km/s. Maxwell's potential coefficients relate line-to-ground voltages of the eight conductors to the charges on the conductors,

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_8 \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{18} \\ P_{21} & P_{22} & \cdots & P_{28} \\ \vdots & \vdots & \vdots & \vdots \\ P_{81} & P_{82} & \cdots & P_{88} \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_8 \end{bmatrix}. \tag{1.6}$$

---

[2] In the program output, these are the matrices "for the system of physical conductors" (each physically existing conductor is represented in them).

1.3. Elimination of Ground Wires and Bundling

Equations 1.3 and 1.6 for all eight conductors are too detailed if one wants to work with phase quantities. They can be reduced to three equations for the three phases. The reduction process is easier to explain if the inverse forms of Eqs. 1.3 and 1.6 are used rather than their original forms. Computation is faster, however, if the reduction process is applied to the original forms. For details see [1]. Assume that the inverse relationship of Eq. 1.6 has been found by inverting [P],

$$\begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_8 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{18} \\ C_{21} & C_{22} & \cdots & C_{28} \\ \vdots & \vdots & \vdots & \vdots \\ C_{81} & C_{82} & \cdots & C_{88} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_8 \end{bmatrix} . \tag{1.7}$$

Since the voltage on the ground wires is zero (assuming that they are not insulated from the towers), one can set $V_7 = 0$ and $V_8 = 0$ in Eq. 1.7, and omit the rows for Q_7 and Q_8 (unless one wants to calculate the charges on the ground wires). This means that the two ground wires numbers 7 and 8 are eliminated by simply scratching the last two rows and columns in Eq. 1.7. Their effect on line performance is contained, however, in the first five equations of Eq. 1.7.

The reduction process is almost as simple for connecting conductors into a bundle to form a phase. Let us see how it works for phase a . Since conductors 1 and 2 form phase a , one can say that $V_1 = V_2 = V_a$. Therefore, one should no longer distinguish between V_1 and V_2 in Eq. 1.7 but call it V_a. This amounts to adding columns 1 and 2 in the matrix to form the new column for V_a. Also, $Q_1 + Q_2 = Q_a$. This means that one must also add rows 1 and 2 to get the new row for Q_a. In other words, bundling is accomplished by first forming a new column by adding the columns of the individual conductors, and then forming a new row by adding the rows of the individual conductors. In this way one obtains the reduced equations[3]

$$\begin{bmatrix} Q_a \\ Q_b \\ Q_c \end{bmatrix} = \begin{bmatrix} C_{aa} & C_{ab} & C_{ac} \\ C_{ba} & C_{bb} & C_{bc} \\ C_{ca} & C_{cb} & C_{cc} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} . \tag{1.8}$$

In the example, $C_{aa} = C_{11} + C_{12} + C_{21} + C_{22}$, etc.

Similarly, Eq. 1.3 can be reduced to

---

[3] In the program output, these are the matrices "for the system of equivalent phase conductors".

$$-\begin{bmatrix} dV_a/dx \\ dV_b/dx \\ dV_c/dx \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}. \tag{1.9}$$

The reduction process for the impedances works the same way as for [C] if one works with [Z]$^{-1}$ rather than with [Z].

1.4. Symmetrical Components

Even Eqs. 1.8 and 1.9 are often too detailed. For example, only positive sequence parameters are needed in power flow studies, or positive and zero sequence parameters in short-circuit studies. Sequence parameters are easily obtained from Eqs. 1.8 and 1.9 by transforming phase quantities into sequence quantities [2]. This transformation changes Eq. 1.9 of the untransposed line into

$$-\begin{bmatrix} dV_{zero}/dx \\ dV_{pos}/dx \\ dV_{neg}/dx \end{bmatrix} = \begin{bmatrix} Z_{zero,zero} & Z_{zero,pos} & Z_{zero,neg} \\ Z_{pos,zero} & Z_{pos,pos} & Z_{pos,neg} \\ Z_{neg,zero} & Z_{neg,pos} & Z_{neg,neg} \end{bmatrix} \begin{bmatrix} I_{zero} \\ I_{pos} \\ I_{neg} \end{bmatrix}. \tag{1.10}$$

with a similar equation corresponding to Eq. 1.8. In the program output, this is the matrix "for the symmetrical components of the equivalent phase conductors".

Transposing a line averages the impedance values and makes the diagonal elements in Eqs. 1.8 and 1.9 equal among themselves, and the off-diagonal elements equal among themselves,

$$Z_s = \frac{1}{3}(Z_{aa} + Z_{bb} + Z_{cc}), \tag{1.11}$$

$$Z_m = \frac{1}{3}(Z_{ab} + Z_{ac} + Z_{bc}). \tag{1.12}$$

If this "balanced" matrix $\begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix}$ of a transposed line is transformed to sequence quantities, then the matrix in Eq. 1.10 becomes diagonal (all off-diagonal elements zero). The computer program always produces the matrix of Eq. 1.10 of the untransposed line. If the line is transposed, simply ignore the off-diagonal elements and use the diagonal elements only (it can be shown that the values of the diagonal elements are the same for transposed and untransposed lines). Also note that the matrix in Eq. 1.10 is not symmetrical, unless the columns "pos" and "neg" are exchanged (this exchange is made in the output).

For untransposed lines, the off-diagonal elements in Eq. 1.10 contain useful information about coupling effects between sequence quantities; they are used in [4] (pp. 93-103) to derive unbalance factors.

1.5. Modal Parameters

As mentioned in Section 1.4, the equations for zero, positive, and negative sequence quantities become decoupled if the line is transposed, that is, the matrix in Eq. 1.10 becomes diagonal in that case. This concept of transforming the original phase quantities with their coupled equations into new quantities with decoupled equations can also be used for untransposed lines by introducing new "modal" quantities

$$[V_{mode}] = [T_v]^{-1}[V_{phase}] \tag{1.13}$$

and

$$[I_{mode}] = [T_i]^{-1}[I_{phase}], \tag{1.14}$$

with

$$[T_v] = [T_i^t]^{-1}. \tag{1.15}$$

For more details on modal parameters, see [2] or [5]. The program has an option to calculate [T_i], as well as modal series impedance, modal shunt capacitance, etc.

1.6. Equivalent π-Circuits

For steady-state solutions, an M-phase line can be represented by an equivalent M-phase π-circuit, which exactly describes the conditions at the line terminals for a specific frequency and length. Equivalent π-circuits cannot be used for electromagnetic transients studies, however.

The equivalent M-phase π-circuit is a generalization of the well-known single-phase equivalent π-circuit of Fig. 1.3 (sometimes called "long line representation").

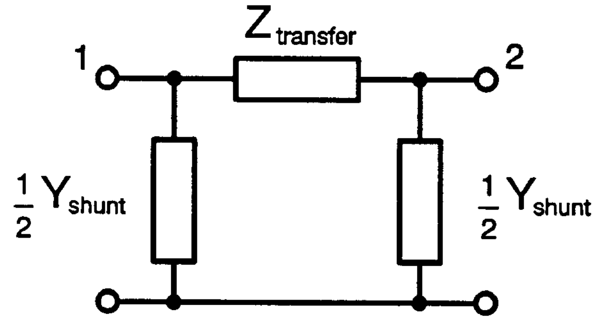


Figure 1.3 Single-phase equivalent π-circuit.

In the circuit of Fig. 1.3 the transfer impedance $Z_{transfer}$ is calculated from

$$Z_{transfer} = \sqrt{\frac{Z}{Y}} \cdot \sinh\left(l \cdot \sqrt{ZY}\right), \tag{1.16}$$

with
Z = series impedance per unit length,
Y = shunt admittance per unit length,
l = length of line,

and Y_{shunt} is calculated from

$$\frac{1}{2}Y_{shunt} = \frac{\tanh\left(\frac{l}{2}\sqrt{ZY}\right)}{\sqrt{\frac{Z}{Y}}}. \tag{1.17}$$

For the M-phase case, the transfer impedance and shunt admittance become matrices [$Z_{transfer}$] and [Y_{shunt}]. The program has an option to produce these matrices, with a technique discussed in [2].

1.7. Electric Field Strength at Ground Level Across Right-of-Way

The electric field strength at ground level is difficult to evaluate if the terrain is irregular or if objects such as vehicles or buildings are close to the line. In the following, it is therefore assumed that the terrain is perfectly flat, that the conductors are perfectly horizontal, and that no objects are nearby.

First, the charges on the conductors are calculated from Eq. 1.7. In the general case,

$$[Q] = [P]^{-1}[V] = [C][V] \quad \text{kC/km} \tag{1.18}$$

or

$$Q_j = \sum_{k=1}^{n} C_{jk} V_k \quad \text{kC/km,} \tag{1.19}$$

where n is the number of conductors, C_{jk} are the elements of the capacitance matrix in F/km, and V_k is the root-mean-square phasor value of the line-to-ground voltage of conductor k in kV.

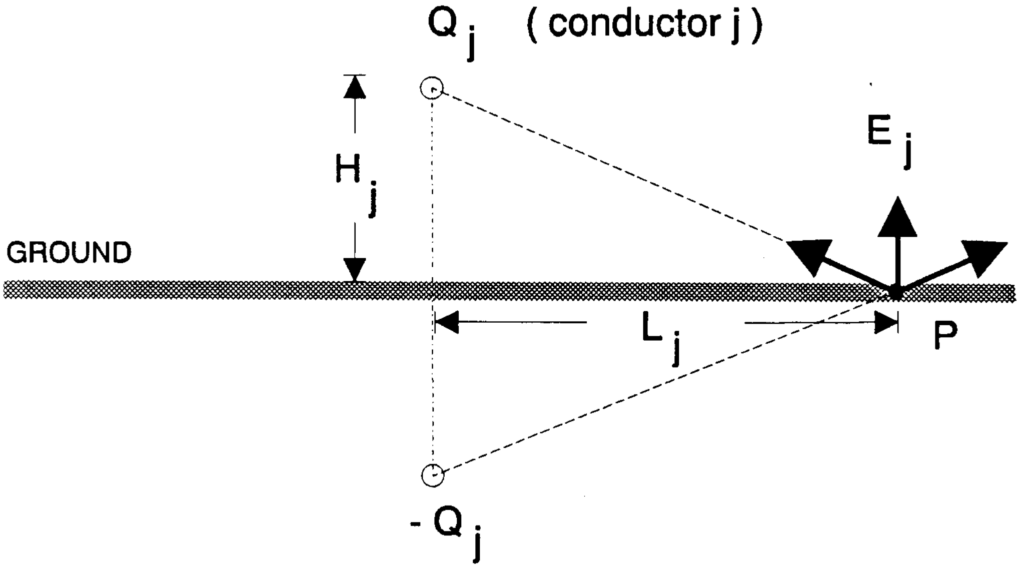


Figure 1.4 Contribution of conductor *j* to field strength in *P*.

The contribution from charge Q_j on conductor *j* and from charge $-Q_j$ on the image of this conductor to the field strength at point *P* (Fig. 1.4) is

$$E_j = \frac{Q_j}{\pi \varepsilon_0} \frac{H_j}{H_j^2 + L_j^2} \quad \text{kV/m} \tag{1.20}$$

if $\varepsilon_0 = 10^{-6}/(36\pi)$ in F/km, and H_j and L_j in meters.

The magnitude of the total electric field strength at point *P* on the ground is

$$E_{total} = \left| \sum_{j=1}^{n} E_j \right| \quad \text{kV/m,} \tag{1.21}$$

which is the value printed by the program. Note that E_{total} is a root-mean-square value, since the voltages were given as root-mean-square values. The instantaneous value of the field strength would therefore be

$$e_{total} = \sqrt{2}\, E_{total} \cos(\omega t + \alpha)\,, \tag{1.22}$$

with α being the angle of the phasor value $\sum_{i=1}^{n} E_i$. For more details, see [4] (pp. 249-254).

1.8. Frequency Dependent Line Model: fdData

The program fdData writes on the "model file" the parameters of the frequency dependent line model (FDL) for the transients program MicroTran. This model [13] represents the line parameters as continuously distributed along the line ("long line representation") and assumes that the series parameters of the line are functions of frequency, i.e., $R = R(\omega)$, $L = L(\omega)$, G = constant, and C = constant.

The FDL model is a travelling wave model in which each propagation mode is described in terms of its characteristic impedance

$$Z_c(\omega) = \sqrt{\frac{R(\omega) + j\omega L(\omega)}{G + j\omega C}} \tag{1.23}$$

and the forward propagation function $e^{-\gamma(\omega)l}$, with

$$\gamma(\omega) = \sqrt{[R(\omega) + j\omega L(\omega)][G + j\omega C]}\,. \tag{1.24}$$

In these functions, R, L, G, and C are in per-unit length and l is the total line length.

For the line model, fdData expands the functions $Y_c(s) = \frac{1}{Z_c(s)}$ and $A(s) = e^{-\gamma(s)l}$,with $s{=}j\omega$, into partial fractions with simple poles. That is,

$$Y_c(s) = k_{Y_0} + \frac{k_{Y1}}{s + p_{Y1}} + \frac{k_{Y2}}{s + p_{Y2}} + \cdots + \frac{k_{Ym}}{s + p_{Ym}}\,, \tag{1.25}$$

and

$$A(s) = \frac{k_{A1}}{s + p_{A1}} + \frac{k_{A2}}{s + p_{A2}} + \cdots + \frac{k_{An}}{s + p_{An}}\,.$$

The residues k_i and the poles p_i of these expansions are written in the line model file. The currents transformation matrix to relate modal and phase coordinates is written at the end of this file.

2. Description of the Data Deck

2.1. Title Card

Use one card for comments which will be printed in the output as identification. All 80 columns may be used, but the first four columns must not be blank.

fdData

2.1a. fdData Model Card

This card is only for the fdData program. It should be omitted for mtLine.

Format:

LINE-MODEL		matrix		FMIN	NPDEC	NDEC	
A19		A10		E10	I10	I10	

Line-Model (1-9) = LINE MODEL (required keyword)

All other fields in this card may be left blank to accept the defaults.

matrix (30-39)

= QEIGEN (Default)

The exact eigenvalues are calculated at each frequency and used to evaluate the propagation function $e^{-\gamma(\omega)l}$. The characteristic impedance function $Z_c(\omega)$ is calculated from the exact eigenvalues and from a real constant transformation matrix. The constant real transformation matrix is evaluated at frequency `FMATRIX` specified in the `FREQUENCY CARD` (default = 1.2 kHz). This constant real transformation matrix is used in MicroTran to convert between phase and modal quantities.

= QREAL

A constant real transformation matrix evaluated at frequency `FMATRIX` specified in the `FREQUENCY CARD` (default = 1.2 kHz) is used to calculate the eigenvalues and line functions $Z_c(\omega)$ and $e^{-\gamma(\omega)l}$ at each frequency. This matrix is used by MicroTran to convert between phase and modal quantities.

= BALANCED

The line is assumed to be balanced or perfectly transposed. The modal parameters are, therefore, exact at all frequencies using a constant transformation matrix. This matrix can be chosen to be real, e.g., Clarke and Karrenbauer transformations. For the balanced case, no transformation matrix is written at the end of the line model file. The transients program MicroTran recognizes the line as balanced and uses Karrenbauer transformation to convert between phase and modal quantities.

FMIN (50-59)

The line functions are synthesized in the interval (`FMIN`, fmax), where fmax = `FMIN` × 10^{NDEC}. Default value is 0.1 Hz.

NPDEC (60-69)

Number of logarithmically spaced frequency points in each decade of the fitting interval. `NPDEC` has to be 10 or a multiple of 10. Default value is 10.

NDEC (70-79)

Length in number of decades of the line-functions synthesis interval. Default is 8 decades.

2.2. Units Card

Use one card to specify whether the British or the metric S.I. system of units is used, and whether the electric field strength under the line is to be calculated. For the electric field strength calculation, a perfectly flat ground is assumed. Values are calculated across the right-of-way from x_{min} to x_{max} in increments of Δx at ground level.

2.2.1. Data in Units Card

mtLine

Format:

UNITS	X_{min}	X_{max}	ΔX	
A8	E10.5	E10.5	E10.5	

UNITS (1-8)

Enter METRIC if the metric S.I. system of units is used. Then all input and output data involving lengths will be in millimeters, meters, and kilometers.

Enter BRITISH if the British system of units is used. Then all input and output data involving lengths will be in inches, feet, and miles.

x_{min} (9-18)

The horizontal distance (meters or feet) on the x-axis in Fig. 1.6, where the first value of electric field strength on the left side of the right-of-way is to be calculated.

x_{max} (19-28)

The horizontal distance (meters or feet) on the x-axis in Fig. 1.6, where the last value of electric field strength on the right side of the right-of-way is to be calculated.

Δx (29-38)

The incremental distance (meters or feet) for calculating values between x_{min} and x_{max}. The electric field strength is calculated as a function of the horizontal distance and printed in the sequence $E\ (x_{min})$, $E\ (x_{min} + \Delta x)$, $E\ (x_{min} + 2\Delta x)$, $E\ (x_{min} + 3\Delta x)$, ... , $E\ (x_{max})$ in kV/m or kV/ft. Leave x_{min}, x_{max}, and Δx blank if no electric field strength output is requested.

2.2.2. Example

UNITS	=	METRIC	
x_{min}	=	-30.	(meters)
x_{max}	=	30.	(meters)
Δx	=	1.0	(meters)

x_{max} (19-28)

The horizontal distance (meters or feet) on the x-axis in Fig. 1.6, where the last value of electric field strength on the right side of the right-of-way is to be calculated.

Δx (29-38)

The incremental distance (meters or feet) for calculating values between x_{min} and x_{max}. The electric field strength is calculated as a function of the horizontal distance and printed in the sequence $E\ (x_{min})$, $E\ (x_{min} + \Delta x)$, $E\ (x_{min} + 2\Delta x)$, $E\ (x_{min} + 3\Delta x)$, ... , $E\ (x_{max})$ in kV/m or kV/ft. Leave x_{min}, x_{max}, and Δx blank if no electric field strength output is requested.

2.2.2. Example

UNITS	=	METRIC	
x_{min}	=	-30.	(meters)
x_{max}	=	30.	(meters)
Δx	=	1.0	(meters)

fdData

Format:

UNITS					GPHA	FDC	
A8					E8	E8	

UNITS (1-8) **as in mtLine above.**

GPHA (51-58)

Shunt conductance from the equivalent phase conductors to ground. It is assumed equal for all phases. Default value is 0.2×10^{-9} S.

FDC (59-66)

"Value" of the DC frequency. For numerical reasons, the DC frequency can be a small number but not exactly zero. Default value is 1.0×10^{-15} Hz.

2.3. Conductor Cards

Up to 100 conductors are allowed. For a bundle of *K* conductors, one can either fill in a separate card for each of the *K conductors, or fill in only one card for the entire bundle by specifying "BUNDLE DATA". In either case, the conductor count is K*, and all *K* conductors will be listed individually in the output.

If any of the first six parameters (PHASE NO., SKIN, RESISTANCE, REACTANCE DATA, DIAMETER) are left blank, then the program will set its value equal to that on the preceding conductor card. Example: If the first eight conductors all have the same resistance, it is sufficient to enter the value on the first card only, and to leave the field blank on cards two to eight. If any of the first six parameters has the value zero, then do not leave the field blank but enter the value zero.

2.3.1. Data Description

Format:

1 2 3	4 5 6 7 8	9 10 11 12 13 14 15 16	17 18	19 20 21 22 23 24 25 26	27 28 29 30 31 32 33 34	35 36 37 38 39 40 41	42 43 44 45 46 47 48	49 50 51 52 53 54 55	56 57 58	59 60 61 62 63 64 65 66	67 68 69 70 71 72	73 74 75 76	77 78 79 80
PHASE NO.	SKIN	RESISTANCE (Ohms/km or Ohms/mi)	REACTANCE DATA		DIAMETER (mm or inches)	HORIZONTAL DISTANCE (m or feet)	HEIGHT (m or feet)		BUNDLE DATA			VOLTAGE	
			TYPE	PARAMETER			at tower	at midspan	NUMBER	SPACING (mm or inches)	ALPHA (degrees)	AMPLITUDE (kV, RMS)	ANGLE (degrees)
I3	E5.4	E8.5	I2	E8.5	E8.5	E7.3	E7.3	E7.3	I3	E8.5	E6.2	E4.1	E4.1

PHASE NO. (1-3)

= 1 to *N*

The PHASE NO. defines which phase the conductor belongs to. Phases must be numbered consecutively from 1 to *N* . Examples: A two-pole DC line would have phases 1,2; a double-circuit three-phase line phases 1,2,3 (first circuit) and 4,5,6 (second circuit). Conductors with identical PHASE NO. will be bundled into one equivalent phase conductor if matrices "for the system of equivalent phase conductors" or for symmetrical components are requested, as explained in Section 1.3. This applies to conductors within a bundle, as well as to parallel circuits (for example, the second circuit in the example above is automatically paralleled with the first circuit if PHASE NO. 1,2,3 is used for the second circuit in place of 4,5,6).

= 0

Conductors with PHASE NO. = 0 are treated as ground wires and eliminated if matrices "for the system of equivalent phase conductors" or for symmetrical components are requested, as explained in Section 1.3. If ground wires are to be retained in these matrices, then treat them as extra phases (for example, two ground wires on a double-circuit line with phases 1,2,3,4,5,6 would have PHASE NO. 7,8).

< 0

Conductor is regarded as non-existent. This was used at one time when the program had a change option. It could be used now if one wants to remove conductors (e.g., ground wires) from a file without having to delete the entire file line.

SKIN (4-8)

= 0.0

No skin effect correction of the resistance is requested.

< 0.0

Resistance and internal inductance of stranded conductors will be corrected for skin effect using Galloway's formula (see Appendix D).

> 0.0

Resistance will be corrected for skin effect with the formula for tubular conductors. Set *SKIN = THICKNESS / DIAMETER*, as shown in Fig. 2.1. For solid conductors, this ratio is 0.5.

fdData

Only `SKIN` > 0.0 is valid for the frequency dependent line model. This setting must be used together with `TYPE` = 4 in column 18 of this card.

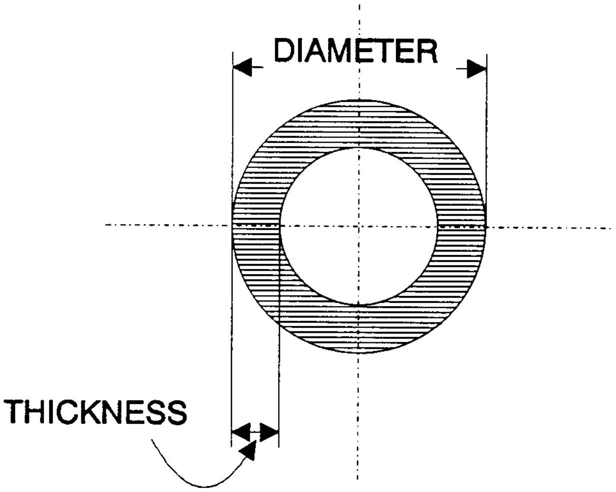


Figure 2.1 Tubular conductor.

At power frequency (but probably not at higher frequencies), stranded conductors can be approximated by a solid conductor of identical cross-section. Steel-reinforced aluminum cables can be represented approximately as tubular conductors, with the steel core ignored, at least at power frequency (but probably not at higher frequencies). This skin effect correction normally assumes that the conductor is nonmagnetic ($\mu_r = 1.0$). The only exception is with TYPE = 4 in REACTANCE DATA, in which case μ_r of the magnetic material will be correctly taken into account in correcting the resistance for skin effect.

RESISTANCE (9-16)

DC conductor resistance (Ω/km or Ω/mile) if resistance is to be corrected for skin effect with SKIN > 0, or AC conductor resistance (Ω/km or Ω/mile) if there is no skin effect correction.

DC resistance (Ω/km or Ω/mile) of one of the outer strands of a stranded conductor if SKIN < 0.

REACTANCE DATA: TYPE/PARAMETER (17-18)/(19-26)

There are four options for reading the data which define the internal reactance of the conductor. Their meaning is explained in Appendix A. The available options are

TYPE

= 0

PARAMETER = reactance at 1 m (or 1 foot) spacing in Ω/km (or Ω/mile). This is regarded as the correct value for whatever frequencies may be defined on the following frequency cards.

= 1

PARAMETER = reactance at 1 m (or 1 foot) spacing at 60 Hz in Ω/km (or Ω/mile). If frequencies other than 60 Hz appear on the frequency cards, then this reactance will be changed proportionally.

= 2

PARAMETER = *GMR* (geometric mean radius) of conductor in millimeters (or inches).

= 3

PARAMETER = ratio *GMR / radius (is* $e^{-1/4}$ for solid, nonmagnetic conductors, at low frequencies, and 1.0 at very high frequencies).

= 4

PARAMETER = relative permeability μ_r. If PARAMETER is less than 1.0, then its value is ignored and $\mu_r = 1.0$ is used instead. The internal reactance is calculated from the geometry of the tubular conductor defined by SKIN. If SKIN is zero, then the program stops with the error message "LAST CONDUCTOR HAS SKIN MISSING. JOB NOT EXECUTED".

= *N*

PARAMETER = relative permeability μ_r. If PARAMETER is less than 1.0, then its value is ignored and $\mu_r = 1.0$ is used instead. For stranded conductors (SKIN < 0.0). *N* = number of outer strands. (See Appendix D.)

fdData

Only `TYPE=4` is accepted by fdData.

DIAMETER (27-34)

Outside diameter of conductor in millimeters (or inches).

HORIZONTAL DISTANCE (35-41)

The horizontal distance of the conductor from the reference point $x = 0$ in meters (or feet), as shown in Fig. 2.2. The reference point $x = 0$ can be anywhere, and all horizontal distances are simply measured from $x = 0$, with a negative value of x to the left of $x = 0$ and a positive value of x to the right of $x = 0$.

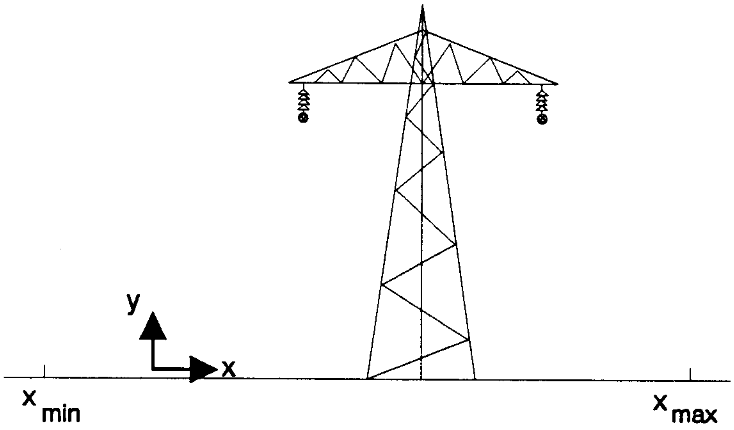


Figure 2.2 Coordinate system for conductor positions.

HEIGHT (42-48) (49-55)

Either specify the height of the conductor at the tower and at midspan in meters (or feet), in which case the average height will be

$$h_{average} = h_{midspan} + \frac{1}{3}(h_{tower} - h_{midspan}), \tag{2.1}$$

or specify the average height in meters (or feet) directly in the first field ("at tower") and leave the second field ("at midspan") blank (not zero!). In the output, only the average height is printed. To obtain worst conditions for the electric field strength at midspan, specify height at midspan in both fields, or in the first field (with blank in second field).

BUNDLE DATA: NUMBER/SPACING/ α (56-72)

Leave this field blank for single conductors.

For bundle conductors (*K* conductors in bundle), there are three input options[4]

(a) Fill in one card for each of the *K* conductors in the bundle, and leave this field blank (time-consuming, but only option available for asymmetrical conductors [9]).

(b) Convert the bundle into a single equivalent conductor with the equations in [4] (pp. 71 and 87), and leave this field blank. This option is time-consuming and can only be used for symmetrical bundles; it is better to use option (c) in this case.

(c) For a symmetrical bundle (*K* conductors all lie on a circle with equidistant spacing, as shown in Fig. 2.3), fill in only one card for the bundle. HORIZONTAL DISTANCE and HEIGHT must specify the location of the center of the bundle, and the parameters NUMBER, SPACING, and α indicated below describe the subconductors arrangement in the bundle.

---

[4] Options (a) and (c) produce identical results. The results from option (b) differ slightly because equal current distribution among the *K* conductors, rather than equal voltages, is assumed in deriving the equations in [4] from Equation (3). In one particular case, the differences appeared only in the fourth significant digit [2] (p. 24).

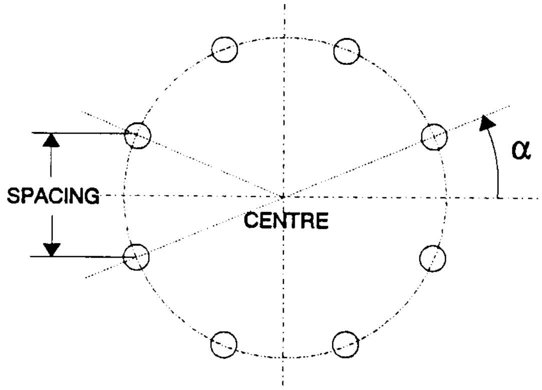


Figure 2.3 Symmetrical bundle.

NUMBER (56-58)

= Number of conductors in a bundle.

SPACING (59-66)

= Spacing between adjacent conductors in mm (or inches).

α (67-72)

= Angular location of first conductor in degrees. Positive angle is measured counter-clockwise from the *x*-axis in Fig. 2.3.

All other parameters on the card refer to the characteristics of the individual conductor within the bundle (for example, the resistance is that of the individual conductor, not of the bundle).

VOLTAGE: AMPLITUDE/ANGLE (73-76)/(77-80)

Root-mean-square phasor value of the voltage between conductor and ground (AMPLITUDE in kV and ANGLE in degrees) if the electric field strength at ground level is to be calculated. A 500 kV three-phase line with phases 1,2,3 could have the following voltages for normal operation:

PHASE	AMPLITUDE	ANGLE
1	288.7	0.
2	288.7	240.
3	288.7 (type as 2887 with format E4.1)	120.

Leave the VOLTAGE field blank if electric field strength calculations are not requested.

fdData

The electric field calculation option is not available in fdData.

2.3.2. Example

A two-pole DC line with twin bundle conductors has the tower configuration of Fig. 2.4 and the following conductor characteristics:

Conductors in bundle:

R = 0.0398 Ω/mile

GMR = 0.7092 inches

DIAMETER = 1.802 inches

SKIN = 0.3871.

Ground wire:

R = 3.1 Ω/mile

reactance at 1 foot spacing = 0.484 Ω/mile at 60 Hz (changed proportionally for other frequencies)

DIAMETER = 0.495 inches

SKIN = 0.5.

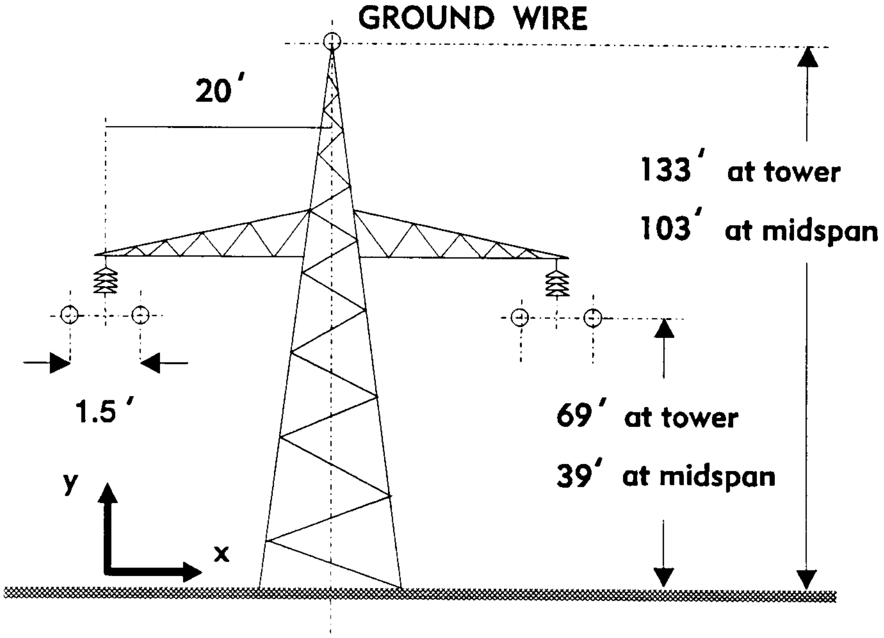


Figure 2.4 Two-pole DC line.

The conductor cards for this example are shown in Fig. 2.5 as EXAMPLE No. 2.

```
*23456789 123456789 123456789 123456789 123456789 123456789 123456789 1233456789

  EXAMPLE NO. 1:

  1      0.0657  1 0.365    1.465   7.75    140.   110.   2  18.
  2      0.0657  1 0.365    1.465   0.75    105.   75.    2  18.
  3      0.0657  1 0.365    1.465   7.75     70.   40.    2  18.
  4      0.0657  1 0.365    1.465  60.      140.   110.
  4      0.0657  1 0.365    1.465  58.5     140.   110.
  5      0.0657  1 0.365    1.465  65.5     105.   75.
  5      0.0657  1 0.365    1.465  67.      105.   75.
  6      0.0657  1 0.365    1.465  58.5     70.    40.
  6      0.0657  1 0.365    1.465  60.      70.    40.
  0      0.588   1 0.484    0.577    2.0    160.  130.
  0      0.588   1 0.484    0.577  65.      160.  130.

  EXAMPLE NO. 2:

  1.3871 .0398   2 .7092   1.802   -0.75   69.    39.
  1.3871    398  2 .7092   1.802     .75   69.    39.
  2.3871 .0398   2 .7092   1.802   40.     49.           2  18.
  0  .5   3.1    1 0.484   .495    20.    133.   103.
```

Figure 2.5 Example of CONDUCTOR cards.

2.4. Frequency Cards

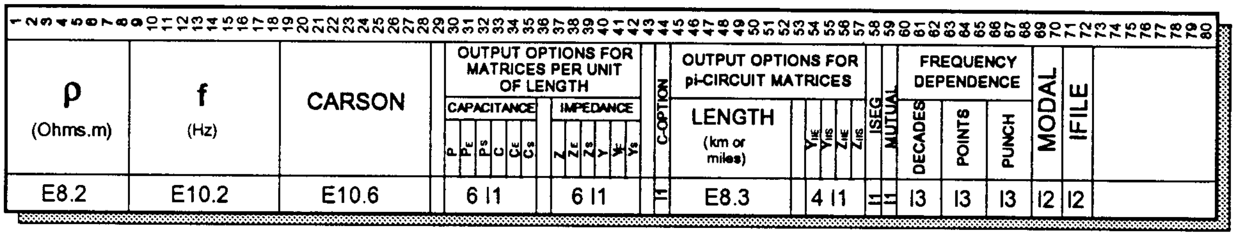
Terminate the `CONDUCTOR` cards with "`&END`" or a "blank card". The `FREQUENCY` card(s) are placed next.

2.4.1. Data Description

mtLine

Any number of frequency cards are allowed. Each frequency card has the form shown below.

Format:



ρ (Ohms.m)	f (Hz)	CARSON		OUTPUT OPTIONS FOR MATRICES PER UNIT OF LENGTH			C-OPTION	OUTPUT OPTIONS FOR pi-CIRCUIT MATRICES			ISEG	MUTUAL	FREQUENCY DEPENDENCE			MODAL	IFILE	
				CAPACITANCE P P_E P_S C C_E C_S		IMPEDANCE Z Z_E Z_S Y Y_E Y_S		LENGTH (km or miles)		Y_{IE} Y_{IS} Z_{IE} Z_{IS}			DECADES	POINTS	PUNCH			
E8.2	E10.2	E10.6		6 I1		6 I1	I1	E8.3		4 I1	I1	I1	I3	I3	I3	I2	I2	

ρ (1-8)

Earth resistivity in Ω·m.

f (9-18)

Frequency in Hz. If DC parameters are required, use a very low frequency (e.g., 10^{-6} Hz), because the program will not accept zero.

CARSON (19-28)

Parameter which controls the number of terms in Carson's infinite series for the earth return impedance (see Appendix B).

= blank

If the field is left blank, then for $a \leq 5$, the infinite series in Eq. B.2 is evaluated with the highest possible accuracy (terms being added until the absolute values of two successive terms inside the braces { } of Eq. B.2 become less than or equal to 10^{-6}). For $a \geq 5$, Eq. B.4 is used. This option should normally be chosen.

= 0.0

No correction terms are added ($\Delta R = 0$ and $\Delta X = 0$, which implies zero earth resistivity).

≥ 1.0

For $a \leq 5$, as many correction terms are used in Eq. B.2 as specified by this value (rounded to nearest integer), but not more than 31. For $a \geq 5$, Eq. B.4 is used.

> 0.0 and < 1.0

For $a \leq 5$, correction terms are being added until the absolute values of two successive terms inside the braces { } of Eq. B.2 become smaller than the value of this parameter. If the value of this parameter is greater than zero but less than 10^{-6}, then it is internally reset to 10^{-6}.

< 0.0

Formula by Gary, Deri et al is used to account for earth return effects (see Appendix E). Use any value less than zero.

P (30)

= 1

$[C]^{-1}$ or $[\omega C]^{-1}$ for the system of physical conductors will be printed. $[C]^{-1}$ is the potential coefficient matrix $[P]$ in Eq. 1.6.

= 0 or blank

No output of this matrix.

P_E (31)

= 1

$[C_E]^{-1}$ or $[\omega C_E]^{-1}$ for the system of equivalent phase conductors will be printed. $[C_E]^{-1}$ is the inverse of the matrix in Eq. 1.8.

= 0 or blank

No output of this matrix.

P_S (32)

= 1

$[C_S]^{-1}$ or $[\omega C_S]^{-1}$ for the symmetrical components of the equivalent phase conductors will be printed.

= 0 or blank

No output of this matrix.

C (33)

= 1

$[C]$ or $[\omega C]$ for the system of physical conductors will be printed. $[C]$ is the matrix in Eq. 1.7.

= 0 or blank

No output of this matrix.

C_E (34)

= 1

$[C_E]$ or $[\omega C_E]$ for the system of equivalent phase conductors will be printed. $[C_E]$ is the matrix in Eq. 1.8.

= 0 or blank

No output of this matrix.

C_S (35)

= 1

[C_S] or [ωC_S] for the symmetrical components of the equivalent phase conductors will be printed.

= 0 or blank

No output of this matrix.

If $C_S = 1$ as well as $Z_S = 1$, the program will also print surge impedance, attenuation, velocity, wavelength, R, X, and ωC for zero and positive sequence of a three-phase circuit (or of the first three-phase circuit if there are more), and of a two-phase circuit (definition in Section 3.1.1).

Z (37)

= 1

[Z] for the system of physical conductors will be printed. This is the matrix in Eq. 1.3.

= 0 or blank

No output of this matrix.

Z_E (38)

= 1

[Z_E] for the system of equivalent phase conductors will be printed. This is the matrix in Eq. 1.9.

= 0 or blank

No output of this matrix.

Z_S (39)

= 1

[Z_S] for the symmetrical components of the equivalent phase conductors will be printed. This is the matrix in Eq. 1.10.

= 0 or blank

No output of this matrix.

Y (40)

= 1

$[Z]^{-1}$ for the system of physical conductors will be printed. This is the inverse of the matrix in Eq. 1.3.

= 0 or blank

No output of this matrix.

Y_E (41)

= 1

$[Z_E]^{-1}$ for the system of equivalent phase conductors will be printed. This is the inverse of the matrix in Eq. 1.9.

= 0 or blank

No output of this matrix.

Y_S (42)

= 1

$[Z_S]^{-1}$ for the symmetrical components of the equivalent phase conductors will be printed. This is the inverse of the matrix in Eq. 1.10.

= 0 or blank

No output of this matrix.

C-OPTION (44)

= 0 or blank

All matrices requested with P, P_E, P_S, C, C_E, C_S will be susceptance matrices $[\omega C]$ or their inverses.

= 1

All matrices requested with P, P_E, P_S, C, C_E, C_S will be capacitance matrices $[\,C\,]$ or their inverses.

LENGTH (45-52)

Line length (km or miles). If LENGTH > 0, an equivalent multiphase π-circuit will be developed for the system of equivalent phase conductors or their symmetrical components with "long line formulas" as described in Section 1.6. An approximate nominal multiphase π-circuit ($[Z_{transfer}] = l \cdot [Z]$ and $[Y_{transfer}] = l \cdot [Y]$) is obtained if the length is specified with a negative sign (e.g., -200.0 instead of 200.0).

$Y_{\pi E}$ (54)

= 1

$[Y_{transfer\_E}]$ ($= [Z_{transfer\_E}]^{-1}$) and $[Y_{shunt\_E}]$ of the multiphase π–circuit for the system of equivalent phase conductors will be printed.

= 0 or blank

No output of these matrices.

$Y_{\pi S}$ (55)

= 1

Same as $Y_{\pi E}$, except that the matrices are transformed to symmetrical components.

= 0 or blank

No output of these matrices.

$Z_{\pi E}$ (56)

= 1

$[Z_{transfer\_E}]$ and $[Z_{shunt\_E}]$ ($= [Y_{shunt\_E}]^{-1}$) of the multiphase π-circuit for the system of equivalent phase conductors will be printed.

= 0 or blank

No output of these matrices.

$Z_{\pi S}$ (57)

= 1

Same as $Z_{\pi\ell}$ = 1, except that the matrices are transformed to symmetrical components.

= 0 or blank

No output of these matrices.

ISEG (58)

Option for ground wire segmentation.

= 0 or blank

Ground wires are continuous and connected to ground at such short intervals that continuous grounding can be assumed. For typical tower spacings of 250 to 300 m, this assumption produces acceptable answers up to about 250 kHz [11].

= 1

Ground wires are "segmented" (interrupted and insulated at certain intervals as shown in Fig. 2.5).

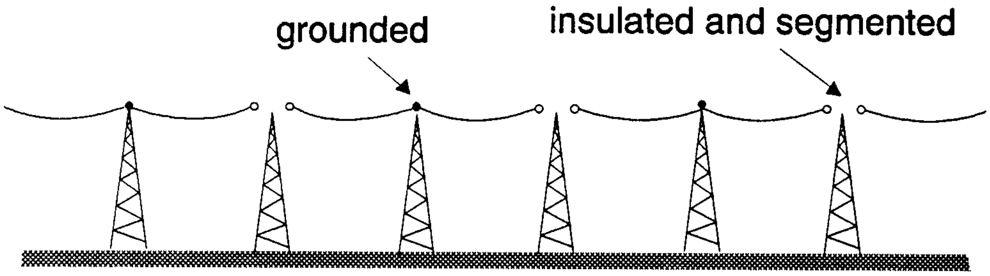


Figure 2.6 Segmented ground wires.

Ground wires are segmented to avoid the losses produced by currents circulating through the loops formed by the ground wire, ground, and two adjacent towers. They act as electrostatic shields for lightning protection, and are therefore included in the capacitance calculations. They are ignored in calculating the impedance matrix for the system of equivalent phase conductors or for their symmetrical components because they carry no current.

MUTUAL (59)

= 1

The mutual impedances from the equivalent phase conductors 1, ..., $N-1$ to the Nth last equivalent phase conductor will be printed, as well as [Z_E]. This is useful for studying interference in communication lines, where the Nth equivalent phase conductor must represent the communication line (any type of conductor can be used for it because the conductor type has no influence on mutual impedances). The longitudinally induced voltage in the Nth equivalent phase conductor is then

$$-\frac{dV_N}{dx} = Z_{N1}I_1 + Z_{N2}I_2 + \cdots + Z_{N,N-1}I_{N-1}. \tag{2.2}$$

In addition, it is assumed that equivalent phase conductors 1,2,3 belong to three-phase circuit I; 4,5,6 to three-phase circuit II, etc. The mutual impedances are then also given for currents expressed in symmetrical components, or

$$\begin{aligned} -\frac{dV_N}{dx} &= Z_{zeroI}I_{zeroI} + Z_{posI}I_{posI} + Z_{negI}I_{negI} \\ &+ Z_{zeroII}I_{zeroII} + Z_{posII}I_{posII} + Z_{negII}I_{negII} \\ &+ \ldots, \end{aligned} \tag{2.3}$$

with I_{zeroI}, I_{posI}, I_{negI} being the zero, positive, negative sequence currents of circuit I, etc. The symmetrical components are unnormalized,

$$\begin{bmatrix} I_{zero} \\ I_{pos} \\ I_{neg} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}, \text{ with } a = e^{j120^\circ}. \tag{2.4}$$

(For normalized symmetrical components, the factor in Eq. 2.26 would be $1/\sqrt{3}$ instead of $1/3$.)

TABLE OF SEQUENCE PARAMETERS: DECADES/POINTS/PUNCH (60-68)

Leave this field blank unless zero and positive sequence parameters are requested as a function of frequency. If requested, the program will calculate the values at 10^{-6} Hz (to approximate DC) and at equidistant points on a logarithmic scale starting from f_{min}, as shown in Fig. 2.6. Specify f_{min} in columns 9-18; columns 30-57, 59, and 69-70 are ignored. The parameters DECADES, POINTS, and PUNCH have the meaning indicated below.

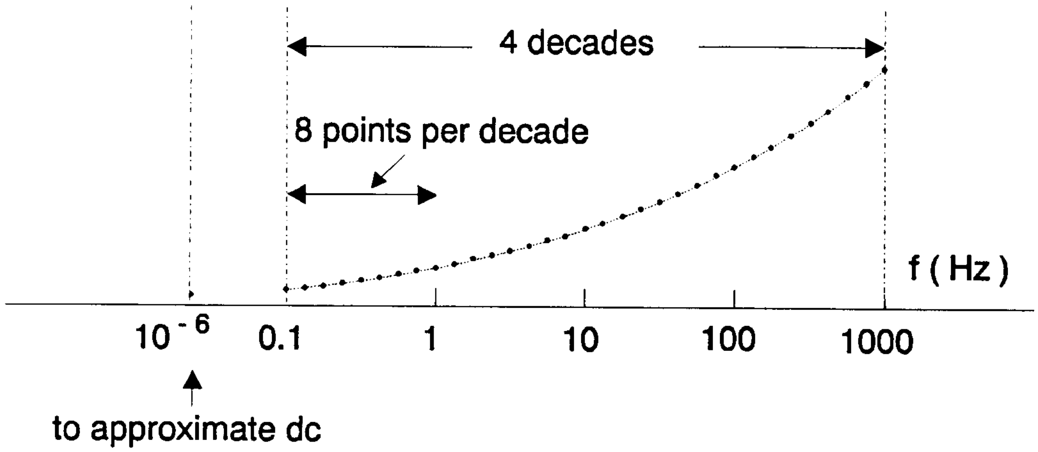


Figure 2.7 Frequency-scan of line parameters.

DECADES (60-62)

= number of decades on the logarithmic frequency scale.

POINTS (63-65)

= number of equidistant points on the logarithmic frequency scale per decade.

PUNCH (66-68)

= 0 or blank

if results are to be printed in the form of attenuation constant α (Np/km or Np/mile), phase constant β (rad/km or rad/mile), R (Ω/km or Ω/mile), L (mH/km or mH/mile), and C (μF/km or μF/mile) for zero and positive sequence as a function of frequency.

= 1

if in addition to printing, α_{zero}, β_{zero}, α_{pos}, β_{pos}, f(Hz) are to be written in a separate file (*punch file*) with the format 5E15.5.

MODAL (69-70)

= 0 or blank

No output of modal parameters.

= ±1

Modal parameters will be printed (R, X, ωC, characteristic impedance, wave velocity, and attenuation for each mode, as well as $[\ T_i\ ]$ of Eq. 1.14). With MODAL = -1, the resistances are set to zero before modal parameters are calculated[5].

= ±2

Modal parameters will be printed for the lossless high-frequency approximation. This approximation is often used in lightning surge studies. It implies that all modes travel with the speed of light, and the surge impedances in phase quantities become $Z_{ii} = 60 \ln(2h_i/r_i)$ and $Z_{ik} = 60 \ln(D_{ik}/d_{ik})$ (more accurately, $2 \cdot 10^{-4} \cdot c$ in place of 60, with c = speed of light in km/s).

= ±3

Modal parameters for the normal case as well as for the lossless high-frequency case will be printed. With MODAL = -3, the resistances are set to zero before modal parameters are calculated. (See footnote.)

IFILE (71-72)

= 0 or blank

No output of nominal π-circuit data to the *punch* file.

≥ 1

Nominal π-circuit data (LENGTH with a negative sign) is written into the *punch* file in a form in which it can be used directly by Microtran's Transients Analysis Program. If this option is used, the frequency card must be followed by *exactly M cards* (M = number of phases) with the pair of node names (FORMAT 2A6), as shown below. Typically, there would be more such requests behind each other to produce transposition scheme. The units for L and C are controlled by the value of IFILE:

---

[5] This produces another lossless approximation which differs from the one obtained with MODAL ±2 (for example, wave velocity in the zero sequence mode will be less than that in the aerial modes).

IFILE = 1: L in mH, C in μF
2: L in mH, ωC in μS
3: X in Ω, C in μF
4: X in Ω, ωC in μS

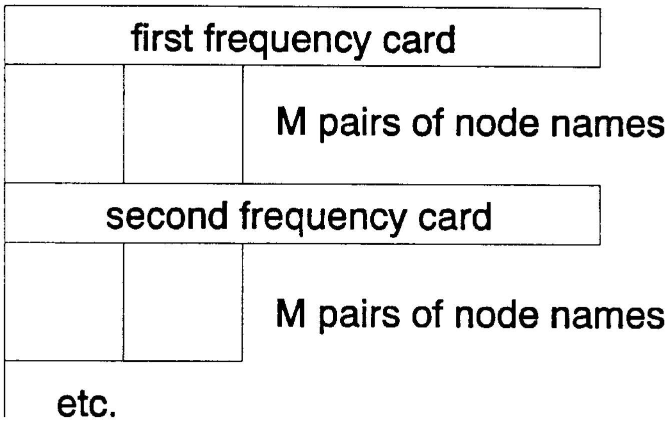


Figure 2.8 FREQUENCY cards for nominal π-circuits.

2.4.2. Example

Example for the case with $\rho = 100\ \Omega\cdot\text{m}$, $f = 60$ Hz and highest accuracy in Carson's series, for which the following output is requested: [C_E] and [Z_E] per unit length, admittance matrices in phase quantities for the equivalent π-circuit of a 200-mile untransposed line, and modal parameters.

```
*23456789 123456789 123456789 123456789 123456789 123456789 123456789 1233456789
  100.    60.                    1   1     1   200.  1               1
```

Figure 2.9 Example of FREQUENCY card.

fdData

Format:

ρ (Ohms.m)	FMATRIX (Hz)		LENGTH (km or miles)		ISEG			
E8.2	E10.2		E8.3		I1			

ρ (1-8)

Earth resistivity in Ω·m. Same meaning as in mtLine.

FMATRIX (9-18)

Frequency in Hz at which the modal transformation matrix Q for the line currents is evaluated. The default value is 1.2 kHz.

LENGTH (45-52)

Length of the line in km for `METRIC` units or in miles for `BRITISH` units, according to `UNITS` card.

ISEG (58)

Ground wire segmentation. Same meaning as in mtLine.

= 0	Ground wires are not segmented.
= 1	Ground wires are segmented.

2.5. fdData .Keyword Cards

fdData

`.KEYWORD` cards are inserted after the `FREQUENCY` card in the fdData input file. They can be placed in any sequence. These cards are optional and provide more detailed control over the synthesis of the frequency dependent line model and of some output listing options. In general, fdData's defaults cover most simulation needs and, other than the `.NODES` option to name the line nodes, the `other` `.KEYWORD` options may normally be omitted.

`.KEYWORD` cards are identified by a dot in column one followed by the option name in upper or lower case (e.g., "`.nodes`" or "`.NODES`"). The parameters and flags that follow the keyword start on column 20 and follow FORTRAN format notation. Most integer control flags are enabled with +1, and disabled with -1. A blank or zero field implies that internal defaults are used.

The following `.KEYWORD` cards are supported:

2.5.1. .NODES

This option assigns pairs of node names to the terminals of an FDL line. fdData produces a line model file with the appropriate card images ready to be merged with MT. If the `.NODES` card is not specified, dummy node names are assigned internally. If not enough node names are supplied, the program supplies the remaining node names internally. Node names are six characters long and are specified in sending_end receiving_end pairs, starting at columns 20, 30, 40, 50, 60, and 70, with three pairs per card. Additional cards are added, as needed.

Format:

```
*23456789 123456789 123456789 123456789 123456789 123456789 123456789 1233456789
*                  –A6–    –A6–    –A6–    –A6–    –A6–    –A6–
.NODES             send-a    recv-a    send-b    recv-b    send-c    recv-c
                   send-d    recv-d    send-e    recv-e    ...
```

2.5.2. .CTLFIT

This keyword overrides default fitting control parameters.

Format:

Example:

```
*23456789 123456789 123456789 123456789 123456789 123456789 123456789 1233456789
*                  I2I2I2I2
.CTLFIT            25-1-1 0
*                  ^^^^^^^^___ iall   (default=0)
*                   | | |_____ ixdyn  (default=1)
*                   | |_______ iquick (default=1)
*                   |_________ normax (default=25)
```

Flags:

NORMAX (20-21)

Maximum number of poles allowed in the approximation of the characteristic admittance and propagation functions. If flag `IXDYN` (see below) is not zero, then the maximum number of poles permitted in the approximation of the propagation function will be `NORMAX` × 1.25. Default value is 25.

IQUICK (22-23)

Flags a faster, though somewhat less accurate approximation process. Type +1 for yes, or -1 for no. Default value is -1 (no).

IXDYN (24-25)

Add extra poles to the approximation of the low frequency region of the propagation function. Type +1 for yes, or -1 for no. Default value is +1 (yes).

IALL (26-27)

Indicates if the user is to be prompted to decide which function is to be approximated.

IALL = 0 means that all functions (characteristic admittance and propagation functions) will be approximated without prompting.

IALL = 1 means that the user will be prompted before any approximation begins. This option is a time saver when for some reason one approximation could not be completed successfully and it must be repeated without going through the entire approximation process. For example, when NORMAX is sufficient for all but one of the functions to be approximated.

2.5.3. .DBGFIT

This flag enables the flag `IDEBUG`, which in turn, controls the amount of intermediate debugging output printed by the program.

Format:

Example:

```
*23456789 123456789 123456789 123456789 123456789 123456789 123456789 1233456789
*                  I2
.dbgfit             1
*                  ^^___ idebug (default=0)
```

Flags:

IDEBUG (20-21)

Controls the amount of debugging output printed by the program. Value can be 0, 1, 2, or 3. The higher the number, the more debugging output is produced. Default value is 0.

2.5.4. .OUTFIT

This flag controls the amount of standard output printed by the program.

Format:

Example:

```
*23456789 123456789 123456789 123456789 123456789 123456789 123456789 1233456789
*                  I2I2
.outfit            -1-1
*                  ^^^^___ iplotf (default=+1)
*                   !_____ icompf (default=+1)
```

Flags:

ICOMPF (20-21)

Controls the printing of a comparison table between the exact parameters calculated from the line configuration and the approximation generated by fdData. Type +1 for yes, or -1 for no. Default value is +1 (yes).

IPLOTF (22-23)

Controls the output of a printer plot comparing the exact parameters calculated from the line configuration and the approximation generated by fdData. Type +1 for yes, or -1 for no. Default value is +1 (yes).

2.6. Sample Fddata Input File

The frames below show examples of input files for fdData for double circuit 3ϕ transmission line. The first frame shown a normal case where all defaults are accepted: no parameters in the `LINE-MODEL` card and no optional `.keyword` cards. The second frame shows the same transmission line but with specifications overriding the default parameters.

```
*  fdData Driver for FDL Line Model
Case Example 1: INPUT DATA FILE WITH DEFAULT OPTIONS
*  Microtran Power System Analysis Corp., June 1992
* ...............................................................................
Line-Model
* ...............................................................................
* BPA'S 500 KV, 174-MILE, COULEE-RAVER DOUBLE CIRCUIT LINE
* ...............................................................................
BRITISH
  1.3636 .05215  4         1.602  -17.188  49.06  49.06
  1.3636 .05215  4         1.602  -18.25   48.0   48.0
  1.3636 .05215  4         1.602  -19.313  49.06  49.06
  2.3636 .05215  4         1.602  -27.188  85.06  85.06
  2.3636 .05215  4         1.602  -28.25   84.0   84.0
  2.3636 .05215  4         1.602  -29.313  85.06  85.06
  3.3636 .05215  4         1.602  -17.188 121.06 121.06
  3.3636 .05215  4         1.602  -18.25  120.0  120.0
  3.3636 .05215  4         1.602  -19.313 121.06 121.06
  4.3636 .05215  4         1.602   17.188 121.06 121.06
  4.3636 .05215  4         1.602   18.25  120.0  120.0
  4.3636 .05215  4         1.602   19.313 121.06 121.06
  5.3636 .05215  4         1.602   27.188  85.06  85.06
  5.3636 .05215  4         1.602   28.25   84.0   84.0
  5.3636 .05215  4         1.602   29.313  85.06  85.06
  6.3636 .05215  4         1.602   17.188  49.06  49.06
  6.3636 .05215  4         1.602   18.25   48.0   48.0
  6.3636 .05215  4         1.602   19.313  49.06  49.06
  0.5    2.61    4          .386  -9.0    163.96 163.96
  0.5    2.61    4          .386   9.0    163.96 163.96
&end
*  FREQUENCY CARD
*   rho                                      length   iseg
    100.                                      174.    1
```

Figure 2.10 Example of fdData data case. Usual case with all default options.

```
*  fdData Driver for FDL Line Model
Case Example 2: INPUT DATA FILE WITH NON-DEFAULT VALUES
*  Microtran Power System Analysis Corp., June 1992
* ..........................................................................
Line-Model                    QREAL              0.1              10        10
* ..........................................................................
* BPA'S 500 KV, 174-MILE, COULEE-RAVER DOUBLE CIRCUIT LINE
* ..........................................................................
BRITISH
  1.3636 .05215  4         1.602  -17.188  49.06  49.06
  1.3636 .05215  4         1.602  -18.25   48.0   48.0
  1.3636 .05215  4         1.602  -19.313  49.06  49.06
  2.3636 .05215  4         1.602  -27.188  85.06  85.06
  2.3636 .05215  4         1.602  -28.25   84.0   84.0
  2.3636 .05215  4         1.602  -29.313  85.06  85.06
  3.3636 .05215  4         1.602  -17.188 121.06 121.06
  3.3636 .05215  4         1.602  -18.25  120.0  120.0
  3.3636 .05215  4         1.602  -19.313 121.06 121.06
  4.3636 .05215  4         1.602   17.188 121.06 121.06
  4.3636 .05215  4         1.602   18.25  120.0  120.0
  4.3636 .05215  4         1.602   19.313 121.06 121.06
  5.3636 .05215  4         1.602   27.188  85.06  85.06
  5.3636 .05215  4         1.602   28.25   84.0   84.0
  5.3636 .05215  4         1.602   29.313  85.06  85.06
  6.3636 .05215  4         1.602   17.188  49.06  49.06
  6.3636 .05215  4         1.602   18.25   48.0   48.0
  6.3636 .05215  4         1.602   19.313  49.06  49.06
  0.5    2.61    4          .386  -9.0    163.96 163.96
  0.5    2.61    4          .386   9.0    163.96 163.96
&end
*  FREQUENCY CARD
*    rho                                    length   iseg
    100.                                     174.    1
.nodes             k-a       m-a       k-b       m-b       k-c       m-c
                   k-d       m-d       k-e       m-e       k-f       m-f
.ctlfit            15-1-1 1
.outfit            -1 1
.dbgfit             0
```

Figure 2.11   Example of fdData data case. Overriding of default options.

3. Description of the Output

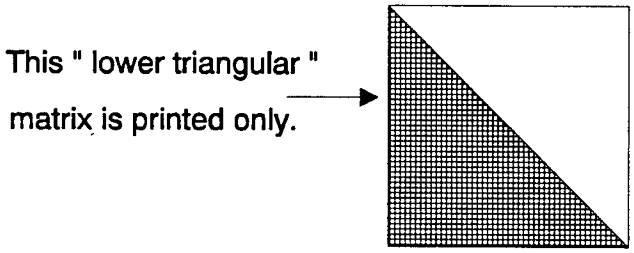
The output should be more or less self-explanatory. Additional remarks have been written into the attached sample output sheets (see Appendix C).

3.1. Listing of Conductor Characteristics

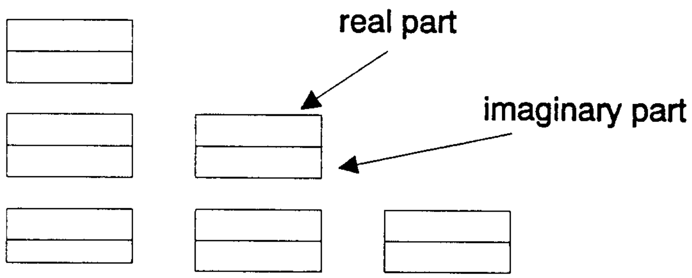
The information contained on the conductor cards of the input data deck is printed for the record more or less in its original form, with the following exceptions: (1) In place of height at tower and midspan, the average height is listed as *y*-coordinate. (2) The order of the conductor cards in the input data deck is arbitrary, while the order in the listing will always be as follows: conductors first encountered with phase numbers 1, 2, 3,..., followed by conductors with already existing phase numbers (= 2nd, 3rd, 4th,... conductors in bundles or parallel circuits), followed by ground wires (phase number = 0). (3) While a single conductor card may specify *M* conductors with the BUNDLE DATA option, all *M* conductors will be listed separately in the output.

3.1.1. Line Parameters

Since all matrices are symmetric, only values in and below the diagonal are printed, as indicated below.



All matrices, except the susceptance (or capacitance) matrices for the system of physical conductors and for the system of equivalent phase conductors, are complex. Real and imaginary parts are printed above each other, as indicated below.



Impedances

The matrix elements of the impedance matrices per kilometer or mile are defined as follows:

$Z_{i,k}$ = mutual impedance between *i* and *k*,

$Z_{i,i}$ = self impedance of *i*, with current returning through ground (and through ground wires if there are any and if they have been eliminated).

Capacitances

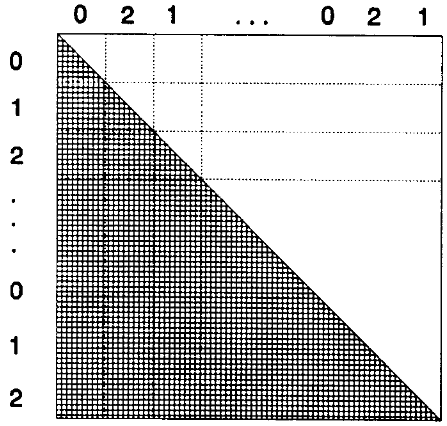
The matrix elements of the susceptance (or capacitance) matrices per kilometer or mile are defined as follows:

$\omega C_{i,k}$ = *negative* value of susceptance between *i* and *k*,

$\omega C_{i,i}$ = sum of all susceptances from *i* to all other conductors and to ground.

Symmetrical Components

Note that the matrices for symmetrical components have their rows ordered in the sequence "zero (0), positive (1), negative (2) of first three-phase circuit, (0), (1), (2) of second three-phase circuit, etc.", whereas the columns have (1) and (2) exchanged and are thus ordered "(0), (2), (1) of first circuit, (0), (2), (1) of second circuit, etc.". This trick makes these matrices symmetrical again, as indicated below.



From this modified row and column numbering, it follows that

$Z_{1,1} = Z_{2,2}$ within any three-phase circuit,
$Z_{1,0} = Z_{0,2}$ within any three-phase circuit,
etc.,
but $Z_{1,0} \neq Z_{0,1}$, etc.

If there are only two equivalent phase conductors, a two-pole DC line is assumed. In this case, zero sequence refers to the operation where equal currents go into both poles and return through ground (and through ground wires if they exist and were eliminated), and positive sequence refers to the operation where the current goes into one pole and returns through the other [2] (p. 35). For three or more equivalent phase conductors, only three-phase circuits are assumed, with numbers 1,2,3 forming the first circuit, numbers 4,5,6 forming the next circuit, etc. If the number of phases were seven or eight, the last one or two phases would simply be ignored. If the number were nine, then three three-phase circuits would be assumed. The transformation to symmetrical components for each three-phase circuit is defined by Eq. 2.25.

4. Error Messages

4.1. Fatal Error Messages

The following messages indicate fatal errors in the input data or potential overflow of tables. In each case, program execution will be terminated and no more input cards will be read from the data deck of this case or of any following cases.

(a) `NO CONDUCTOR FOR EQUIV. PHASE NO. _. JOB NOT EXECUTED.`

If numbering of phases is not consecutive (Example: Sequence 1,2,3,5,6 has number 4 missing).

(b) `MORE THAN 100 CONDUCTORS. JOB NOT EXECUTED.`

If case contains more than 100 conductors.

(c) `LAST CONDUCTOR IDENTICAL WITH _TH CONDUCTOR OF SORTED INPUT. JOB NOT EXECUTED.`

If two conductors appear in an identical geometric location.

(d) `LAST CONDUCTOR HAS SKIN MISSING. JOB NOT EXECUTED.`

If the internal reactance is to be calculated from the geometry of the tubular conductor, as requested with `TYPE` = 4, then `SKIN` must be specified.

(e) `"UNITS" IS UNDEFINED. JOB NOT EXECUTED.`

If `UNITS` is not equal to either `METRIC` or `BRITISH`.

(f) `ELECTRIC FIELD STRENGTH CANNOT BE CALCULATED AT MORE THAN 2525 POINTS. JOB NOT EXECUTED.`

If the electric field strength is to be calculated at more than 2525 points. Check x_{min}, x_{max}, and Δx.

4.2. Non-Fatal Error Messages

The following error messages stop only execution of the particular case, but proceed to the next DATA DECK of the following case.

(a) `MATRICES FOR LINE LENGTH = _ MILES (KM). CANNOT BE CALCULATED WITH NUMBER OF EQUIVALENT CONDUCTORS = _.`

If equivalent or nominal multiphase π-circuits are requested for cases which have more than 50 equivalent phase conductors or none at all.

(b)

```
MATRICES FOR LINE LENGTH = _ MILES (KM). CANNOT BE CAL-
CULATED WITH NUMBER OF NECESSARY SECTIONS = 2**33.
```

If 2^{33} or more nominal π-circuits have to be connected in cascade to get an equivalent π–circuit for the specified length (means 33 or more doublings).

5. Appendix A: Geometric Mean Radius and Internal Impedance

Equation 1.1 uses the geometric mean radius *GMR* instead of the actual radius *r* to account for the contribution which the internal inductance makes to the total inductance. Originally, the total inductance for perfectly conducting earth ($\rho = 0$ or $\Delta X_{ii} = 0$) is defined as

$$L_{(\rho=0)} = 2 \cdot 10^{-4} \ln \frac{r}{GMR} + 2 \cdot 10^{-4} \ln \frac{2h-r}{r} \quad \text{in H/km,} \tag{A.1}$$

where the first term represents the internal inductance and the second term the external inductance.

Since $r \ll 2h$, $2h - r$ is normally replaced by $2h$ in the second term, then

$$L_{(\rho=0)} = 2 \cdot 10^{-4} \ln \frac{2h}{GMR}, \tag{A.2}$$

as used in Eq. 1.1.

The geometric mean radius *GMR* is a function of

- conductor type,
- relative permeability μ_r for magnetic conductors, and
- frequency ($GMR = r$) at very high frequencies where all current flows on the surface).

It can be calculated for all types of conductors if skin effect is negligible [6]. Often, it can be looked up in tables. North American books frequently give the reactance at one foot spacing X_A, which is related to *GMR* by

$$X_A = 2\omega \cdot 10^{-4} \ln \frac{1}{GMR} \quad \text{in } \Omega\text{/km,} \tag{A.3}$$

with *GMR* in feet (or in meters if X_A is reactance at one meter spacing). The concept of geometric mean radius was originally developed for nonmagnetic conductors at frequencies which are low enough to ignore skin effect. In that case, its meaning is purely geometric, namely, geometric mean distance among all points on the conductor cross section area, e.g., $GMR/r = e^{-1/4}$ for solid, round, nonmagnetic conductors. Nowadays, it is just used as a number to account for the internal inductance part for all types of conductors, and loses its geometric meaning; still calling it "geometric mean radius" is, therefore, questionable.

If skin effect on the internal inductance is to be taken into account, and if formulas for it can be found for the specific type of conductor, then it is not *GMR* but the internal reactance $\omega L'_{internal}$ which one obtains [7,8]. If *GMR* is retained, then it can be found from the internal reactance,

$$\frac{GMR}{r} = e^{-(\omega L'_{internal}/2\omega \cdot 10^{-4})}, \tag{A.4}$$

with $\omega L'_{internal}$ in Ω/km. With increasing frequency, the internal inductance decreases and eventually becomes negligible. Since the internal inductance is only a small part of the total inductance, the skin effect on the total inductance is so small that it is practically not noticeable.

6. Appendix B: Carson's Correction Terms

Carson's correction terms ΔR and ΔX in Eqs. 1.1 and 1.2 account for the earth return effect and are functions of the angle ϕ ($\phi = 0$ for self impedance, $\phi = \phi_{ik}$ in Fig. 1.2 for mutual impedance), and of the parameter a:

$$a = 4\pi\sqrt{5} \cdot 10^{-4} \cdot D \cdot \sqrt{\frac{f}{\rho}}, \tag{B.1}$$

with $D = 2h_i$ in meters for self impedance,
$\quad\;\; = D_{ik}$ in meters for mutual impedance,
$\rho =$ earth resistivity in Ω·m.

ΔR and ΔX become zero for $a \rightarrow \infty$ (very low earth resistivity). Carson gives an infinite integral for ΔR and ΔX, which he developed into the sum of four infinite series for $a \leq 5$ [3]. Rearranged for easier programming, it can be written as one series,

$$\begin{aligned}\Delta R = 4\omega 10^{-4}\Big\{ & \frac{\pi}{8} \\ & -b_1 a\cos\phi \\ & +b_2\left[(c_2 - \ln a)a^2\cos 2\phi + \phi a^2 \sin 2\phi\right] \\ & +b_3 a^3 \cos 3\phi \\ & -d_4 a^4 \cos 4\phi \\ & -b_5 a^5 \cos 5\phi \\ & +b_6\left[(c_6 - \ln a)a^6 \cos 6\phi + \phi a^6 \sin 6\phi]\right] \\ & +b_7 a^7 \cos 7\phi \\ & -d_8 a^8 \cos 8\phi \\ & -\ldots \Big\} \text{ in } \Omega/\text{km}.\end{aligned}$$

$$\begin{aligned}\Delta X = 4\omega 10^{-4}\Big\{ & \frac{1}{2}(0.6159315 - \ln a) \\ & +b_1 a\cos\phi \\ & -d_2 a^2 \cos 2\phi \\ & +b_3 a^3 \cos 3\phi \\ & -b_4\left[(c_4 - \ln a)a^4 \cos 4\phi + \phi a^4 \sin 4\phi\right] \\ & +b_5 a^5 \cos 5\phi \\ & -d_6 a^6 \cos 6\phi \\ & +b_7 a^7 \cos 7\phi \\ & -b_8\left[(c_8 - \ln a)a^8 \cos 8\phi + \phi a^8 \sin 8\phi\right] \\ & +\ldots \Big\} \text{ in } \Omega/\text{km}.\end{aligned} \tag{B.2}$$

Each four successive terms form a repetitive pattern. The coefficients b_i, c_i, and d_i are constants which can be precalculated and stored in lists. They are obtained from the recursive formulas:

$$b_i = b_{i-2}\frac{\text{sign}}{i(i+2)}, \tag{B.3}$$

with the starting value $b_1 = \sqrt{2}/6$ for odd subscripts and $b_2 = 1/16$ for even subscripts;

$$c_i = c_{i-2} + \frac{1}{i} + \frac{1}{i+2},$$

with the starting value $c_2 = 1.3659315$;

$$d_i = \frac{\pi}{4} b_i,$$

with sign = ±1 changing after each four successive terms (sign = +1 for $i = 1, 2, 3, 4$; sign = -1 for $i = 5, 6, 7, 8$, etc.).

For $a > 5$, the following finite series [10] is used:

$$\Delta R = \left(\frac{\cos\phi}{a} - \frac{\sqrt{2}\cos 2\phi}{a^2} + \frac{\cos 3\phi}{a^3} + \frac{3\cos 5\phi}{a^5} - \frac{45\cos 7\phi}{a^7} \right) \cdot \frac{4\omega 10^{-4}}{\sqrt{2}} \quad \text{in } \Omega/\text{km}, \qquad \text{(B.4a)}$$

$$\Delta X = \left(\frac{\cos\phi}{a} \qquad - \frac{\cos 3\phi}{a^3} + \frac{3\cos 5\phi}{a^5} + \frac{45\cos 7\phi}{a^7} \right) \cdot \frac{4\omega 10^{-4}}{\sqrt{2}} \quad \text{in } \Omega/\text{km}. \qquad \text{(B.4b)}$$

The trigonometric functions are calculated directly from the geometry,

$$\cos\phi_{ik} = \frac{h_i + h_k}{D_{ik}} \quad \text{and} \quad \sin\phi_{ik} = \frac{x_{ik}}{D_{ik}},$$

and for higher terms in the series form the recursive formulas

$$a^i \cos i\phi = \left[a^{i-1}\cos(i-1)\phi \cdot \cos\phi - a^{i-1}\sin(i-1)\phi \cdot \sin\phi \right] \cdot a \qquad \text{(B.5a)}$$

$$a^i \sin i\phi = \left[a^{i-1}\cos(i-1)\phi \cdot \sin\phi + a^{i-1}\sin(i-1)\phi \cdot \cos\phi \right] \cdot a. \qquad \text{(B.5b)}$$

For power circuits at power frequency, only few terms are needed in the infinite series of Eq. B.2. However, at higher frequencies and for wider spacings (for example, in interference calculations), more and more terms must be taken into account as the parameter a becomes larger and larger. Once Carson's series starts to converge, it does so fairly rapidly. How misleading the results can be with too few terms in the series of Eq. B.2 is illustrated for the case of $a = 4$ and $\phi = 0$: if the series were truncated after the 1st, 2nd, ..., 15th term, the percent error in R_{ii} would be

+312, -748, -16, +798, -416, +365, -121, -93, +28, -15, +5.2, +1.7, -0.35, +0.14, -0.04.

8. Appendix D: Internal Impedance of Stranded Conductors

For power line carrier problems, reasonably accurate attenuation constants are very important. Replacing a stranded conductor by one tubular conductor of equal cross-section is not good enough for such purposes. Instead, the internal impedance formula from [7] should be used:

$$R_{internal} = \omega L_{internal} = \frac{2.25\sqrt{\omega\mu_0\mu_r\rho}}{r\,\pi(2+n)\sqrt{2}} \quad \Omega/\text{m}, \tag{D.1}$$

or with $\frac{\rho}{\pi r^2} = R$,

$$R_{internal} = \omega L_{internal} = \frac{4.5\sqrt{5}\cdot 10^{-4}}{2+n}\sqrt{\omega\mu_r R} \quad \Omega/\text{m}, \tag{D.2}$$

where R = DC resistance of one of the outer strands of a stranded conductor (Ω/m),

μ_r = relative permeability,

μ_0 = $4\pi \cdot 10^{-7}$ (H/m),

ω = angular frequency,

ρ = conductor resistivity ($\Omega\cdot$m),

r = radius of each outer strand (m),

n = number of outer strands.

The factor 2.25 in Eq. D.1 was found experimentally from field plotting in an electrolytic tank. The formula gives reasonably accurate results at frequencies above two to five kilohertz for the most commonly used stranded conductors with the number of outer strands either being 6, 12, 18, or 24.

Figure D.1 compares measured attenuation constants with those calculated with the above formula. In [7], it is shown that the measured attenuation constants come from the aerial mode which has a slightly slower wave velocity than the other aerial mode. That mode was chosen on the same basis here. Input data which differ slightly from those given in [7], however, were used:

(1) Phase conductor 150 mm^2 Aldrey was assumed to have 37 strands (18 on the outside), as defined in DIN 48201, with conductor diameter = 15.8 mm, strand diameter

= 2.25 mm, and conductor DC resistance = 0.223 Ω/km (latter from Brown Boveri handbook).

(2) The relative permeability of the steel earth wire was assumed to be 50 to 100 (a Siemens handbook says that these are typical values, with the actual value depending on the current density). It has seven strands (six outer strands), with strand diameter = 2.67 mm and $\rho = 20 \cdot 10^{-8}$ Ω·m from [7].

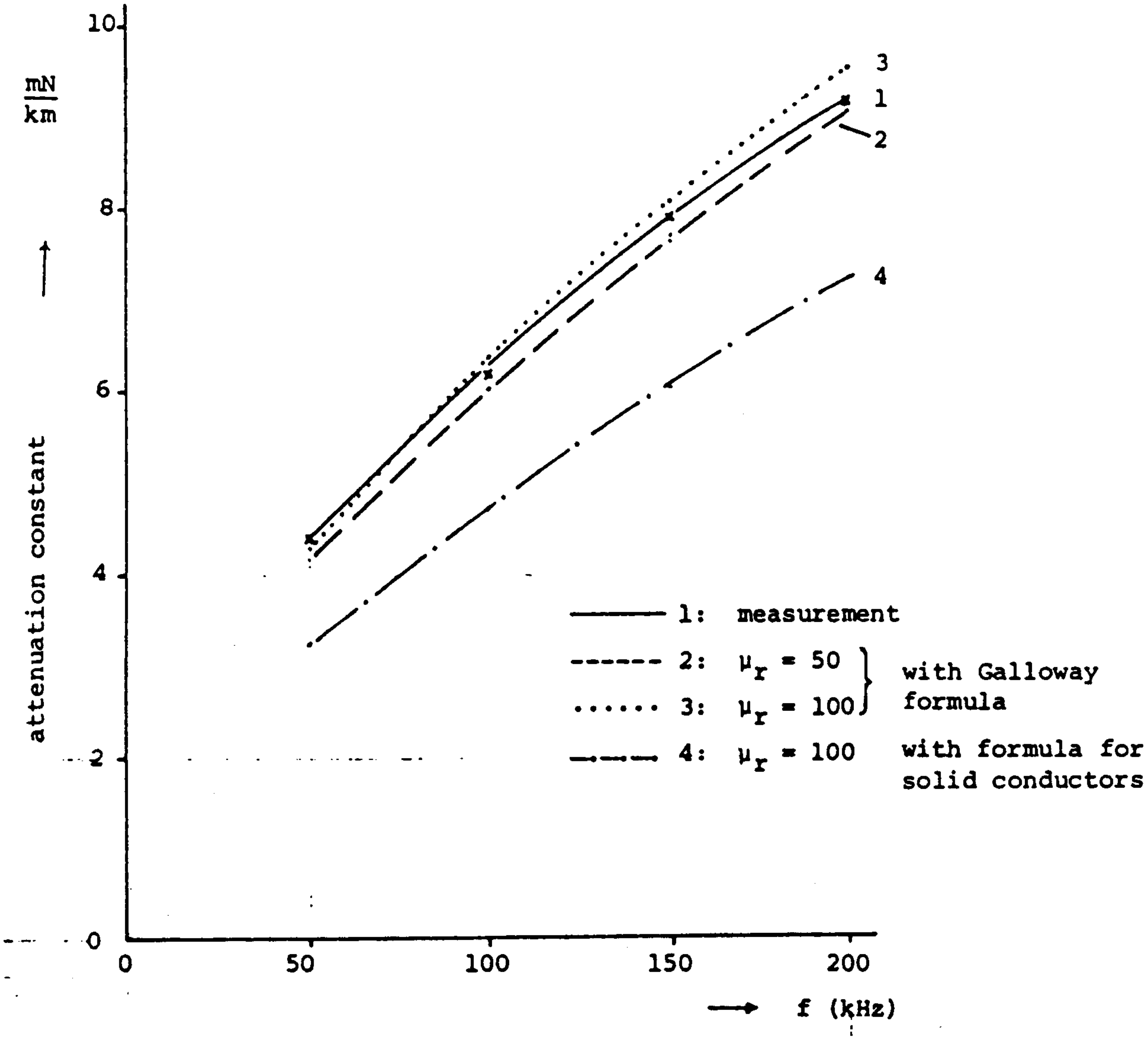


Figure D.1 Comparison between measured and calculated attenuation constants.

9. Appendix E: Formula by Gary, Deri et al

A much simpler way to account for earth return effects has recently been proposed by Gary, Deri et al [12], based on a suggestion by Dubanton. Instead of adding Carson's correction terms ΔR, ΔX, a complex depth

$$p = \sqrt{\frac{\rho}{j\omega\mu_0}} \tag{E.1}$$

is added to the height in Eqs. 1.1 and 1.2 of Section 1 of this manual, thereby replacing $2h_i$ by $2(h_i + p)$ in Eq. 1.1 and D_{ik} by $\sqrt{(h_i + h_k + 2p)^2 + x_{ik}^2}$ in Eq. 1.2 (x_{ik} = horizontal distance between conductors i and k). This simple formula produces results which are amazingly close to those obtained with Carson's correction terms, as shown in Fig. E.1 below.

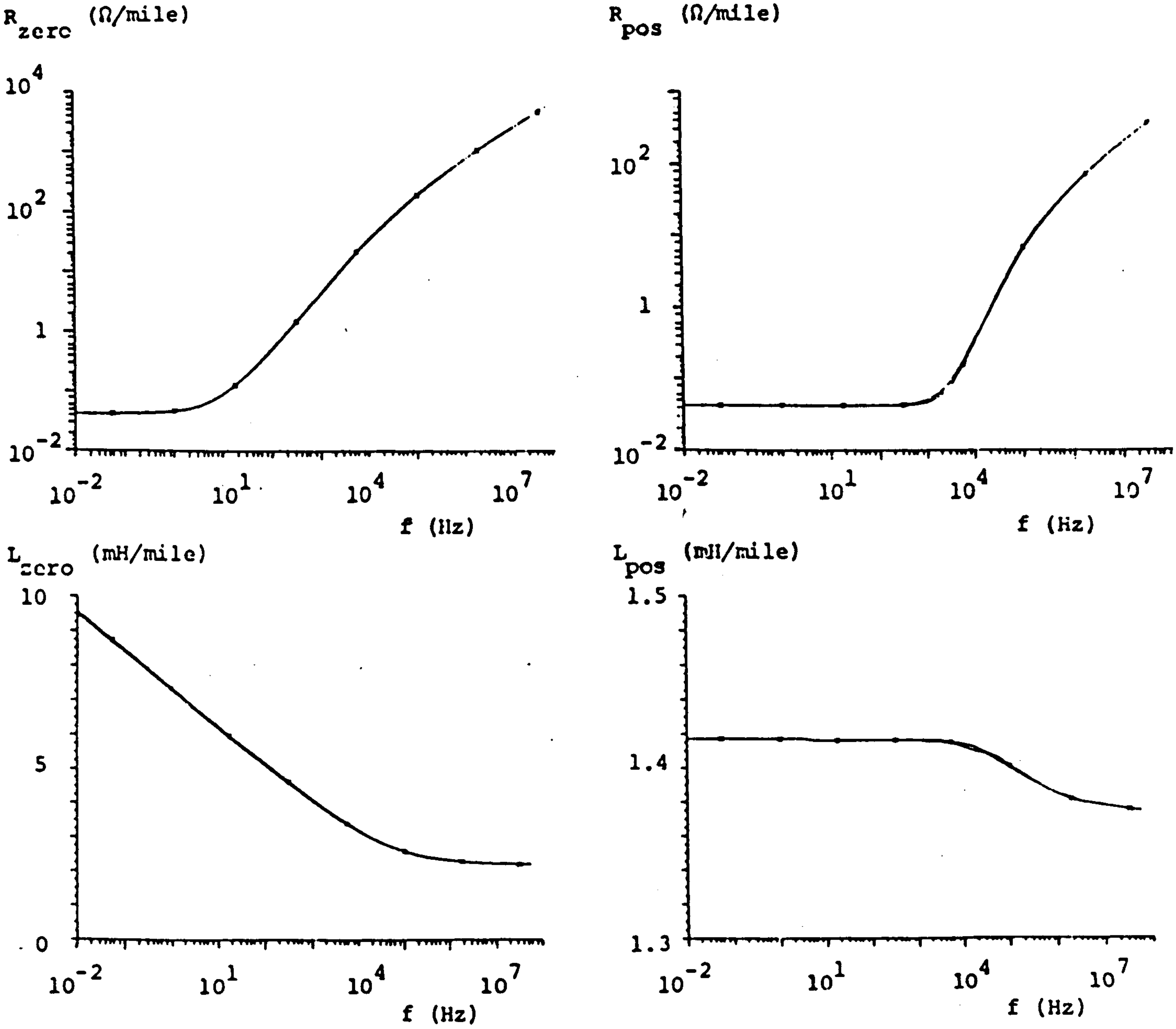


Figure E.1 Comparison between Carson formula and formula by Gary, Deri et al for a typical 500 kV line with bundle conductors (skin effect in conductors ignored).

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