TACLINK®
Electrical Network Analysis Tools

REFERENCE MANUAL

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1. OVERVIEW

TACLINK is a sophisticated electrical network analysis tool developed primarily for analyzing power systems where grounding effects must be evaluated. TACLINK analyses steady state effects as opposed to transients. For transient analyses, other software such as an Electromagnetic Transients Program must be used. TACLINK can analyze normal operation steady state conditions as well as faults and other unusual conditions.

The term grounding is used in this manual. Often the term earthing is used. They have identical meaning.

TACLINK represents an electrical network in a detailed basic format of real conductors and components. Many other analytical methods use symmetrical components or are "bus-based" such as load-flow and fault analysis programs. It is difficult to determine the split of ground fault current or induced currents with these programs. For example, the division of current between a substation ground grid and connected sky-wires on overhead lines and/or cable sheaths.

In TACLINK, the electrical network, including grounding features, is represented as a full network of individual impedances, current sources and coupled circuits. The results of the calculations contain all voltages and currents that flow through the network. Therefore, if a transmission line tower has been modelled somewhere in the network, with a ground rod having a certain resistance and attached sky-wires of some type, the program will calculate the voltage rise of the tower and flow of current to the soil. It will do this for every tower, ground grid and other circuit element modelled.

The program is based on nodal network analysis, which requires data entry in the format of currents and admittances, all of which are complex $(r + jx)$ quantities. It is quite complicated to prepare data for nodal network analysis. A number of pre-defined network components such as three-phase power sources, coupled lines and three-phase transformers are provided to simplify data entry

TACLINK has been used for relatively complicated models. In one case a complete rapid transit system about 27 km long was modelled. The system has up to 30 parallel conductors in some places, being formed by the running rails, power cables and ground wires. It was split into segments about 100 metres long, requiring more than 5000 nodes.

2. DOING CALCULATIONS

The security key supplied with the program, must be attached to the computer parallel printer port to enable the programs to run.

The present versions of TACLINK are windows "console" programs. This means that they are text-based programs that run in a text window. There is no Graphical User Interface. Any 32 bit version of Microsoft Windows may be used. TACLINK has been used with Windows 98, NT4, ME and NT2000.

The programs can be started in several ways:

- By double clicking on the icon for the program.

- By double clicking on the program file name (e.g. **TACLINK.EXE**) in the File Manager.

- By dragging a TACLINK data file from the File Manager onto the program icon.

- By opening a "DOS" or "Command Prompt" window and typing the program name followed by the data file name on the command line e.g.:

    TACLINK Tldemo1.dat

    For this to work, the programs must be installed in a directory that is included in the **PATH** of the computer.

TACLINK programs are "filter" programs in that they filter the input data and produce an output file of results.

It is necessary to have an input data file available before a program can be run. The sample files can be used for demonstration. They are regular text files that can be edited with the Windows NotePad editor or any other text editor. If Windows 98 or ME is used, the file may become too large for NotePad and WordPad will need to be used. If a word processor such as Word Perfect, Word for Windows or even WordPad is used, the files must be saved in text mode.

Use the File Manager to drag the file **Tldemo1.dat** onto the icon for **TACLINK.EXE**.

Providing there are no errors in the data, the file should be loaded and the calculation should proceed. After it is completed, there will be files: **TLDEMO1.LOG** and **TLDEMO1.OUT** in the same directory where the input data file was located.

For models that automatically calculate the capacitance of modules , there will be another file with name extension **.CAP** that contains all the capacitance information.

3. ANALYSIS OF MODELS

The term "model" is used frequently to refer to the computer model of the actual electrical system. As discussed in Section 2, TACLINK uses a "filter" process to filter input data and generate an output file of results from it. There are three main steps to carrying out a TACLINK analysis:

Develop the input data file.

Do the calculation.

Review the results and extract the required information.

3.1 Developing the Input Data File

3.1.1 Model Data Format

The input data file for all TACLINK analyses is a standard text format file. It can be created, viewed and modified with any text editor such as the NotePad program or a word processor such as Microsoft's Word for Windows in text mode.

For complicated models with many nodes, a spreadsheet program can be used to generate the input data. With a spreadsheet, it is possible to assign numbers to nodes and have the numbers increase in sequence where there are many similar or the same segments, as may happen when a length of transmission line is being modelled. The appropriate area of the spreadsheet can be saved in text mode or blocked and copied to a NotePad file. Spreadsheet programs often use tab characters as column separators when the spreadsheet is saved in text mode. This does not present a problem as TACLINK treats tabs as if they are spaces.

The input data file format makes use of <u>keywords</u> or <u>keyletters</u> that are interpreted by the program. A keyletter is placed at the start of a line and is followed by appropriate data. A keyword appears on a line by itself and requires that the lines following have appropriate information on them.

The following is an example of <u>keyletter</u> use. A letter is always the first character on the data line:

```
Z    5.37    0.0    TWR23   GND
```

This line specifies that there is `Z` object, which is an impedance of `5.37 + j0.0` Ω connected between the node `TWR23` and `GND`. `TWR23` could be the node name for a transmission tower. Node `GND` or node `0` (zero not the letter O) is always "remote ground". The ground resistance of a tower could be represented by this entry. Note that the impedance can have any non-zero value. Negative reactance can be used for capacitance and even negative resistance is valid.

The following is an example of <u>keyword</u> use. Keywords are used for more complex network objects:

```
source_z         Power source at Mountain
ma   mb   mc     Phase bus nodes
mgrid            Ground bus node
138              Line-to-line kV
0.0   8.0        Self impedance of source
0.0   0.0        Mutual impedance of source
0.0              Phase angle of phase A voltage in degrees
```

These lines demonstrate the application of the keyword **source_z**. On the first line, the program reads the keyword **source_z** and ignores the user comment **Power source at Mountain**. Internally, the program will extract whatever information is required from a line of data and then move on to the next line. Comment text that appears after valid data is ignored. The danger here is that if too little information is entered on a line with a trailing comment, the program will try to get the missing information from the comment. For example, if the user entered the following in place of the line after **source_z**:

ma   mb   Phase bus nodes

the program will use **Phase** as the name of the third phase bus node. Usually only a few comments are required in a data file and the * method described later, is used most often.

The keyword **source_z** provides for simplified data entry of a three phase power source using self and mutual impedances for the source. It requires six following lines of information:

> The three phase nodes of the source - **ma   mb   mc**
>
> The ground node of the source - **mgrid**
>
> The nominal line-to-line kV - **138**
>
> The self-impedance of the source - **0.0   8.0**
>
> The mutual impedance of the source - **0.0   0.0**
>
> The phase angle of the source - **0.0**

These parameters are discussed in more detail in Section 5.

The last line of the file must have the keyword **END** to signify the end of data. Other lines could be added after **END**, but they will be ignored.

A complete comment line can be inserted by starting the line with an asterisk - *****. Blank lines can also be left to group the data. Blank and ***** lines are ignored.

3.1.2 Calculation Frequency

AC impedances are frequency dependent. The keyletter **F** can be used to specify a particular calculation frequency. The following line somewhere in the input data file will set the frequency for calculations to **50.0 Hz** for all the data in the input file.

        F   50.0

If no frequency is specified, TACLINK will use a frequency of **60 Hz**. The actual frequency used will be stated in the results file.

It is important to note that only impedances generated by the program will be based on the specified frequency. It is possible to specify impedances in r + jx format and those impedances will remain the same value regardless of what frequency is specified using the **F** keyletter. Parameters that are not modified by the frequency keyletter, are those specified by the **Z** or **C** keyletter. Any other impedances generated by the program, such as parallel line, pipeline or cable impedances with or without capacitance effects, will use the specified frequency.

3.1.3 Node Naming

Any combination of letters, numbers, hyphens "-" and underscores "_" can be used to designate or name nodes. Spaces, punctuation and other symbols (e.g. **#%&!~":@** etc.) cannot be used.

Node names can be entered in upper or lower case. The program will convert all lower case to upper case and the output file will contain only the upper case versions. Therefore, node names with the same letter and number sequence, but with different letter cases, will be interpreted as the same node. For example, the nodes **Twr14a** and **TWR14A** are the same node.

The following are all valid node names:

        23   PH_A   pL-12   Twr14a

Any number of letters and numbers can be used in a anode name. The widths of the output listing columns are automatically adjusted depending on the length of the longest node name, therefore use of long node names will result in wide blocks of output that may exceed page width in listings. Use of longer node names will also use slightly more computer memory during calculation, because memory is individually allocated for storing each name. This is not a major use of memory compared with the memory used for the actual calculations.

For some modules, such as three-phase transformer modules, the program will add "internal" nodes so that impedances can be incorporated with the ideal transformer to simulate a real transformer. These nodes will start with the @ symbol. For example: **@T12BP**. The nodes are generated by the program. The user cannot give a nodes a name starting with @....

WARNING The naming of nodes and model configuration is completely flexible. Any naming scheme can be devised by the user. Particularly with large models, a naming scheme should be used that makes it difficult to accidentally use the same names in different parts of the model. There is no reasonable way to check for errors of this type. For example, if the names **PHA**, **PHB**,

PHC were used at one end of a long transmission line model and, in error, the same names were used at the other end, they will be interpreted as the same nodes. TACLINK will solve the model as if the two ends of the line were interconnected.

3.2 Sample Data File

A simple example has been provided to illustrate how a TACLINK input data file is developed. The example is in file **Tldemo.dat.** The sample network is shown in Figure 1 as a block diagram and in Figure 2 in the detailed format required for preparation of the input data for the program. The figures can be found in Appendix B.

The model consists of a central substation called Quadra supplied at 138 kV via overhead lines from power sources at Mountain and Norfolk. Substation Quadra steps the 138 kV power down to 12 kV, which is supplied to in industrial plant called Radium, through an underground cable. Radium has 8 MVA of in-plant generation, which could be a turbine generator or contribution from spinning electric motors at the time of a fault on the system.

Figure 1 shows most of the information needed for the analysis:

Mountain Substation is equivalent to a Y-connected power source with a short circuit level of 10 kA and a ground resistance of 0.55 Ω. In real life, it could represent a connection to a higher voltage system such as 230 or 500 kV. Usually a power source will have a different 3-phase fault level to the single-line-to-ground fault level. This can be correctly modelled by TACLINK, but has not been done here in order to simplify the demonstration model.

Norfolk Substation is similar to Mountain, but has a lower short circuit level of 4 kA and a higher ground resistance of 1.3 Ω.

The line between Mountain and Quadra has a vertical format with a single steel sky-wire on top. It is 17 km long. The line between Norfolk and Quadra has an 'H'-frame format and is 8 km long. It has two sky-wires and uses a different conductor size.

Usually transmission lines will have towers every few hundred metres. There may be 50 towers along 17 km of line. Each tower will be grounded to ground rods, or through its footings, if it is a steel tower. Each tower may therefore have a different ground resistance. To simplify the example, the number of towers along each line has been limited to three. Each has a different ground resistance.

Quadra Substation has a single 20 MVA transformer connected Y-Δ. The transformer has 9% impedance and the substation has a ground resistance of 1 Ω.

Radium Plant is connected by 300 metres of three conductor 750 MCM cable with an aluminum sheath and external #4/0 copper ground wire. It is assumed that the cable sheath and external ground wire are insulated from the soil. At Radium Plant, the spinning motors and turbine generator are equivalent to an 8 MW source with three-phase fault level of 2 kA and neutral resistance of 35 Ω. The neutral resistance has been chosen to be quite high to limit the generator ground fault current to about 200 amps. The generator neutral is connected to the plant ground

system, represented by node **RGRID**. The effective plant ground impedance is a pure resistance of 2.2 Ω between node **RGRID** and remote ground.

Refer now to the input data file listing in Appendix A and to Figure 2 in Appendix B.

The following are the first few lines in the file:

```
* Lines starting with an asterisk can be used for comments. They are
* ignored by the program. Also, blank lines can be left.
```

As stated, any line starting with an asterisk ***** is merely a comment entered by the user and is ignored by the program. Blank lines are also ignored, so data can be split up into blocks separated by blank lines, to make for easier reading.

```
f  60
```

This line indicates that the analysis should use a frequency of 60 Hz. The line could be left out as the default frequency is 60 Hz. If the power system operated at 50 Hz, it would be essential to add a line stating:

```
f  50
```

```
source_z           Power source at Mountain
ma   mb   mc       Phase bus nodes
mgrid              Ground bus node
138                Line-to-line kV
0.0   8.0          Self impedance of source
0.0   0.0          Mutual impedance of source
0.0                Phase angle of phase A voltage in degrees
```

These lines demonstrate the application of keyword data and show an alternative comment format. Once the required data has been entered on a line, comments may be added after it. On the first line, the program reads the keyword **source_z** and ignores the comment **Power source at Mountain**. Internally, the program will extract whatever information is required from a line of data and then move on to the next line. The comments that appear after the valid data are ignored.

The keyword is compared with a valid list of keywords. The program will stop, with an error message, if an invalid keyword is used. keywords are not "case-sensitive". All input data is converted to upper case internally, therefore the following would all be acceptable for this keyword: **source_z, Source_Z or SOURCE_Z**.

The comments give a good explanation of the **source_z** keyword. It describes a three-phase voltage source that is connected between the ground node **mgrid** and phase nodes **ma mb mc. mgrid** represents the ground grid of the source. **ma mb mc** represent the A, B and C phase buses at the substation.

ma mb mc and **mgrid** are nodes. They could be specified by numbers, but letters have been used to make it easier to understand the data and to make modifications later.

The line-to-line voltage of the source is 138 kV

The source self-impedance is `0.0 + j8.0` Ω. Often if the short circuit level is determined by a transformer impedance, the source can be quite well simulated by a pure reactance like this. If better data is available, there may be a resistive part to the source impedance as well as reactive. Section 5 goes into greater depth on this subject and on the significance of the source mutual impedance. In the demonstration example, the mutual impedance has been set to zero.

The last line of the source group of data specifies the phase angle of the source voltage. This is necessary because three-phase transformers can cause phase shift that must be accounted for. There is a three-phase transformer at Quadra Substation, that causes a 30° phase shift. If phase shift was not incorporated in the power sources, the generation at the Radium Plant would be out of step with the 138 kV system and quite large currents would circulate. In real life, the phase shift can be changed to control power flow in an interconnected system. Usually, for ground fault studies such as this, there should be no circulating current before the short circuit is applied, other than within the power sources. If circulating current is found to occur, there is probably an error in the input data[1]!

```
z      0.55   0.0    mgrid gnd
```

This line indicates that an impedance of `0.55 + j0.0` Ω is connected between node `mgrid` and node `gnd`. It represents the ground resistance of the substation at Mountain as a pure resistance of `0.55` Ω. A node named `gnd` or `0` (zero) always means "remote ground" or the rest of the earth. This name and number must not be used for any other node that is not "remote ground".

```
parallel_line          Section 1 of transmission line from
*                      Mountain to substation Quadra
4                      number of parallel conductors
ma    mb   mc    mgrid  from nodes
m1a   m1b  m1c   m1g    to nodes
477 ACSR               size and type of first conductor
0.6  28.0             x and y coordinates of first conductor - metres
477 ACSR               size and type of second conductor
0.6  24.0             x and y coordinates of second conductor
477 ACSR               size and type of third conductor
0.6  20.0             x and y coordinates of third conductor
1ca3/8 steel          size and type of sky-wire 3/8 inch steel
0.0  32.0             x and y coordinates of sky-wire
42.0                  soil resistivity
2000.0                length metres
```

Again, the comments next to each line of this block of data help to explain the entry format. The first line has the keyword `parallel_line` for a segment of the model that describes a set of parallel conductors. The lines following are required when this keyword is used.

---

[1] If a model uses lines with capacitance, the phase shift may not be a multiple of 30° and the correct shift may have to be found by trial and error.

First the number of parallel conductors is given so that the program knows how many nodes and conductors will be involved. There will be four conductors for this line, being the A, B and C phases and the overhead sky-wire or ground wire. The conductors are strung from the A, B and C buses and the ground grid at Substation Mountain to the respective insulators and tower ground at Tower #1. The node names for Tower #1 have been chosen as **m1a, m1b, m1c** and **m1g** to represent the first tower on the line from Mountain.

Each conductor has two lines of data. The first gives the conductor size and type **477 ACSR** When the program reads the conductor size and type, it refers to a database in the file **COND.DAT** to read the Geometric Mean Radius (GMR) and ac resistance (R_{ac}) of the conductor. **COND.DAT** is a text file that can be edited to add any type of conductor to the database.

The second line **0.6   28.0** is the x and y distance from a reference point on the ground surface. The x and y co-ordinates of the conductor are obtained from the cross-section of the transmission line shown in Figure 1. The x = 0 point has been chosen at the pole. Ground level is always the y = 0 reference. Therefore, this conductor is located at x = +0.6 or 0.6 metres to the right of the pole (on a side-mounted insulator 0.6 metres long). Its height is 28 metres above ground. This should be the average height allowing for sag.

The sky-wire is 3/8 inch diameter steel. As steel has non-linear magnetic properties, the GMR and R_{ac} depend on the current flowing in the sky-wire. The sky-wire designation **1ca...** has been chosen to indicate that the GMR and R_{ac} are for a current of **100** amps. The actual current in the sky-wires will be different from this and there is some error in not using the correct parameters for the actual current in each span of the transmission line.

The last two parameters of the **parallel_line** keyword are the soil resistivity and length of the line segment. The **parallel_line** segment will be converted into an impedance matrix inside the program. The impedances are dependent on the soil resistivity, which is 42 Ω-metres.

For demonstration purposes, the lengths of the segments between transmission line towers have been made quite large (2000 metres in this case), to reduce the complexity of the model to only three towers along each transmission line.

```
z    7.0    0.0    m1g    gnd            tower resistance to ground
```

This line indicates that an impedance of 7 Ω is inserted between the tower ground node **m1g** and remote ground **gnd** to represent the tower ground resistance.

The input data file continues with similar **parallel_line** statements for different length segments of the rest of the line from Mountain to Quadra. The towers also have differing ground resistances.

This is followed by a set of data comprising source, line segments and tower resistances for the Norfolk source and line to Quadra. The Norfolk line has a different cross-section, number of parallel conductors and conductor size. This demonstrates the flexibility of TACLINK in that every parallel line segment can be different. It illustrates how the same ground node **n1g,**

n2g, n3g can be used at each tower for two of the line conductors. When this is done, the two sky-wires are interconnected at each tower. It is possible to give each sky-wire its own node if the interconnection is not desired.

```
source_z            Power source at Radium plant
ra   rb  rc
rstar
12
0.0   3.6
0.0   0.0
-30.0
```

The Radium Industrial Plant is modelled as a 12 kV power source. It is similar to the other sources, but a phase angle of -30° has been used so that the Radium generation will be in the correct phase relationship with the secondary of the transformer at Quadra.

```
three_cond_gnd                  cable from Y-delta transformer to Radium plant
1  1                            number of cables, number of ground wires
qsa  qsb  qsc  qgrid  qgrid     from nodes
ra   rb   rc   rg     rg        to nodes
0.0319  0.0818                  cable core GMR and Rac (750 MCM copper)
1.1  1.15  al                   sheath inside & outside radius & sheath metal
0.01579 0.278                   ground wire GMR & Rac (#4/0 copper)
60.0                            soil resistivity
0.0  -1.0  1.0  -1.0            x,y locations of cable followed by ground-wire
300.0                           length metres
```

This keyword **three_cond_gnd** indicates that there is a three conductor cable between the Quadra transformer and Radium Plant. The keyword can be used to specify one or more cables, with any number of parallel ground wires (including zero). The comments help to explain each line of data. Additional explanation is needed for the line **1.1   1.15   al**. It specifies that the cable sheath inside radius is 1.1 inch and outside radius is 1.15 inch. The sheath is therefore 0.05 inch thick. The sheath metal is **al** = aluminum.

```
wye_delta               transformer
qpa  qpb  qpc           primary nodes
qsa  qsb  qsc           secondary nodes
qgrid                   ground node
138.0                   primary voltage
12.0                    secondary voltage
20.0                    MVA
9.0                     impedance
```

This block of data specifies the transformer at Quadra Substation. The comments explain each line of data.

It is a Y-Δ transformer with the primary Y - connected. By convention, the secondary voltage will lag 30° on the primary voltage. The primary and secondary voltages are line-to-line kV. The transformer is modelled in a simplified form. There is no magnetizing current and the impedance is assumed to be a pure reactance. Transformer data can include winding resistive losses,

magnetizing current and iron losses by using the keyword **wye_delta_detail**[2]. More complicated data entry is required.

When the program is run, it will create three internal nodes for the transformer, because the transformer data entered is converted into three ideal single phase transformers, with impedances connected in series with the primary of each. These nodes appear in the results listing with names starting with the symbol @.

The above data groups can be entered in any convenient order.

The last keyword is **END**. It signifies the end of the data. The program will not read the file any further and will start the calculation.

The input data file described above, **Tldemo.dat**, is for a balanced system without any faults on it. When the data is analyzed by the program, there should be no circulating currents other than within the power sources and all nodes should have the expected line-to-ground voltages. If there is current circulating, other than within the sources, there must be an error in the model or data preparation.

A second demonstration file, **Tldemo1.dat**, is provided. It is identical to **Tldemo.dat** except that a line-to-ground fault has been simulated by added a resistance of 1 milli-Ω between phase C and the ground grid at Quadra Substation. The fault is simulated with the following line that may be found near the start of the file:

```
z   0.001  0.0  qpc  qgrid     Fault at Quadra
```

3.3 Doing the Calculation

Using the Windows Explorer, drag **Tldemo.dat**, provided, onto the icon for TACLINK. A console window will open and TACLINK will process the data file. While it is doing this, it will print something similar to the following on the screen:

```
TACLINK AC Version 1.0 DATE: May 02 1996
Copyright: Ground-it.com Consulting Ltd.
Reading data from input file...
Renumbering nodes
Inverting submatrices and impedances
Solving main matrix
Back substitution
Calculating currents and writing results to output file
```

There will now be two results files in the **Taclink** sub-directory - **tldemo.log** and **tldemo.out**.

TACLINK will not run if the input data file does not exist or the **COND.DAT** or **MESSAGE.TXT** file is missing or not in the same directory as the program **.EXE** file.

---

[2] This has not yet been implemented at August 2, 2007.

If there are any errors in the input data file, the program will stop and display the error message.

3.4 Reviewing the Results of the Calculation

The calculation results can be viewed using a text editing program such as NotePad.

If you edit the **tldemo.log** file, you will see the following:

```
THREE PHASE SOURCE - Impedance option
Phase nodes:   MA   MB   MC
Ground node:   MGRID
Line-to-line kV:     138.000
  Self impedance      0.0000 j     8.0000 ohms
Mutual impedance      0.0000 j     0.0000 ohms
Phase angle     0.0000 degrees

PARALLEL_LINE
Number of conductors: 4
From Node: MA MB MC MGRID
  To Node: M1A M1B M1C M1G
   477 ACSR at x:  0.600  y: 28.000
   477 ACSR at x:  0.600  y: 24.000
   477 ACSR at x:  0.600  y: 20.000
1CA3/8 STEEL at x:  0.000  y: 32.000
Soil resistivity:    42.0
Length:  2000.0
```

The **.log** file repeats some of the input data to show it has been correctly interpreted by the program. When the calculation is done, the detailed information about parts of the model that are developed from keyword modules, is lost and is replaced by impedance matrices. Similarly, three-phase transformer modules will be replaced by three or more single phase units and added internal impedances. The **.log** file provides a way of checking that the input data for the special objects has been correctly interpreted by the program.

If the model included parallel lines **with capacitance**, a **.CAP** file will be created. It contains all the capacitances that were added by the program in developing the parallel line impedances and details of the capacitive currents that flow. Capacitance listings can be quite extensive and are therefore provided in a separate file. Usually capacitive currents information is not required and the file does not have to be kept.

If you review the results file **tldemo.out**, you will see a perfectly balanced system in which no currents circulate except in the matrices representing the power sources. There are not yet any faults in the system modelled.

The calculation result file for a single-line-to-ground fault case, **tldemo1.out**, is now reviewed.

The first part of the results file should look like the following:

```
Started at: Wed Aug 12 15:18:46 1998

TACLINK Visual C++ Windows 95/NT AC Version 1 Date: Aug 11 1998
Copyright: Ground-it.com Consulting Ltd.
Input File Name: C:\Samples\Taclink\Tldemo1.dat. Calculation frequency:   60.0

Type         Real             Imaginary     From      To
  Z          0.001000          0.000000      QPC     QGRID
  I          0.000000       -9959.292144     MGRID     MA
  I      -8625.000000        4979.646072     MGRID     MB
  I       8625.000000        4979.646072     MGRID     MC
```

The first part of the detailed listing is a list of the simple impedances and current sources in the model. The first one is an impedance '**Z'** of **0.001** + **j0.0** Ω between nodes **QPC** and **QGRID**. This is a ground fault resistance of 1 milli-Ω that was added from phase C to ground.

The last three lines of the above block are three single-phase current sources that represent the power source at Mountain Substation. This is clear because the nodes involved are the node names selected for that source. Internally, TACLINK has converted the three phase power source into three single-phase current sources with appropriate phase angles. Later in the file, the following admittance matrix will be found connected to the same nodes:

```
Matrix No:   1   Type: Y
 MGRID MGRID MGRID
   MA     MB     MC
  0.000000  -0.125000   0.000000    0.000000   0.000000    0.000000
  0.000000   0.000000   0.000000   -0.125000   0.000000    0.000000
  0.000000   0.000000   0.000000    0.000000   0.000000   -0.125000
```

This is the admittance matrix for Mountain source. The conventional concept of a three-phase voltage source with impedance has been replaced by a three-phase current source shunted by admittances. Because there was no mutual impedance in the source, the admittance matrix only has non-zero values of **-j0.125** $^1/_Ω$ on the diagonal. This corresponds with the source impedance of **8** **Ω.**

In all the matrix listings, the rows have alternating real and imaginary impedance or admittance values in (R + jX) format. The above matrix is therefore a 3 x 3 matrix of complex quantities. The Type designation can be Z or Y for impedance or admittance respectively.

Going back to the top of the file, the listing of simple elements, i.e. single impedances and current sources, is continued to cover all the three phase sources and other impedances such as ground resistances of substations and towers.

The next block of data lists the transformers in the model:

```
Transformer No: 1
Connected between nodes @T1A QGRID and QSA QSB - Ratio:      6.6395     0.0000


Transformer No: 2
Connected between nodes @T1B QGRID and QSB QSC - Ratio:      6.6395     0.0000


Transformer No: 3
Connected between nodes @T1C QGRID and QSC QSA - Ratio:      6.6395     0.0000
```

This is the translation of the three-phase Y-Δ transformer into three single phase units by the program. The first two node names for each transformer are the nodes to which the primary winding is connected. The nodes **@T1A, @T1B** and **@T1C** are internal nodes associated with phases A, B and C. One end of each transformer primary winding is connected to **QGRID** for the Y connection. The second two node names are the nodes to which the secondary winding of each transformer is connected. It can be seen that this forms a Δ loop going from **QSA** to **QSB, QSB** to **QSC** and **QSC** to **QSA**.

In the listing of current sources and impedances, there are three impedances:

```
  Z         0.000000      85.698000     QPA    @T1A
  Z         0.000000      85.698000     QPB    @T1B
  Z         0.000000      85.698000     QPC    @T1C
```

These represent the transformer internal impedance (pure reactance) corresponding with an impedance of 9% for a 20 MVA transformer. The impedances are connected between the primary terminals and the internal nodes of the transformer.

Matrix No: 2 in the listing of matrices, is an impedance matrix representing the segment of transmission line from Mountain Substation to the first tower:

```
Matrix No:   2  Type: Z
  MA  MB  MC MGRID
 M1A M1B M1C   M1G
  0.350751    1.670670   0.107834    0.754794   0.108558    0.649376   0.106420    0.754888
  0.107834    0.754794   0.352188    1.668889   0.109295    0.753003   0.107121    0.650735
  0.108558    0.649376   0.109295    0.753003   0.353674    1.667089   0.107834    0.588938
  0.106420    0.754888   0.107121    0.650735   0.107834    0.588938   9.689322    3.817546
```

The actual conductor sizes, spacing and location above the soil have been used to determine the self-impedance of each conductor (on the diagonal of the 4 x 4 matrix) and all combinations of mutual impedance between pairs of conductors. For example, the first and second numbers on the first row **0.350751 +j1.670670** Ω represent the self impedance of the A phase conductor. The last two numbers on the last row **9.689322 +j3.817546** Ω represent the self-impedance of the sky-wire. The last two numbers on the first row represent the mutual impedance of **0.106420 +j0.754888** Ω between the sky-wire and the phase A conductor.

The program automatically generates these impedance matrices for each span of transmission line.

The tower resistances are all listed in the listing of current sources and impedances against the appropriate node pairs. For example:

```
Z          5.000000          0.000000     N2G     GND
```

represents the ground resistance of tower 2 along the line from Norfolk Substation.

Matrix No. 12 in the listing is the translation of the three conductor cable phase conductors, sheath and ground wire into a full 5 x 5 impedance matrix:

```
Matrix No:  12  Type: Z
 QSA QSB QSC QGRID QGRID
  RA  RB  RC RGRID RGRID
  0.033010   0.251621  0.017758   0.229430  0.017759   0.229430  0.017765   0.227158  0.017758   0.146527
  0.017758   0.229430  0.033010   0.251621  0.017759   0.229430  0.017765   0.227158  0.017758   0.147114
  0.017759   0.229430  0.017759   0.229430  0.033011   0.251620  0.017765   0.227158  0.017759   0.146816
  0.017765   0.227158  0.017765   0.227158  0.017765   0.227158  0.054604   0.226860  0.017758   0.146819
  0.017758   0.146527  0.017758   0.147114  0.017759   0.146816  0.017758   0.146819  0.069592   0.267527
```

The calculation results start with a listing of all the nodal voltages[3]. Part is reproduced below:

```
Nodal voltages with respect to node GND:
 Node          Real            Imaginary          Magnitude
  QPC       2603.443035      2295.983699        3471.232747
 QGRID      2597.853014      2291.406483        3464.012695
   MA      76592.102693      1607.532594       76608.970467
   MB     -43286.862756    -67085.184572       79838.427316
   MC     -20953.535667     45263.125268       49877.862484
 MGRID     -1155.560213      -979.398506        1514.774188
  M1A      77301.376912       482.132978       77302.880442
  M1B     -42331.302562    -68467.067332       80496.450143
  M1C     -18190.878643     40230.420109       44151.950896
  M1G      -465.708950      -260.902563         533.811740
```

The fault occurred between nodes **QPC** and **QGRID**. As the fault resistance was non-zero, these nodes have slightly differing voltages of **3471** and **3464** volts. The voltage of node **QGRID** indicates the voltage rise of the Substation Quadra ground grid during the fault. It can be used to assess safety at the Quadra Substation, for example, for step and touch potential calculation.

The division of fault current between the ground grid and other grounding conductors can be found as follows:

---

[3] In the current version of the program, the order in which the nodes are listed is determined by the order in which they were encountered as the program read through the input data.

Quadra ground grid is represented by a resistance of 1 Ω between **QGRID** and **GND**. The current flowing in this resistance can be read from the listing of currents flowing in the impedance branches of the network. The currents flowing in the fault resistance and ground grid resistances for Quadra and Radium have been extracted from this table:

```
From    To    -------Impedance - ohms---------    -----------------Current - amps-----------------
Node   Node      Real           Imaginary            Real           Imaginary          Magnitude
 QPC   QGRID    0.001000        0.000000          5590.020220      4577.216571        7224.903985
QGRID   GND     1.000000        0.000000          2597.853014      2291.406483        3464.012695
RGRID   GND     2.200000        0.000000          1239.777612       915.363266        1541.083527
```

One can see that the current flowing through the Quadra ground grid is **3464** amps and the fault current is **7225** amps. Therefore about 48% of the fault current flows to ground through the ground grid. The rest of the fault current flows through the transmission line sky-wires and cable sheath and ground wire bond to Radium. By looking at the ground current at the Radium 2.2 Ω ground resistance **RGRID** – **GND**, one can see that **1541** amps flows into the plant ground electrode.

Other information is readily available:

The normal 138 kV line-to-neutral voltage should be **79674** volts. It can be seen by looking at the listing of nodal voltages with respect to Node **GND**, that the phase voltages at Mountain are **MA = 76609** volts, **MB = 79838** volts and **MC = 49878** volts. Also, the Mountain ground grid **MGRID** has a voltage rise of **1515** volts.

As all nodal voltages and currents in all branches are reported, a complete picture of the effect of the ground fault can be obtained. For example, the voltage rise of Tower #1 along the line from Mountain is given by node **M1G** and is **534** volts. This voltage includes both the conductive effects along the sky-wire from Quadra to Tower #1 and the mutual coupling effects between the phase conductors and sky-wire.

The transformer listing in the output, lists the currents flowing in the primary and secondary windings of each transformer. As the transformer primary is Y connected, the primary winding currents equal the currents being supplied by the two transmission lines. This can be checked for phase B of the transformer as follows:

Phase B corresponds with transformer No. 2:
```
T  2 primary      -324.830806      -143.791223      355.233681
```

The last section of the Mountain transmission line has its phase B connected between nodes **m3b** and **qpb**. The last section of Norfolk is similarly between nodes **n3b** and **qpb**. The currents in these segments of transmission line can be found in the matrix current listings for Matrix No. 5 and No. 10. The currents must be added vectorially as there will be a phase shift between the two lines:

Current Branch	real	imaginary	magnitude
m3b – **qpb**	-361.776742	-286.766746	461.646594
n3b – **qpb**	36.945936	142.975524	147.671942
Total from both lines	-324.830806	-143.791222	355.233681

The total from both lines compares exactly (except for the last decimal of the imaginary part) with the T 2 primary current. One can see that the total current from the lines cannot be obtained by merely adding the magnitude of the current from each line, which would result in about 609 amps.

Matrix currents for Matrices No. 1 , No. 6 and No. 11 are the currents that circulate within the three phase sources[4].

The last few lines of the file indicate how sparse the network analysis was and gives the calculation completion times. TACLINK uses a matrix to solve the networks. The matrix is symmetrical and therefore only the diagonal and one triangular half needs be stored.

```
Main matrix storage locations used: 300 out of maximum 1275 =   23.5 %
Completed at: Thu May 02 15:31:37 1996
Compute time: 0 hr. 0 min. 3 sec.
```

For transmission type networks, there are many elements in the matrix that have zero values. It is not necessary to store the zeroes. There is some fill-in of matrix elements as the matrix is solved. The number of zero elements can be maximized and the amount of fill-in of zeroes during the calculation can be minimized. In large models, the sparsity tends to be more effective. For example, in a 5300 node model, the sparsity was 1.1%. A problem such as that can be analyzed in 11 Megabytes of memory versus around 500 Megabytes, as would be needed if sparsity was not exploited.

---

[4] The matrices referred to here are sub-matrices for segments of the model, not the main overall matrix that is used to solve the complete network.

4. CALCULATION METHODOLOGY

TACLINK uses nodal network analysis as a basis for analyzing electrical networks. It incorporates the features discussed below.

Reference [1] describes the two alternative network analysis methods, nodal and mesh analysis. Mesh analysis uses the property that the voltage drop around each loop (or mesh) in the network, must add up to zero. Nodal analysis uses the property that at each node in the network, the current/s flowing into the node must equal the current/s flowing out of it. In other words, the sum of all the currents at a node must be zero.

Nodal analysis has been found to be the easiest and most flexible to apply to general electrical network analysis.

Other methods exist and have been used. For example, the single or double-sided elimination method [2,3] has been used. It allows an extended transmission system to be represented as a series of possibly hundreds of interconnected segments representing each span of the line. The segments are combined into a single equivalent at the location of interest, the solution of which is reduced to a few equations. Back-substitution is used to obtain information about all the segments.

The reduction in the number of equations to be solved was important when computer memory was limited and sparsity techniques had not become widely used. Using sparsity, the computer memory requirements become comparable for the two systems. The elimination methods have another serious disadvantage.

Using the elimination method, it is very difficult to simulate loops or faults that are not at the central location of interest. While the elimination method allows a certain type of network consisting of a central substation and radiating transmission line, to be simulated efficiently, it cannot simulate systems that do not fit this format.

4.1 Symmetrical Components

Many proven computer analysis methods exist that use symmetrical components [4] to simulated transmission systems. Utilities use these computer programs to model complete transmission systems for load flow determination and the prediction of the effects of system faults and other anomalies.

The symmetrical component method was developed before the age of computers, as a way to simplify the analysis of three-phase power systems. Instead of analyzing an unsymmetrical network as a combined vectored system, the symmetrical components method breaks it down into three symmetrical sub-systems called the positive, negative and zero sequence networks. Each of these networks is reduced to an equivalent impedance at the point of interest. The three impedances are then combined to determine the required information, for example single-line-to-ground fault current. The established computer programs for symmetrical component analyses probably all use nodal network analysis to resolve the three sequence networks.

The symmetrical component approach to system analysis is well entrenched in the electrical power systems industry and electrical engineers involved with transmission and distribution systems, have grown to think in these terms. For example, they have a feel for levels of "zero sequence current" in terms of ground fault capability, or "positive sequence impedance" in terms of system strength. Usually they work in "per unit" terms where the whole network is based on a system MVA and kV. Actual results are derived from the base information returned by the network analysis.

The symmetrical components method is very effective in modeling complete systems. However, it is difficult to apply to detailed analyses. For example, a segment of a transmission system covering a length of many km, say between two substations, may be represented as a single set of positive, negative and zero sequence impedances. This is adequate for calculating the fault current at either substation, but does not allow calculation of the current induced in a sky-wire connected to some of the towers, or the voltage rise of the towers resulting from that sky-wire current.

TACLINK was developed to enable a complete detailed analysis of a power transmission and/or distribution system, therefore, symmetrical components were not used. TACLINK analyses can be extended to include the smallest details of a power system. Because there is complete flexibility in TACLINK, virtually any kind of system can be modelled exactly. For example, the following systems are very difficult or impossible to simulate with symmetrical components:

Six-phase or N-phase systems, where N = any number.
DC systems with or without ground contact.
Unsymmetrical line configurations.
Combined three-phase and single and/or double phase systems.
Interconnected grounding networks.
Transit systems with power cables in parallel with running rails.
Pipelines in parallel with electrical transmission lines.
Unusual transformer connections. where the currents and voltages in all windings are re-
    quired.

TACLINK's approach i.e. not using the symmetrical components analysis method, does not prevent symmetrical component data from being used for input. There is a simple relationship between the self and mutual impedance values used by TACLINK and the positive and zero sequence impedance values used with symmetrical components:

If Z_s and Z_m are self and mutual impedances and Z_1, Z_2 and Z_0 are positive negative and zero symmetrical component impedances, the following relationships can be written:

$$Z_1 = Z_s - Z_m \qquad Z_2 = Z_s - Z_m \qquad Z_0 = Z_s + 2Z_m$$

and

$$Z_m = \frac{Z_0 - Z_1}{3} \qquad Z_s = \frac{Z_0 + 2Z_1}{3}$$

These can be used to convert from symmetrical component impedances to self and mutual impedances.

4.2 Nodal Analysis

In nodal analysis, the network is represented as a series of points between which circuit elements are connected. A simple nodal network is shown in Figure 1.

Node   A connection point is called a node. At an instant in time, each node in a network will have a particular voltage and the ends of all elements connected to it, will have this same voltage.

Branch   A circuit element forms a branch in the network. It connect two nodes together such the resistance of 10 Ω between nodes 1 and 2 in Figure 4.1.
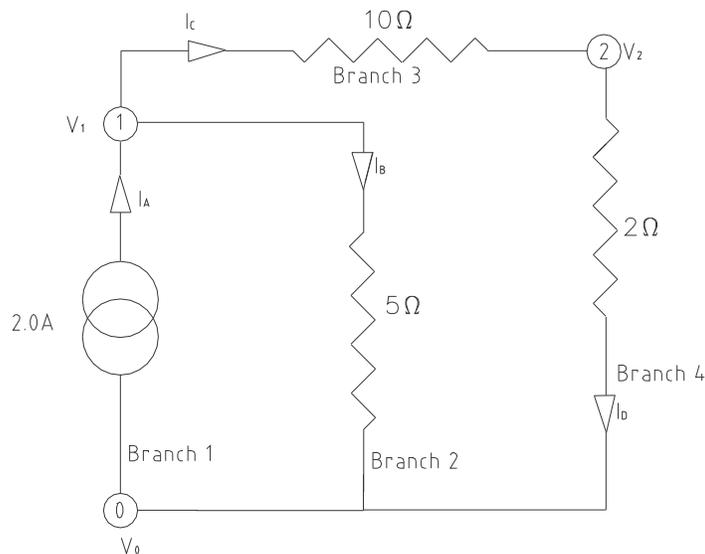
Figure 4.1 Simple Nodal Network.

Because nodal network analysis is based on the sum of all the currents at every node being zero, it is easiest to use current sources to provide the source of electrical power to the network. In Figure 4.1, the currents flowing in each branch have been designated as I_A, I_B, I_C and I_D.

For Figure 4.1, one can write the following three simultaneous equations, one for each node:

$$
\begin{array}{lllll}
\text{Node 0:} & I_A + & I_B + & & I_D & = 0 \\
\text{Node 1:} & I_A + & I_B + & I_C & & = 0 \\
\text{Node 2:} & & & I_C + & I_D & = 0
\end{array}
$$

There are four unknowns and three equations, therefore, the equations cannot be solved. However, one can solve the equations by assigning voltages V_0, V_1 and V_2 to each node. By Ohm's law, the current in each branch is equal to the voltage difference between the nodes

divided by the resistance. The currents I_A, I_B, I_C and I_D can then be expressed in terms of the voltages and the circuit elements and there are only three unknowns in the three equations:

$$\begin{aligned}
\text{Node 0:} \quad & 2.0 + (V_0-V_1)/5.0+(V_0-V_2)/2 && = 0 \\
\text{Node 1:} \quad & -2.0 + (V_1 - V_0)/5 +(V_1-V_2)/10 && = 0 \\
\text{Node 2:} \quad & (V_2-V_1)/10 + (V_2-V_0)/2 && = 0
\end{aligned}$$

In these equations, the current source is merely expressed as its real value of 2.0 amps in the first two equations.

One can see that all the resistances in the network are being used to divide into voltages. It simplifies matters considerably to represent the resistances as $1/R$, or conductances in $1/\Omega$ or mhos. In general terms, when inductances and capacitances are involved to form complex valued impedances, as is discussed later, the inverted impedance is called an admittance. The analysis method is therefore usually called nodal **admittance** network analysis.

Using conductances and expanding the bracket portions of the equations, one gets the following:

$$\begin{aligned}
\text{Node 0:} \quad & 2.0 + 0.2V_0-0.2V_1+0.5V_0-0.5V_2 && = 0 \\
\text{Node 1:} \quad & -2.0 + 0.2V_1-0.2V_0+0.1V_1-0.1V_2 && = 0 \\
\text{Node 2:} \quad & 0.1V_2-0.1V_1+0.5V_2-0.5V_0 && = 0
\end{aligned}$$

These can be rearranged to group the unknowns V_0, V_1 and V_2 in each equation. The known current source is also moved to the right hand side:

$$\begin{aligned}
\text{Node 0:} \quad & (0.2+0.5)V_0 & -0.2V_1 & -0.5V_2 & = -2.0 \\
\text{Node 1:} \quad & -0.2V_0 & (0.2+0.1)V_1 & -0.1V_2 & = 2.0 \\
\text{Node 2:} \quad & -0.5V_0 & -0.1V_1 & (0.1+0.5)V_2 & = 0
\end{aligned}$$

When this is done for different networks, the following rules emerge for each equation. Here the general concept of an ac admittance is also applied:

1. The coefficient of the voltage of the node represented by that equation is the sum of all the admittance's connected to that node. For example, in the second equation written for node 1, the coefficient of V_1 is the sum of the admittance's of the 5 Ω and 10 Ω resistances connected to that node, or $(0.2 + 0.1)$ mho.

2. The coefficient of each other voltage is the negative of the admittance's connected between the node for which the equation in being written and the other node. For example at node 1, there is a resistance of 5 Ω between node 1 and node 0, therefore in the second equation which is written for node 1, the coefficient of V_0 must be $-^1/_5$ or -0.2 mho.

3. The term on the right hand side of each equation is the sum of the current sources connected to the node the equation is written for. If the current source flows to the node, it has a positive sign and if it flows from the node it has a negative sign. Using the conventional current flow direction, the current flows into node 1, therefore, the right hand side of the second equation is +2.0.

The above describes the basic implementation of nodal admittance network analysis. It should be possible to solve the three equations of the absolute voltage of nodes 0, 1 and 2. However, it is not, because inspection shows that the third equation is a combination of the first two. It is not solvable because the network is floating in space. Usually, node 0 would be a ground or zero voltage reference. Therefore V_0 should be made equal to 0 and the first equation can be eliminated. The equations are now reduced to:

Node 1:	$(0.2+0.1)V_1$	$-0.1V_2$	$= 2.0$
Node 2:	$-0.1V_1$	$(0.1+0.5)V_2$	$= 0$

They can be solved by hand to give the following results:

V_1	$=$	7.05882 volts
V_2	$=$	1.17642 volts

The currents in the branches can be calculated from the node voltage difference times the admittance of each branch. The following results are obtained:

I_A	$=$	2.0	(current source)
I_B	$=$	1.41176	
I_C	$=$	0.58824	
I_D	$=$	0.58824	
I_B+I_C	$=$	2.0	

I_C and I_D should be and are the same. The last line shows that the branch currents do add up to zero because I_B+I_C = the current source connected to that node. The results of any nodal analysis can be verified by summing the currents at each node and checking that they do sum to zero.

4.2.1 Matrix Process

The equation format lends itself to matrix solution methods of the form:

$$|Y| \times |V| = |I|$$

where Y is the network admittance matrix, V is the vector of unknown node voltages and I is the vector of current sources.

The equation coefficient rules developed above can be applied to the matrix representation as follows. Nodes should be assigned the numbers 1 through N and the matrix will have rows and columns 1 through N. Column 0 is eliminated as it is made the remote ground reference:

1. Each coefficient on the diagonal of the matrix is the sum of all the admittance's connected to the node corresponding with that row and column number. Therefore, Y_{ii} will be the sum of all the admittance's connected to node i.

2. Each off-diagonal coefficient of the matrix is the negative of the sum of the admittance's connected between the node corresponding with that row and the node corresponding

with the column number. Therefore, $Y_{ij} = Y_{ji}$ = the negative of the sum of the admittance's connected between nodes i and j.

3. Each coefficient of the right-hand side vector I is the sum of the current sources connected to the node corresponding with the row number. If the current source flows to the node, it has a positive sign and if it flows from the node it has a negative sign.

Various matrix methods can be used to solve the matrix equation.

4.2.2 AC Systems

The example and description of the nodal network analysis process so far, has used a dc current source and pure resistances. This can be extended to ac systems where each network element or branch has an ac impedance value and the current sources are all vector quantities with magnitude and phase angle.

This could be applied using complex number notation in polar or rectangular format. Rectangular format is the simplest to apply. The various values are represented as real and imaginary number of the form r + jx where j is the complex operator = $\sqrt{-1}$. Addition and subtraction are implemented by adding or subtracting the corresponding real and imaginary parts of each complex number. Multiplication and division involve the following equations:

$$\text{if } X = a + jb \text{ and } Y = c + jd$$

$$X \times Y = (ac - bd) + j(ad + bc)$$

$$\frac{X}{Y} = \frac{ac + bd}{c^2 + d^2} + j\frac{bc - ad}{c^2 + d^2}$$

4.2.3 Sparsity

The example used to develop the nodal network analysis concept is very simple and produces a "full matrix". This means that all the coefficients in the matrix have non-zero values.

A full matrix implies that every node in the network has an admittance connected between it and every other node in the network. In reality, this is seldom the case, except in small, simple networks. This can be appreciated when considering, for example, a transmission line. Nodes at one end will not be connected to nodes at the other. In fact, any node will usually only be connected to immediately adjacent nodes in the network representing the transmission system.

In large networks, it is not uncommon to find that 99% or more of the matrix has coefficients with zero values. It is not necessary to store the zero values when the matrix is developed in the computer. However, there is some "filling in" of zero values when the matrix equation is solved, i.e. some matrix coefficients that were initially zero, will become non-zero as the solution proceeds. The amount of filling in can be minimized by optimizing the order of the node numbering.

The matrix is also symmetrical about the diagonal, therefore only the diagonal and one triangular half needs be stored in computer memory.

The end effect of applying sparse matrix techniques is that computer memory requirements increase approximately linearly with the number of nodes in the network rather than as a square law. This makes the nodal method computer memory requirement similar to that of the elimination methods discussed above, but it does not have the limitations of the elimination method.

4.2.4 Coupled Circuit Representation

In ac power system networks, most branches consist of elements representing parallel conductors.
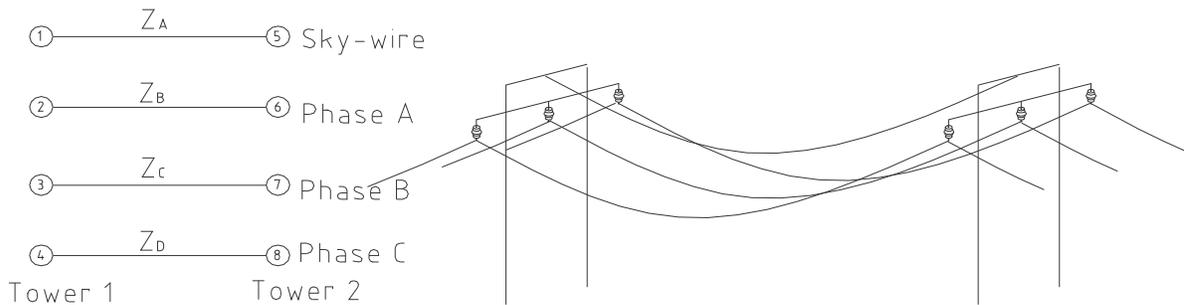
Figure 4.2 Coupled Circuit

An example is a span of overhead line between two towers. Nodes could be assigned to each tower for the phase conductors and sky-wire as shown in Figure 4.2. An impedance, representing each conductor's self-impedance is connected between corresponding nodes as follows:

Z_A Sky-wire impedance between nodes 1 and 5
Z_B Phase A impedance between nodes 2 and 6
Z_C Phase B impedance between nodes 3 and 7
Z_D Phase C impedance between nodes 4 and 8

Each conductor in a group of parallel conductors, will be inductively coupled to all the others. That is to say that current flowing in one conductor will induce voltage in all the others, due to the ac magnetic field that develops around the first conductor. At the same time, the current in each other conductor, will induce a voltage in the first conductor. The induced voltages affect the currents circulating in the conductors and there is no simple way to account for this.

Even passive conductors such as sky-wires, will have voltage induced in them that will cause current to circulate and induce voltage back in the phase conductors. The effect of this is to

apparently reduce the impedance of the phase conductors due to the "shielding" effect of the sky-wire.

The method used to account for inductive or mutual coupling, is to consider each group of parallel conductors, such as the four in the example, a sub-system in the overall network. The amount of coupling between conductor pairs is determined by the mutual impedance between each pair of conductors in the group. Mutual impedance has units of Ω. These are the same as volts per amp. Therefore, if the mutual impedance between two conductors is $Z\,\Omega$, it means that a current of 1 amp in one of the conductors will induce Z volts in the other and vice versa. Methods used to calculate mutual impedances are discussed later.

Considering the group on its own, it is possible to develop a set of simultaneous equations of a similar format to the main network equations. This can be demonstrated by considering the three conductor coupled segment in Figure 4.3.
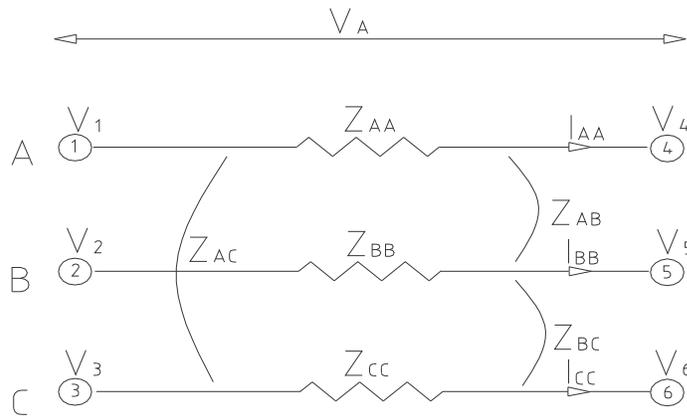
Figure 4.3 Three Coupled Conductors

The self impedance of each conductor is given by impedances of the form Z_{ii} where $i = A$ or B or C. The mutual impedances between each pair of conductors is given by impedances Z_{ij} where i and j are different and applicable to the two conductors. Therefore Z_{AC} will be the mutual impedance between conductors A and C. The concept can be extended to any number of parallel conductors.

4.2.5 Transformers

Transformers can be implemented in nodal admittance analyses as ideal single-phase transformers. Figure 4.4 shows such a transformer with a primary to secondary voltage ratio of N:1.
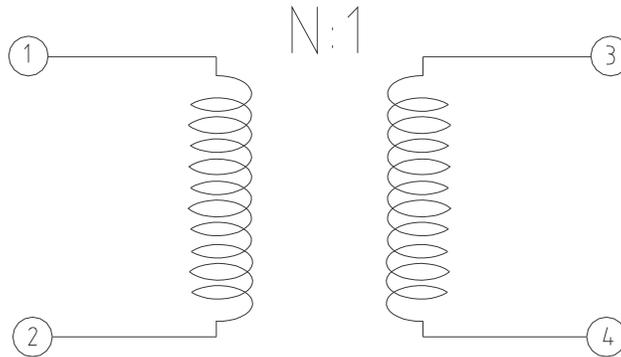
Figure 4.4.. Ideal Single Phase Transformer

Ideal transformers have no losses or magnetizing current. These real effects can be simulated by adding impedances in series with the windings to represent losses and transformer reactance and across the windings to represent the magnetizing current. As the transformers are ideal, it is only necessary to add a combined impedance on either the primary or secondary side, because it is perfectly reflected through to the other side.

With ideal single-phase transformers, it is possible to develop any complex transformer such as three phase Y - Δ or three winding Y - Y - Δ.

Transformers are included in TACLINK by adding another equation and another unknown to the set of simultaneous equations. The additional unknown is the primary current of the transformer.

If the ratio is N:1, the secondary current will be $\dfrac{primary\ current}{N}$.

5. PROGRAM KEYWORDS & KEYLETTERS

The TACLINK input data format makes use of keywords and keyletters. They can be in upper or lower case or a mix of upper and lower case. A keyword or keyletter must be the first entry on a new line.

Data must be organized on sequential lines in the input data file. Each line must terminated by a carriage return. Completely blank lines are ignored. When more than one entry is required on a line, the entries must be separated by one or more space and/or tab characters. Leading spaces are ignored. Commas and other punctuation should not be used to delimitate between data items.

Keyletters form the most basic data entry for TACLINK. They enable impedances, current sources and coupled circuits to be modelled and comments to be recorded. Keywords build on the basic capability of keyletters to provide an easier data entry for more complex objects and eliminate the need for some pre-calculation.

Internally, the program converts modules that are specified by keywords into the more basic keyletter format. The format of the output is therefore the same as if the input had used keyletters throughout. There is always sufficient information in the output data to determine how the input modules were interpreted.

Circuit elements are considered to run **from** one or more nodes **to** one or more nodes. These are referred to as the "from nodes" and "to nodes". Note that the correct number of nodes must always be entered in the data. Sometimes conductors in the keyword modules will be joined. For example, in a parallel line segment with two sky-wires, sky wires may be joined at the towers. The full number of nodes must still be used, but the sky-wire nodes will have the same node name at each end of the segment.

All vector quantities use rectangular co-ordinates of the format r + jx. Polar co-ordinates r ∠θ are not used.

5.1 Keyletters

Keyletters must be the first entry on a new line in the input text file. Except for the *, they are always followed by numerical data.

*   Start of a comment line that is ignored by the program. Can be anywhere in the file. Any text can be entered. The complete line is ignored.

            Example:

            `* This part of the model represents the Power Plant`

C   Basic user supplied coupled circuit matrix - It indicates that the data following describes a length of coupled conductors between two sets of nodes as shown in Figure 5.1. There can be any number of parallel conductors.
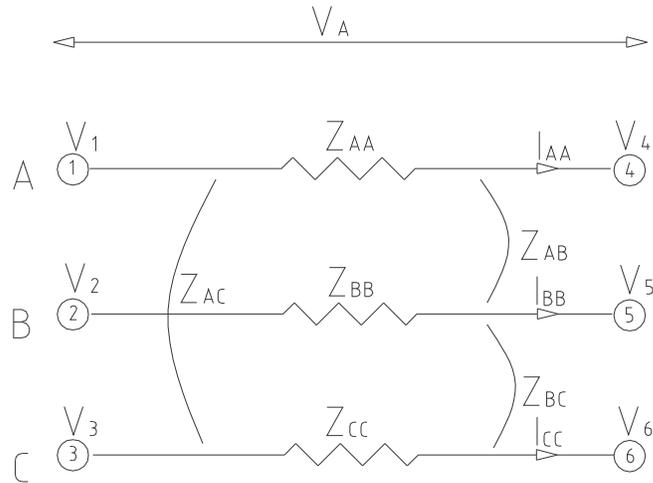
Figure 5.1 Coupled Circuit with Three Conductors

The first line has the letter **C** followed by the number of parallel conductors. The next two lines start with the letter **M** and are followed by the **from nodes** and the **to nodes**. The **from nodes** are on the first of the two lines. There must be the same number of nodes on each line as there are parallel conductors.

The lines following, list the matrix of self and mutual impedances or admittances for the coupled circuit. Whether it is an admittance or impedance matrix, is determined by the keyletter at the start of each line. The keyletter **Z** denotes an impedance matrix and **Y** denotes an admittance matrix. Mixing impedances and admittances within the same matrix would be invalid. Doing so will stop the program with an error message.

The format of the matrix is for the number of rows and columns to be the same as the number of parallel conductors, which is the same as the number of **from nodes** or **to nodes**. Each impedance or admittance entry in the matrix, is a complex number consisting of real part followed by imaginary part. R_{ij} is the real part of the impedance or admittance in row **i** and column **j**. X_{ij} is the imaginary part. The matrix entries must be as follows (example is for a 3 x 3 impedance matrix):

```
Z       R₁₁     X₁₁     R₁₂     X₁₂     R₁₃     X₁₃
Z       R₂₁     X₂₁     R₂₂     X₂₂     R₂₃     X₂₃
Z       R₃₁     X₃₁     R₃₂     X₃₂     R₃₃     X₃₃
```

In the matrix, the entries with the same i and j subscripts, 11, 22 and 33 are the self-impedances of the corresponding conductors 1, 2 and 3. It can be seen these are on the diagonal of the matrix. For example, R_{33} X_{33} is the self impedance of the 3rd conductor.

The other entries where the subscripts are different, 12, 13, 23, 21, 31, 32 are the mutual impedances between each pair of parallel conductors. For example, R_{23} X_{23} is the mutual impedance between the 2nd and 3rd conductors.

The matrix should be symmetrical about the diagonal and entered in full. The program assumes symmetry and only stores and uses the diagonal and upper right triangle to conserve memory.

A suitable matrix can be developed by the user, using a line constants or similar program.

Example of a 3 wire coupled circuit between nodes 1a, 1b 1c and 2a, 2b 2c. The matrix is an impedance, or Z matrix:

```
c    3
m    1a    1b    1c
m    2a    2b    2c
z    0.32 0.94 0.17 0.43 0.08 0.29
z    0.17 0.43 0.32 0.94 0.21 0.45
z    0.08 0.29 0.21 0.45 0.32 0.94
```

F   Frequency specification. This must be followed, on the same line, by a single number representing the calculation frequency. The program will use the frequency specified for all internal impedance calculations. These are conductor self and mutual coupling impedances, line capacitances and pipeline impedances. If the frequency keyletter is used more than once, the program will stop with an error message. The algorithms may not be valid if the frequency is made too high.

Example to set the calculation frequency to 50 Hz:

F   50.0

I   Current source. This is a single current vector. It must be followed, on the same line, by the value of the current in complex vector form and the **from** and **to nodes**.

Example: To add a current source with a magnitude of 1000 amps and phase angle 120° between nodes **millgn** and **pha12**:

I   -500.0   866.0   millgn   pha12

T   Ideal single-phase transformer. This uses a similar data format to that of the **Z** and **I** keyletters. Ideal transformers must be specified using two **T** lines. The first has the information about the transformer primary and the second about the secondary. Only the voltages and nodes are specified.
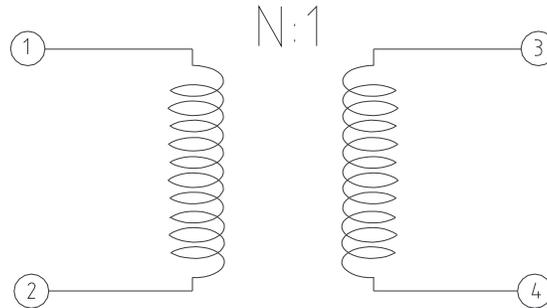
Figure 5.2 Ideal Transformer

Example: To specify an ideal transformer that transforms 40 kV between nodes 12 and 13 to 2.4 kV between nodes 14 and 15.

```
T     40.0    0.0    12    13
T      2.4    0.0    14    15
```

As can be seen, the voltage is entered as a vector with real and imaginary parts, followed by the node numbers. Internally, the primary and secondary voltages are translated into a transformer ratio, which could be complex to introduce a phase shift. As the transformer is ideal, only the ratio is important, but it is convenient to use real voltage levels.

Z   Basic single impedance - This specifies an impedance between a pair of nodes.

Example: An impedance of 12.3 + j18.4 Ω between nodes 9 and 13.

```
Z     12.3    18.4    9     13
```

There can be more than one impedance between a pair of nodes. The effect is for them to be placed in parallel. Capacitances can be entered using a -ve imaginary part with the real part zero for a lossless capacitor. Pure resistances have the imaginary part set to zero. Zero value impedances (0.0 + j0.0)cannot be used. Rather use a very small value like 1 milli-Ω (0.001 + j0.0). This is often useful for an applied short circuit as the program will report the current in every **Z** component. If it is a short circuit element, the current in the short circuit will be conveniently listed in the output file.

5.2 Keywords

Keywords must be the first entry on a new line in the input text file. Keywords never have other entries on the same line.

Many keywords require the conductor parameters "GMR" and "R_{ac}" [4].

GMR is the **g**eometric **m**ean **r**adius of the conductor. This is a the radius of a thin shell that is used as the basis for calculating the reactance of the conductor. For solid non-magnetic conductors, it can be calculated from the physical radius. For other conductors such as stranded and ACSR, there is no simple relationship. GMR is therefore usually obtained from tables of conductor data in books or manufacturer's catalogues.

R_{ac} is the ac resistance of the conductor at the frequency and ambient temperature applicable for the analysis. For small non-magnetic conductors it is the same as the dc resistance and can be calculated from the cross-sectional area of the conductor and resistivity of the metal. Users will usually obtain R_{ac} from tables in books or manufacturer's catalogues. Note that although the program will calculate real and imaginary impedances for the frequency specified by the **F** keyletter, it will not adjust the value of R_{ac} which must be chosen correctly for the frequency being used.

The keyword data uses a mix of units of measure. Metric measure is used for conductor location co-ordinates and length. These must be given in metres. Soil resistivity must also be given in Ω-metres. The units of measure most commonly used in North America are used for other parameters as the most widely available data is listed in these units. (The choice of feet for GMR seems strange as most conductors have GMR's much smaller than 1 foot). Conductor radius is required rather than diameter:

GMR	feet
R_{ac}	Ω/mile
Cable sheath inside and outside radius	inches

Many keywords require the entry of x,y co-ordinate information. A bundle of parallel conductors is viewed in cross section. The position of each conductor is given in metres as an x and y offset from the axis. The zero point on the y-axis is always at the soil surface. The zero point in the x-axis can be chosen to facilitate the data entry. For example, when specifying the cross-sectional x,y data for an overhead line on single poles, it is often convenient to use the pole as the zero x-point. For buried conductors such as cables and pipes, the y co-ordinate should be negative[5].

Only the **PARALLEL_LINE_C** keyword automatically calculates capacitance for overhead lines. It is planned to add capacitance calculation to the cable modules in future versions of the program

---

[5] The current version of the program cannot handle conductors that are below the soil surface. If conductors are located with y co-ordinate -ve, they will all be moved up so that none are below ground.

by adding **_c** to the end of the keyword. Cable capacitance can be included in calculations done with the present versions of the program by adding appropriate impedances with negative reactance values at the ends of cable segments.

All the keywords that specify parallel conductor systems such as cables with ground wires or overhead line conductors, produce a fully coupled system. They can therefore be used to model inductive coupling effects between parallel circuits by including all the conductors in one module.

Ground wires referred to in the modules are considered as insulated conductors. They can be overhead or underground in ducts or buried, however, it is assumed there is no ground contact. If ground contact is required in a model, an appropriate ground resistance must be added at the ends of each span of ground wire.

Three phase transformers of various types can be modelled. North American standards are for transformers to be connected so that if the connection is Y-Y or delta-delta, the higher voltage winding is labelled H1, H2, H3 and low-voltage X1, X2, X3. There is no phase shift between H1 and X1. If the transformer is Y-Delta or Delta-Y, the high side leads the low side by 30 degrees. i.e. H1 leads X1 by 30 degrees.

In the descriptions below, items enclosed in $<\ \ >$: denote the entry of a single value.

BUNDLE_PLUS_ONE　　　This keyword has limited application. It was developed to model the grounding contribution of many secondary cable sheaths to the ground impedance of a substation that supplies a distribution system. Often in distribution systems, underground cables are used to run feeders out from the substation to a point where they are terminated at overhead pole lines. There may be duct-bank systems with a number of cables and a single ground wire.

The keyword can be used to model the effective impedance of the group of parallel cable sheaths and ground wire. The modeling is efficient because the group of parallel cables and ground wires is reduced to a 2 x 2 matrix with all the cable sheaths represented as a single equivalent coupled with the single ground wire. If the ground wire is not required to be separated, a 1 x 1 matrix, or simple equivalent impedance can be obtained by using the keyword **REDUCE_BUNDLE_1.**

Data format:

```
BUNDLE_PLUS_ONE
<number of types>
<number of first type> <number of second type> ....
<from node 1> <from node 2>
<to node 1> <to node 2>
<1st inside radius> <1st outside radius> <1st sheath type>
<2nd inside radius> <2nd outside radius> <2nd sheath type>
.
.
.
<ground conductor GMR> <ground conductor Rac>
<soil resistivity>
x,y locations of cables and ground wire
<length>
```

The <number of types> is the number of different cable sheath types in the bundle. It is essentially the number of different sheath sizes. If all the cables are the same, there is only 1 type.

<number of first> <number of second> ..... is the number of each cable type. For example, if there were three different cables types, 2 cables of the first type, 4 of the second and 3 of the third, this line would be **2 4 3**.

The group of sheaths and the ground wire must run from two nodes to two other nodes. The nodes could be the same at one end or the other, but there must be two entries for each of these lines.

The required radii are the sheath inside and outside radii in inches. The <sheath type> has only three valid entries: **LEAD** means lead sheath, **AL** means aluminum and **CU** means copper. The program uses the following values of resistivity for the different metals:

> **LEAD** $21.9\ \mu\Omega$-cm
>
> **AL** $2.8\ \mu\Omega$-cm
>
> **CU** $1.724\ \mu\Omega$-cm
>
> Tip: concentric neutral cables often have tinned copper wire sheaths. The number of wires and their diameter can be used to calculate an equivalent copper cylindrical sheath with inside radius equal to the outside radius of the cable insulation and the outside radius slightly larger so that the cross-sectional area of the sheath equals the cross-section of the real copper wires.

The number of lines of sheath radius and sheath type must match the number of cable types. For example, if there are 3 cable types, there must be three lines of radius and sheath type information.

The ground wire is specified by one line containing the GMR in feet and R_{ac} in Ω/mile.

Soil resistivity is required in Ω-metres.

The location of the centre of each cable as a co-ordinate in the x,y cross-section must be given on a single line. This line may become quite long if there are many cables as each will require two numbers for each cable. The ground wire location is the last entry. For buried conductors, the y-coordinate should be negative.

The length of the parallel bundle must be given in metres.

Example:

```
BUNDLE_PLUS_ONE
3
2  1  2
a1  a1
b1  b1
1.01  1.11  AL
0.89  0.97  LEAD
0.95  1.01  AL
0.01902  0.235
250
0  0  0.2  0  0  0.2  0.2  0.2  0.4  0.2  0.4  0
2400
```

CABLES_AND_GROUND   This keyword is quite versatile. It is used to specify a bundle of any number of single conductor concentric neutral cables in parallel with any number of ground wires. There is no reduction in the size of the matrix. All conductors are available individually, so the keyword can be used to model cables with open ended sheaths and other unusual situations.

As the ground wires can be above or below ground, it is possible to calculate the effects of buried cables on parallel overhead lines. The overhead line conductors would be treated as ground wires in the data entry, but ground wire is only a terminology and they can be connected to phase circuits.

Either the number of cables or the number of ground wires can be zero. This enable modeling cables without any external ground wires or just a set of ground wires. The latter option is rather pointless as the **PARALLEL_LINE** keyword provides more flexibility for a parallel set of ground or other conductors.

Limitations are that all the concentric neutral cables in the bundle must be the same size with the same size phase conductor and sheath internal and external radii. Similarly, all the ground conductors must be the same. This is often acceptable if a set of three concentric neutral cables is being modelled. See **DIFF_CABLES_GND** for systems with different sized concentric neutral cables.

Data format:

```
CABLES_AND_GROUND
<number of cables> <number of ground wires>
from nodes
to nodes
<cable core GMR> <cable core Rac>
<sheath inside radius> <sheath outside radius> <sheath metal type>
<ground wire GMR> <ground wire Rac>
<soil_resistivity>
x,y locations of cables followed by ground-wires
<length>
```

The <number of cables> is the number of concentric neutral cables in the bundle. They must all be identical having the same core size and sheath dimensions.

The <number of ground wires> indicates the number of ground wires that are all the same, each having the same GMR and R_{ac}.

Each cable has two from nodes and two to nodes for the core and the sheath. Each ground wire has one from node and one to node. The nodes are entered in the order core, sheath, core, sheath,..... for each cable followed by each ground wire. Therefore, if there were three cables and 2 ground wires, there will be 8 from nodes and 8 to nodes. If the ground wires are joined at each end of the segment, the node names for the ground wires should be the same.

The cable core GMR is in feet and R_{ac} in Ω/mile.

The required radii are the cable sheath inside and outside radii in inches. The <sheath metal type> has only three valid entries: **LEAD** means lead sheath, **AL** means aluminum and **CU** means copper. The program uses the following values of resistivity for the different metals:

> **LEAD**   21.9 $\mu\Omega$-cm
>
> **AL**   2.8 $\mu\Omega$-cm
>
> **CU**   1.724 $\mu\Omega$-cm
>
> Tip: concentric neutral cables often have tinned copper wire sheaths. The number of wires and their diameter can be used to calculate an equivalent copper cylindrical sheath with inside radius equal to the outside radius of the cable insulation and the outside radius slightly larger so that the cross-sectional area of the sheath equals the cross-section of the real copper wires.

The ground wire GMR is in feet and R_{ac} in Ω/mile.

Soil resistivity is in Ω-metres.

The location of the centre of each cable as a co-ordinate in the x,y cross-section, must be given on a single line. This line may become quite long if there are many

cables as each will require two numbers for each cable. The ground wire locations follow the last cable entry. For buried conductors, the y-coordinate should be negative.

The length of the parallel bundle must be given in metres.

Example:

```
CABLES_AND_GROUND
3  2
a1  a1sh  b1  b1sh  c1  c1sh  g1  g1
a2  a2sh  b2  b2sh  c2  c2sh  g2  g2
0.03  0.51
0.75  0.756  CU
0.01902  0.235
270
0  0  0.2  0  0  0.2  0.2  0.2  0.4  0
1350
```

CROSS_BONDED   This keyword is similar to **CABLES_AND_GROUND**, but it simplifies entry of cross-bonded cable systems. In a three-phase cross-bonded cable system, there are three single conductor cables run in parallel. The load currents induce voltages in the cable sheaths that may be dangerous and/or cause sheath currents to circulate and overheat the cables. Cross-bonding splits the cable run into three segments. The sheaths are interconnected so that the induced voltages cancel out.

The module was originally developed to reduce computer memory usage. It condenses a set of three sheath rotations into a single matrix, eliminating the intermediate sets of nodes. 12 nodes are eliminated from the main matrix in this way.

It is quite complicated to prepare the cross-bonding data correctly. The cable configuration is also restricted in that the sheaths must be interconnected at each cross-bonding point and there can be no grounds at the cross-bonding points. It is probably quicker to set up a model with three segments of **CABLES_AND_GROUND** and to ignore the fact that more nodes must be used as this has a minimal impact on the more recent sparse versions of TACLINK.

Data format:

```
CROSS_BONDED
<number of cables> <number of ground wires>
from nodes
to nodes
<cable core GMR> <cable core Rac>
<cable inside radius> <cable outside radius> <sheath metal type>
<ground wire GMR> <ground wire Rac>
<soil resistivity>
x,y locations of cables followed by ground-wires (1st section)
index (1st section)
<length (1st section)>
x,y locations of cables followed by ground-wires (2nd)
index (2nd)
<length (2nd)>
x,y locations of cables followed by ground-wires (3rd)
index (3rd)
<length (3rd)>
```

The <number of cables> must be a multiple of three i.e. 3, 6, 9,..... The from and to nodes are listed in order:

<a1 phase> <a1 sheath> <b1 phase> <b1 sheath> <c1 phase> <c1 sheath> <a2 phase> <a2 sheath> <b2 phase> <b2 sheath> <c2 phase> <c2 sheath>.....<ground wire 1> <ground wire 2>.....

The cable core GMR is in feet and R_{ac} in Ω/mile.

The required radii are the cable sheath inside and outside radii in inches. The <sheath metal type> has only three valid entries: **LEAD** means lead sheath, **AL** means aluminum and **CU** means copper. The program uses the following values of resistivity for the different metals:

LEAD	21.9 $\mu\Omega$-cm
AL	2.8 $\mu\Omega$-cm
CU	1.724 $\mu\Omega$-cm

The ground wire GMR is in feet and R_{ac} in Ω/mile.

Soil resistivity is in Ω-metres.

For each of the three sections:

The location of the centre of each cable as a co-ordinate in the x,y cross-section, must be given in order, on a single line. This line may become quite long if there are many cables as each will require two numbers for each cable. The ground wire locations follow the last cable entry. For buried conductors, the y-coordinate should be negative.

A set of indices is required to state how the sheath circuits are connected and rotated. This is most easily explained with an example.

If there are 3 cables, the indices could be: 3 1 2. This means phase 1 has sheath 3, phase 2 has sheath 1 and phase 3 has sheath 2. For 6 cables, there would be 6 indices e.g. 3 1 2 2 1 3 and so on.

The length of the parallel bundle must be given in metres.

Example of 6 cables with the first section 530 metres long, second section 515 metres long and last section 560 metres long. Soil resistivity is 270 Ω-metres:

```
CROSS_BONDED
6  2
a1   g  b1   g  c1   g  a1   g  b1   g  c1   g   g   g
a2  g2  b2  g2  c2  g2  a3  g2  b3  g2  c3  g2  g2  g2
0.03  0.51
0.75  0.756  CU
0.01902  0.235
270
0  0  0.2  0  0  0.2  0.2  0.2  0.4  0.2  0.4  0  0.4  0.2  0.4  0
2 3 1 3 1 2
530
0  0  0.2  0  0  0.2  0.2  0.2  0.4  0.2  0.4  0  0.4  0.2  0.4  0
3 1 2 1 2 3
515
0  0  0.2  0  0  0.2  0.2  0.2  0.4  0.2  0.4  0  0.4  0.2  0.4  0
1 2 3 2 3 1
560
```

DELTA_DELTA   This keyword is used for simplified data entry of Δ-Δ transformers. The data format is the same as for **WYE_DELTA** and **WYE_WYE** except there are no ground nodes. See the **WYE_DELTA** keyword for more information:

```
DELTA_DELTA
pa  pb  pc
sa  sb  sc
<primary kV>
<secondary kV>
<MVA rating>
<percent impedance>
```

DELTA_WYE This keyword is used for simplified data entry of Δ-Y transformers. A corresponding **WYE_DELTA** keyword is provided for Y-Δ transformers. See the **WYE_DELTA** keyword for the data format, which is identical except that the ground node is on the secondary Y side.

DIFF_CABLES_GND   This keyword is similar to **CABLES_AND_GROUND** but it allows groups of three concentric neutral cables to have different parameters. Therefore,

it can only be used if there is a multiple of three concentric cables e.g. 3, 6, 9, ...
plus any number of ground wires including none.

The data format is the same as `CABLES_AND_GROUND,` but there must be a series of
cable parameter lines, one for each group of three cables. The ground wires must
all have the same parameters.

Data format:

```
DIFF_CABLES_GND
<number of cables> <number of ground wires>
from nodes
to nodes
<cable 1 core GMR> <cable 1 core Rac>
<sheath 1 inside radius> <sheath 1 outside radius> <sheath 1 metal type>
<cable 2 core GMR> <cable 2 core Rac>
<sheath 2 inside radius> <sheath 2 outside radius> <sheath 2 metal type>
.
.

<ground wire GMR> <ground wire Rac>
<soil_resistivity>
x,y locations of cables followed by ground-wires
<length>
```

The <number of cables> is the total number of concentric neutral cables in the
bundle. It must be a multiple of three.

The <number of ground wires> indicates the number of ground wires. They must
all be the same, each having the same GMR and R_{ac}.

Each cable has two from nodes and two to nodes for the core and the sheath. Each
ground wire has one from node and one to node. The nodes are entered in the or-
der core, sheath, core, sheath,..... for each cable followed by each ground wire.
Therefore, if there were three cables and 2 ground wires, there will be 8 from
nodes and 8 to nodes. If the ground wires are joined at each end of the segment,
the node names for the ground wires should be the same.

The cable core GMR is in feet and R_{ac} in Ω/mile.

The required radii are the cable sheath inside and outside radii in inches. The
<sheath metal type> has only three valid entries: `LEAD` means lead sheath, `AL`
means aluminum and `CU` means copper. The program uses the following values of
resistivity for the different metals:

`LEAD`	21.9 $\mu\Omega$-cm
`AL`	2.8 $\mu\Omega$-cm
`CU`	1.724 $\mu\Omega$-cm

A pair of lines describing the core parameters and sheath are required for each group of three cables.

The ground wire GMR is in feet and R_{ac} in Ω/mile.

Soil resistivity is in Ω-metres.

The location of the centre of each cable as a co-ordinate in the x,y cross-section, must be given on a single line. This line may become quite long if there are many cables, as each will require two numbers for each cable. The ground wire locations follow the last cable entry. For buried conductors, the y-coordinate should be negative.

The length of the parallel bundle must be given in metres.

Example:

```
DIFF_CABLES_GND
6  2
a1   g  b1   g   c1   g  a1   g  b1   g  c1   g   g   g
a2  g2  b2  g2  c2  g2  a3  g2  b3  g2  c3  g2  g2  g2
0.03  0.51
0.75  0.756  CU
0.02  0.7
0.65  0.656  CU
0.01902  0.235
270
0  0  0.2  0  0  0.2  0.2  0.2  0.4  0.2  0.4  0  0.4  0.2  0.4  0
550
```

END   This is the last keyword in the file. It signals that there is no more input data. It must be used, or the program will stop with an error message.

PARALLEL_LINE

PARALLEL_LINE_C   These two keywords are used for any arrangement of parallel conductors such as between towers of a transmission line. The keyword version that ends in **_C** will calculate line capacitance, which is significant for long lines, as well as the conductor self and mutual impedances. There can be any number of parallel conductors.

Data entry is simplified by the use of a conductor parameter database that can be edited by the user. The standard conductor sizes and types are listed in the database, for example 266.8 ACSR or #4/0 Cu. TACLINK will look up the corresponding GMR, R_{ac} and diameter of the conductor from the database. Other conductor sizes and types can be added to the database and given unique names. The database is described in Section 6.

If the `PARALLEL_LINE_C` keyword is used, another output file with the name extension `.CAP` will be generated. It will contain the information about capacitances that the program calculated and added to the model. The information is placed in a separate file because it can become quite extensive and often does not need to be retained.

Data format (Use only one of the keywords):

```
PARALLEL_LINE
PARALLEL_LINE_C
<number of conductors>
from nodes
to nodes
<size of 1st conductor> <type of 1st conductor>
<x coordinate of 1st conductor> <y coordinate of 1st conductor>
<size of 2nd conductor> <type of 2nd conductor>
<x coordinate of 2nd conductor> <y coordinate of 2nd conductor>
        .
        .
        .
<size of nth conductor> <type of nth conductor>
<x coordinate of nth conductor> <y coordinate of nth conductor>
<soil resistivity>
<length>
```

The <number of conductors> is the total number of all the parallel conductors in the segment. For example, if there are two three-phase circuits on structures that have two sky or shield wires, the number of conductors would be 8.

The list of "from nodes" and "to nodes" must contain node names for every conductor. In the above example with 8 conductors, there must be 8 from nodes and 8 to nodes. As for other modules, if two conductors are connected at either end, the same node name can be given to each. This could happen in the case of a double sky-wire line as both sky wires could be connected to the towers at each end of a line segment.

Conductor information is required for every conductor using two lines. The first line has the <size> and <type>. As discussed in Section 6, these are merely convenient descriptive names. They must have matching data in the conductor database. The second line has the conductor location in the group of parallel conductors. It is specified as an x-y view looking at the cross-section of the line. Any zero reference can be used for the x dimension. The y zero is ground level. Conductors cannot be located underground. x-y dimensions are in metres.

If there are 8 parallel conductors, as in the above example, there must be 8 pairs of lines specifying the size, type and x-y location of each, even if some of the conductors are the same size and type.

Two conductors cannot be placed in the same location. If a double or quad conductor formation is required, it can be done using 2 or four conductors for each

phase, spacing them properly and giving them the same nodes at each end. The bundling will happen automatically.

The last two lines of the **parallel_line** module have the soil resistivity in Ω-metres and length in metres.

Example of a three conductor transmission line with Arbutus AAAC phase conductors and an aluminum optical ground wire near the top of the pole.

```
parallel_line
4
46a  46b  46c  46g
a1a  a1b  a1c  a1g
ARBUTUS  AAAC
1.016  19.05
ARBUTUS  AAAC
-1.016  17.526
ARBUTUS  AAAC
1.016  16.002
40/46OGW AAAC
0.2032  21.184
645
600
```

REDUCE_BUNDLE_1 This keyword is identical to **BUNDLE_PLUS_ONE** but reduces the bundle to a single equivalent impedance. Data entry is identical to **BUNDLE_PLUS_ONE**, except that there is only one "from node" and one "to node". See **BUNDLE_PLUS_ONE** for data entry format.

Example: (only part is shown)

```
REDUCE_BUNDLE_1
3
2  1  2
a1
b1
1.01  1.11  AL
.
.
.
```

SOURCE_P This is one of several keywords starting with **SOURCE_** that can be used to specify a three-phase power source.

Because TACLINK uses nodal network analysis, power sources are required in the form of current sources. This can be done for a three-phase source using the **I** keyletter three times to specify 3 current sources, with the appropriate phase angles and a 3 x 3 admittance matrix. The **SOURCE_*** keywords (where * is **P**, **S** or

Z) greatly simplify this by developing the current sources and matrix from simple input data. The calculation results contain the detailed current sources and matrix.

SOURCE_P is the per-unit symmetrical components version of the keyword. It should be used when the power source is given as per-unit positive and zero sequence impedances on a particular base. The data format is:

```
SOURCE_P
a  b  c
g
<line-to-line kV>
<base kV> <base MVA>
<positive sequ. impedance r> <positive sequ. impedance x>
<zero sequ. impedance r> <zero sequ. impedance x>
<phase angle>
```

a   b   c are the phase bus node names of the power source. **g** is the ground node name. Usually the ground resistance of a power source substation will be connected between **g** and ground.

The **<line-to-line kV>** is the nominal pre-fault operating line-to-line kV of the system. It does not have to be the same as the **base kV**.

<base kV> <base MVA> are the base voltage and MVA values applicable to the per-unit sequence impedances.

The positive and zero sequence impedances are in per-unit values on the above base values and must be given in real and imaginary notation. Often only the reactive (imaginary) part is used. The real part is then zero.

The last entry for the power source is the phase angle of Phase A. It is usually 0°, but may need to be + or -30° when there are power sources on opposite sides of three-phase transformers. It may be some other value when there are long lines with capacitance in the model.

Example:

```
source_p
sub3a   sub3b   sub3c
sub3g
140
138  100
0.12  0.33
0.14  0.49
60.0
```

SOURCE_S   This is the "ohms" version of the three-phase power source. It is the same as the per-unit version except that the sequence impedances are in Ω and the line specifying base kV and MVA is omitted. See **SOURCE_P** for more information.

Example:

```
source_s
sub3a   sub3b   sub3c
sub3g
140
4.2  8.0
0.4  1.0
60.0
```

SOURCE_Z   This is the non-symmetrical components version of the three-phase power source. It is the same as the **SOURCE_S** version except that self and mutual impedances of the source are used instead of sequence impedances. The data format is:

```
SOURCE_Z
a   b   c
g
<line-to-line kV>
<self impedance real> <self impedance imaginary>
<mutual impedance real> <mutual impedance imaginary>
<phase angle>
```

Self and mutual impedances are related to positive and zeros sequence impedances as follows: $Z_{pos} = Z_{self} - Z_{mutual}$ and $Z_{zero} = Z_{self} + 2Z_{mutual}$.

Example:

```
source_z
sub3a   sub3b   sub3c
sub3g
140
4.2  8.0
0.4  1.0
60.0
```

THREE_COND_GND   This keyword is used to specify a bundle of any number of three conductor cables in parallel with any number of ground wires. There is no reduction in the size of the matrix. All conductors are available individually, so the keyword can be used to model cables with open ended sheaths and other unusual situations.

As the ground wires can be above or below ground, it is possible to calculate the effects of buried cables on parallel overhead lines. The overhead line conductors are treated as ground wires in the data entry, but ground wire is only a terminology and they can be connected to phase circuits.

Either the number of cables or the number of ground wires can be zero. This enable modeling cables without any external ground wires or just a set of ground wires. The latter option is rather pointless as the **PARALLEL_LINE** keyword provides more flexibility for a parallel set of ground or other conductors.

Limitations are that all the cables in the bundle must be the same size with the same size phase conductors and sheath internal and external radii. Similarly, all the ground conductors must be the same.

Data format:

```
THREE_COND_GND
<number of cables> <number of ground wires>
from nodes
to nodes
<cable core GMR> <cable core Rac>
<sheath inside radius> <sheath outside radius> sheath_metal_type>
<ground wire GMR> <ground wire Rac>
<soil resistivity>
x,y locations of cables followed by ground-wires
<length>
```

The <number of cables> is the number of three conductor cables in the bundle. They must all be identical having the same core size and sheath dimensions.

The <number of ground wires> indicates the number of ground wires that are all the same, each having the same GMR and R_{ac}.

Each cable has four from nodes and four to nodes for the three phase conductors and the sheath. Each ground wire has one from node and one to node. The nodes are entered in the order phase A, B, C, sheath, phase A, B, C, sheath,..... for each cable followed by each ground wire. Therefore, if there were two cables and 2 ground wires, there will be 10 from nodes and 10 to nodes. If the ground wires are joined at each end of the segment, the node names for the ground wires should be the same.

The cable core GMR is in feet and R_{ac} in Ω/mile.

The required radii are the cable sheath inside and outside radii in inches. The <sheath metal type> has only three valid entries: **LEAD** means lead sheath, **AL** means aluminum and **CU** means copper. The program uses the following values of resistivity for the different metals:

LEAD	21.9 $\mu\Omega$-cm
AL	2.8 $\mu\Omega$-cm
CU	1.724 $\mu\Omega$-cm

The ground wire GMR is in feet and R_{ac} in Ω/mile.

Soil resistivity is in Ω-metres.

The location of the centre of each cable as a co-ordinate in the x,y cross-section, must be given on a single line. This line may become quite long if there are many cables as each will require two numbers for each cable. The ground wire locations

follow the last cable entry. For buried conductors, the y-coordinate should be negative.

The length of the parallel bundle must be given in metres.

Example (The cables are in parallel at the "from" end):

```
THREE_COND_GND
2  2
a1  b1  c1  g1  a1  b1  c1  g1  g1  g1
a2  b2  c2  g2  a3  b3  c3  g2  g2  g2
0.03  0.51
0.95  1.05  LEAD
0.01902  0.235
270
0  0  0.2  0  0  0.2  0.2  0.2
1850
```

WIRE_PIPE This is similar to `parallel_line`. As well as allowing lines with more than one parallel conductor to be specified, it allows any number of parallel buried steel pipelines to be included. The pipeline segment is converted to a π network which is properly coupled with the other conductors. This is quite accurate providing the pipe segments are short enough. The program will print warning messages if the segments are too long. When this occurs, the segment should be split into two or more shorter length segments.

The keyword can be used for parallel systems that consist of only wires, in which case it is the same as `parallel_line` or systems that only have pipes and no parallel wires. Note that the wires and pipes can have different lengths. This was done because often a parallel pipeline is at an angle to the power line. Its incremental length may be different from the power line length. The calculation uses the wire length for the self-impedances of the wires and the mutual impedances between the wires. It uses the pipe length for the pipe impedances and the mutual impedances between pipes (if there is more than one pipe) and between pipes and wires.

Data format:

```
WIRE_PIPE
<number of wires> <number of pipes>
from nodes
to nodes
<size of 1st conductor> <type of 1st conductor>
<x coordinate of 1st conductor> <y coordinate of 1st conductor>
<size of 2nd conductor> <type of 2nd conductor>
<x coordinate of 2nd conductor> <y coordinate of 2nd conductor>
       .
       .
       .
<size of nth conductor> <type of nth conductor>
```

```
<x coordinate of nth conductor> <y coordinate of nth conductor>
<wire length>

<1st pipe diameter> <wall thickness> <μ steel> <ρ steel> <Rcoat>
<x coordinate of 1st pipe> <y coordinate of 1st pipe>
<2nd pipe diameter> <wall thickness> <μ steel> <ρ steel> <Rcoat>
<x coordinate of 2nd pipe> <y coordinate of 2nd pipe>
        .
        .
        .
<nth pipe diameter> <wall thickness> <μ steel> <ρ steel> <Rcoat>
<x coordinate of nth pipe> <y coordinate of nth pipe>
<pipe length>
<soil resistivity>
```

See the **parallel_line** and **parallel_line_c** keywords for the conductor data requirements.

For the pipes, the outside diameter of the pipe and wall thickness are in inches. μ steel is a dimensionless number being the ratio of the magnetic properties of the pipe steel compared with air. A typical value is 300. ρ steel is the resistivity of the pipe steel in $\mu\Omega$-metres. It is typically 0.17 $\mu\Omega$-metres. R_{coat} is the coating resistance in kΩ-ft^2. It is the leakage resistance across 1 square foot of the pipe coating and should not be confused with the coating resistivity. Values can vary widely from 1 to 1000 kΩ-ft^2 depending on the age of the pipeline.

In the present version, it is not possible to specify the coating thickness or dielectric constant. They are assumed to be 40 mils and 2.3 respectively. The calculation of the pipe impedance always includes the effect of the coating capacitance, which is in parallel with the coating resistance.

The location of the centre of each wire or pipe, as a co-ordinate in the x,y cross-section, must be given on the lines indicated. For buried conductors, the y-coordinate should be negative. The pipe must be buried and have a negative y co-ordinate

The keyword is only for buried pipelines. It cannot be used for above-ground pipelines.

WYE_DELTA This keyword is used for simplified data entry of Y-Δ transformers. A corresponding **DELTA_WYE** keyword is provided for Δ-Y transformers. The data format is:

```
WYE_DELTA
pa   pb   pc
sa   sb   sc
pg
<primary kV>
<secondary kV>
```

```
<MVA rating>
<percent impedance>
```

`pa, pb` and **`pc`** are the primary side phase nodes of the transformer. **`sa, sb`** and **`sc`** are the secondary phase nodes. **`pg`** is the primary ground node or star point. **`<primary kV>`** and **`<secondary kV>`** are the line-to-line primary and secondary voltages respectively. **`<percent impedance>`** is the impedance of the transformer in percent, based on the MVA rating. If the transformer has several MVA ratings with different cooling, the correct MVA rating must be used with the percent impedance. Usually this is given for the lowest MVA rating.

All transformer modules are converted to sets of single-phase transformers by TACLINK. The transformer impedance is added using internal nodes that are given names like @T1A. The '@' symbol is reserved for this and cannot be used for other node names.

Transformer impedance is assumed to be a pure reactance. The winding resistance is ignored as is the magnetizing impedance. These effects can be added using external impedances in series with the terminals or across them.

Example of a 20 MVA 138:12 kV Y-Δ transformer with 9.1% impedance:

```
wye_delta
qpa   qpb   qpc
qsa   qsb   qsc
qgrid
138.0
12.0
20.0
9.1
```

WYE_WYE   This keyword is used for simplified data entry of Y-Y transformers. The data format is the same as for **WYE_DELTA**, except there are two ground nodes - **`pg`** is the primary star point and **`sg`** is the secondary star point. See the **WYE_DELTA** keyword for more information:

```
WYE_WYE
pa   pb   pc
sa   sb   sc
pg   sg
<primary kV>
<secondary kV>
<MVA rating>
<percent impedance>
```

WYE_WYE_DELTA_TEST

WYE_WYE_DELTA_TEE   These keywords are used for simplified data entry of Y-Y-Δ three-winding transformers. Two versions are provided. They use either test data

(**WYE_WYE_DELTA_TEST)** or the equivalent tee circuit for the transformer
(**WYE_WYE_DELTA_TEE)**.

For both of these keywords, the transformer windings are, by convention, called
High, Low and Tertiary. The High winding is the primary Y winding. Low is the
secondary Y. Tertiary is the third Δ winding.

The **_TEST** version uses positive and zero symmetrical component impedances
that are obtained directly from testing the transformer. These impedances are
named HL, HT and LT using the first letter of the High, Low and Tertiary names.
The impedances are measured by short-circuiting the second winding while meas-
uring the first. For the positive sequence measurement, a small three phase voltage
is applied to the first winding. For the zero sequence measurement, a single-phase
voltage is applied to the three terminals in parallel. The impedances are given by
the voltage divided by the current.

For example, the HL impedance is the impedance at the High or primary terminals
with the Low or secondary terminals short circuited.

The **_TEE** version uses the equivalent T impedances Z_H, Z_L and Z_T of the trans-
former. These are related to the test impedances as follows.

$$Z_H = \frac{1}{2}(Z_{HL} + Z_{HT} - Z_{LT})$$

$$Z_L = \frac{1}{2}(Z_{HL} + Z_{LT} - Z_{HT})$$

$$Z_T = \frac{1}{2}(Z_{LT} + Z_{HT} - Z_{HL})$$

All impedances are in percent based on the winding kV and a base MVA. Usually,
the MVA will be the transformer rating for the test data.

Note that even if the Δ winding is not used, at least one corner must be connected
to a path to ground or TACLINK will fail with a "floating components" error mes-
sage.

TACLINK models the transformer as two sets of 3 single phase transformers. The
first set represents the H-L windings and the second set the H-T windings. Because
the TACLINK transformer element is perfectly coupled, there is no need to have
another set of windings to represent the L-T coupling because this is implicit in that
there is L-H and H-T coupling. The impedances are modelled by adding impedances
to the equivalent circuit.

The required impedances are self and mutual impedances for each winding. The
concept of winding self-impedance is easy to visualise. It is really the impedance
due to transformer leakage reactance and winding resistance. The resistance is usu-
ally neglected as being much smaller than the reactance.

When a three winding transformer is modelled, the calculation results will contain 6 single phase transformers and three impedance matrices. 9 '@' nodes will be added by the program, to include the impedance matrices.

The data formats are:

```
wye_wye_delta_test
pa   pb   pc
sa   sb   sc
ta   tb   tc
pg   sg
<primary kV>
<secondary kV>
<tertiary kV>
<base MVA>
<positive HL> <positive HT> <positive LT>
<zero HL> <zero HT> <zero LT>
```

or

```
wye_wye_delta_tee
pa   pb   pc
sa   sb   sc
ta   tb   tc
pg   sg
<primary kV>
<seconmdary kV>
<tertiary kV>
<base MVA>
<positive H> <positive L> <positive T>
<zero H> <zero L> <zero T>
```

`pa, pb` and `pc` are the primary side phase nodes of the transformer. `sa, sb` and `sc` are the secondary phase nodes. . `ta, tb` and `tc` are the tertiary phase nodes. `pg` is the primary ground node or star point. `sg` is the secondary ground node or star point.

The `<primary kV>, <secondary kV>` and `<tertiary kV>` are line to line kV for the primary, secondary and tertiary windings. `<base MVA>` is the MVA used for the impedances.

`positive` and `zero` refer to the positive sequence and zero sequence impedances in percent based on the winding kV and base MVA used. HL, HT and LT are the test impedances for `wye_wye_delta_test` and H, L and T are the equivalent tee impedances for `wye_wye_delta_tee`.

6. CONDUCTOR PARAMETER DATABASE

TACLINK requires that a text file named **COND.DAT** be located in the same directory as the program files or on the computer PATH. TACLINK will first look in the program directory for

this file and then all the directories listed in the PATH environment variable. The first file found will be used.

COND.DAT contains a database of conductor parameters that are used by the program to calculate self-impedances and line capacitance, using the keyword **parallel_line** or **parallel_line_c**. The file can be edited by the user to add, change or delete any of the items. Every conductor size and type that is specified in a **parallel_line** module, must have corresponding data in this file or the program will stop with an error message.

The data file size is virtually unlimited. Only needed data is loaded by the program, so that memory is not wasted. The whole file is, however, quickly scanned for basic data errors, each time the program runs. Errors that will be detected are:

>   Duplicated entries, where both the conductor size and type (see below) are the same.

>   Missing data. All the required fields must be filled on each data line.

>   Non-numerical data where numbers are required.

The format of the data in the **COND.DAT** text file is for each line to have 6 parameters, separated by spaces, describing the properties of the conductor:

`<size> <type> <GMR> <Rac> <Rdc> <diameter> Add any comments here`

The line may continue with a comment as is shown. The comment is ignored.

Example:

`300 ACSR 0.0241 0.311 0.311 0.700 30-2/7 30 strands 2 layers al/7 steel`

Entries are not case sensitive and are converted to upper case by the program. **ACSR** & **acSR** will be the same type of conductor.

`<size>` and `<type>` are merely descriptors. They are not used mathematically. The impedance is computed from the parameters that follow. Having two descriptors makes it easier to list conductors that are the same size, but made from different materials. For example #4/0 Cu and #4/0 ACSR are two different conductors. Both are #4/0.

size   Can be any combination of up to 30 letters, numbers and symbols to identify the conductor. In the example above, **300** is the size of the conductor in MCM or kCM.

type   This is also a descriptor. The word used has no effect on the parameters. There are only a few valid entries. The type helps to distinguish between the same size conductor, but different types, for example **300 Cu** for copper or **300 ACSR** for ACSR.

Valid types are:

AAAC   All Aluminum Conductor

ACSR	Aluminum Conductor Steel Reinforced	
AL	Aluminum	
ALSOLID	Solid Aluminum	
ALUMOWELD	Alumoweld Type	
CU	Copper	
RAIL	Railway rails. As for steel conductors, the parameters of steel railway rails are dependent on the ac current flowing in them. The naming used is illustrated by the example **1CA115**, which is for a 115 lbs./yard rail carrying 100 amps at 60 Hz.	
STEEL	Steel - for sky-wires etc. There are a few steel conductor entries in the table provided with the program. For example **1CA3/8** is used for a 3/8 inch diameter steel conductor carrying 100 amps at 60 Hz.	

GMR   This conductor Geometric Mean Radius [4] in feet. It is usually found in tables of conductor properties. For steel conductors, both **GMR** and R_{ac} depend on the current flowing and it may be necessary to have several entries using different ac currents.

R_{ac} The ac resistance of the conductor in Ω/mile. It is usually found in tables of conductor properties for a range of temperatures and frequencies. R_{ac} is used for ac calculations (TACLINK).

R_{dc} The dc resistance of the conductor in Ω/mile. It is usually found in tables of conductor properties for a range of temperatures. R_{dc} is used for dc calculations (TACDC).

diameter   The diameter of the round conductor in inches. This is only used by the ac program, to calculate line capacitance.

If the R_{dc} and **diameter** are not known, **-1.0** can be entered as a filler, however, dc calculations and ac calculations with capacitance, will not be possible for those conductors.

7. CALCULATION METHODOLOGY

7.1 Self and Mutual Impedances

Conductor self and mutual impedances are calculated using equations developed by J.R. Carson [5].

The equations developed by Carson form an infinite, but converging series of terms. H.W. Dommel [6,9] developed a convenient form of the series to facilitate computer calculation of enough terms to achieve high accuracy under all conditions. Carson's equations are only valid for conductors above ground, however, in a later paper, he shows that the impedances of conductors buried at "typical distances below the earth's surface", are substantially the same as conductors at zero height above ground.

TACLINK uses the Carson series for all self and mutual impedance calculations. The only exceptions are:

1. Self impedance of cable sheaths.

2. Mutual impedance between a cable sheath and the core conductor of that cable.

Where parallel conductor systems contain cables, pipes and wires or more than one cable, Carson will still be used for the mutual impedances between two cable sheaths and between a cable sheath and the core conductor of another cable. For a three conductor cable, the mutual impedance between a core and the sheath is calculated as if the core was in the centre of the cable. In reality, each core is offset from the centre. The mutual impedances between the cores are calculated from geometry based on the inside diameter of the sheath. The conductors and insulation are assumed to be circular and in a triangular formation inside the sheath.

A different procedure is used for the impedances in Items 1 and 2 above. It is based on Chapter III of [7], which is also based on Carson's work.

Self and mutual impedance calculations based on Carson's work assume that the conductors and the parallel exposures are infinitely long. This is reasonable for long transmission and distribution lines. It should also work quite well for lines that are formed out of a number of shorter end-to-end segments that are joined, as in a line with nodes for each tower. The combined effect is the same as a long line.

There are alternative methods for calculating the mutual impedance between short conductors, but these will not compensate properly for end-to-end segments where there is coupling between conductors in different adjacent segments. Very complex coupled systems would be needed to apply the short conductor process and properly compensate for the adjacent segments. As there is no reasonable alternative to Carson, it is used by most electrical utilities and engineers involved with transmission and distribution system.

Carson assumes that all conductors are above the surface of the earth. TACLINK's version of Carson includes the height factor, which has some effect on self and mutual impedances. In the

past, the height was usually not considered when calculating conductor self-impedances. The error in making this assumption was small.

To avoid other errors in applying Carson, TACLINK will move a set of conductors so that all are above the earth surface if any are specified with negative height. As stated above, the effect on impedances is small. An exception is that pipeline impedances are always calculated for the actual burial depth.

The self impedance calculations use the parameters Geometric Mean Radius (GMR) and ac resistance (R_{ac}) of the conductor.

The original concept of GMR was that it represented the radius of a thin cylinder within which the internal reactance of a conductor exists. This could be calculated for solid or hollow conductors that are not magnetic and small enough that skin effects are negligible. The name GMR is misleading for large conductors with skin effect and conductors with magnetic properties such as ACSR conductors. However, it can be determined for these conductors and is still widely used.

Due to skin effect and magnetic effects of steel cored conductors, ac resistance changes with frequency. Even at 60 Hz, it is different from dc resistance for large conductors.

The conductor impedance keywords require GMR and R_{ac}. They can usually be found in tables published by conductor manufacturers and some other books [10,11].

For magnetic conductors such as steel static wires on transmission lines, both GMR and R_{ac} are dependent on the current flowing in the conductor. The non-linear characteristics for some steel conductors can be found in graphical format in [4]. This is an effect that TACLINK cannot presently simulate. An iterative approach could be used where an initial guess is made as to the current flowing in the steel cable and the impedance is based on the GMR and R_{ac} for that current. When the actual current has been calculated, a new impedance can be used based on the GMR and R_{ac} for the calculated current. This may modify the current, requiring that the process be repeated a number of times.

7.2 Capacitance

When parallel conductors are modelled with capacitance, the capacitance is added as a matrix of shunt values. As each capacitance exists as a distributed element along the parallel conductor segment, it is split into two parts that are added to the nodes at each end of the segment.

First the shunt capacitance matrix is calculated by forming Maxwell's potential coefficient matrix and inverting it [9]. The coefficient matrix assumes that the air is lossless, the earth is at zero potential and the conductor radii are an order of magnitude smaller than the spacing between conductors. These are usually reasonable assumptions.

The diagonal values of the matrix are given by:

$$P_{ii}^{'} = \frac{1}{2\pi\varepsilon_0} \ln \frac{2h_i}{r_i}$$

The off-diagonal values are given by:

$$P_{ik}^{'} = P_{ki}^{'} = \frac{1}{2\pi\varepsilon_0} \ln \frac{D_{ik}}{d_{ik}}$$

In these equations ε_0 is the permittivity of free space. h_i is the height the conductor is above ground. r_i is the radius of the conductor. D_{ik} is the distance between one conductor and the image of the other one below the surface of the earth. d_{ik} is the direct distance between the two conductors.

When the potential coefficient matrix is inverted, the values returned represent the capacitances as follows:

Diagonal elements are the sum of all capacitances between a conductor and each other conductor and ground.

Off-diagonal elements are the negative shunt capacitances between pairs of conductors.

The capacitance to ground of each conductor can therefore be calculated by adding the associated off-diagonal values.

Once the capacitances are known, the program calculates the negative reactance of each capacitance and adds twice that value (½ the capacitance) to each end of the parallel line segment.

7.3 Pipelines

Pipelines can be analyzed using transmission line theory as applied in radio frequency transmission lines [8]. In the same way that an electrical co-axial cable has a characteristic impedance Z_0 and velocity of propagation γ, a pipeline has a characteristic impedance and velocity of propagation. Z_0 for a co-axial cable may have a value of 50 or 75 Ω. It is much lower for a pipeline and is also a complex impedance rather than a pure resistance.

TACLINK uses nodal network analysis and cannot directly incorporate calculations based on transmission line theory. However, provided the pipeline lengths are short, they can be quite accurately simulated by lumped impedances. For a long pipeline, many short segments can be used.

The suggested criteria for a short pipeline [8] is $0.1\frac{1}{\gamma}$ if γ is in /km units. TACLINK checks the length used and will print warning messages if the lengths are too long. The lengths should be shortened until there are no warning messages, or the calculation error may be excessive.

Pipelines can be included in TACLINK using the **WIRE_PIPE** keyword. When this keyword is encountered, the mutual impedances between the wire conductor/s and the pipeline/s are calculated using Carson's equations, as for other coupled circuits. The self-impedances of the wires are calculated in the same way. The pipeline segment is converted into a π-equivalent circuit using lumped impedances as follows:

- Algorithms from [8] are used to calculate the impedance of the length of pipe when a short-circuit is applied at the other end and when an open-circuit is applied.

- The self-impedance of the pipeline segment is the short-circuit impedance value.

- The open-circuit impedance value gives the ground contact of the pipeline segment. This is doubled and added to the pipeline node at each end.

The method used has been tested against another computer program CONIND, developed by Ground-it.com Consulting Ltd. The results agreed well.

8. REFERENCES

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3. F. Dawalibi, Ground Fault Current Distribution Between Soil and Neutral Conductors", IEEE Trans. on PAS, Vol. PAS-99, No. 2, March/April, 1980.

4. C.F. Wagner, R.D. Evans, "Symmetrical Components", McGraw Hill Book Company, 1933

5. J.R. Carson, "Wave Propagation in Overhead Wires with Ground Return", Bell System Technical Journal Vol. 5 pp 539-555, October 1926.

6. H.W. Dommel: Discussion following "Electromagnetic Effects of Overhead Transmission Lines - Practical Problems, Safeguards and Methods of Calculation", IEEE Trans. vol PAS-93 issue 3 892-904, May-June 1974.

7. E. Clark, "Circuit Analysis of A-C Power Systems - Volume II", John Wiley & Sons, Inc., 1957.

8. "Mutual Design Considerations for Overhead AC Transmission Lines and Gas Transmission Pipelines, Volume 1 Engineering Analysis - Final Report", EPRI EL-904, AGA Cat. No. L51278, September 1978.

9. H.W. Dommel et al, "Electromagnetic Transients Program Reference Manual (EMTP Theory Book)", Prepared for Bonneville Power Administration, Portland, Oregon, August 1986.

10. "Electrical Transmission and Distribution Reference Book", Central Station Engineers, Westinghouse Electric Corporation, 1964.

11. "Transmission Line Reference Book - 345 kV and Above/Second Edition", Electric Power Research Institute, Palo Alto, California, 1982.

Listing of sample input data file:

```
* Lines starting with an asterisk can be used for comments. They are
* ignored by the program. Also, blank lines can be used.

f 60


source_z                           Power source at Mountain
ma   mb   mc                       Phase bus nodes
mgrid                              Ground bus node
138                                Line-to-line kV
0.0   8.0                          Self impedance of source
0.0   0.0                          Mutual impedance of source
0.0                                Phase angle of phase A voltage in degrees
z   0.55    0.0 mgrid    gnd


parallel_line                      Section 1 of transmission line from
*                                  Mountain to substation Quadra
4                                  number of parallel conductors
ma    mb    mc    mgrid            from nodes
m1a   m1b   m1c   m1g              to nodes
477 ACSR                           size and type of first conductor
0.6   28.0                         x and y coordinates of first cond - metres
477 ACSR                           size and type of second conductor
0.6   24.0                         x and y coordinates of second conductor
477 ACSR                           size and type of third conductor
0.6   20.0                         x and y coordinates of third conductor
1ca3/8 steel                       size and type of sky-wire 3/8 inch steel
0.0   32.0                         x and y coordinates of sky-wire
42.0                               soil_resistivity
2000.0                             length metres

z    7.0   0.0   m1g    gnd        tower resistance to ground


parallel_line
4
m1a   m1b   m1c   m1g
m2a   m2b   m2c   m2g
477 ACSR
0.6   28.0
477 ACSR
0.6   24.0
477 ACSR
0.6   20.0
1ca3/8 steel
0.0   32.0
42.0
5000.0

z    4.0   0.0    m2g    gnd
```

```
parallel_line
4
m2a  m2b  m2c  m2g
m3a  m3b  m3c  m3g
477 ACSR
0.6  28.0
477 ACSR
0.6  24.0
477 ACSR
0.6  20.0
1ca3/8 steel
0.0  32.0
42.0
5000.0

z   6.0   0.0   m3g   gnd

parallel_line
4
m3a  m3b  m3c  m3g
qpa   qpb   qpc   qgrid
477 ACSR
0.6  28.0
477 ACSR
0.6  24.0
477 ACSR
0.6  20.0
1ca3/8 steel
0.0  32.0
42.0
5000.0

source_z                      Power source Norfolk
na  nb  nc
ngrid
138
0.0  20.0
0.0  0.0
0.0
z   1.3   0.0  ngrid   gnd

parallel_line                 Section 1 of transmission line from
*                             Norfolk to substation Quadra
5
na   nb   nc   ngrid    ngrid
n1a  n1b  n1c  n1g      n1g
336.4 ACSR
0.0  20.0
336.4 ACSR
4.0  20.0
336.4 ACSR
8.0  20.0
1ca3/8 steel
2.0  26.0
1ca3/8 steel
6.0  26.0
30.0
1000.0
```

```
z  10.0    0.0    n1g    gnd

parallel_line
5
n1a  n1b  n1c  n1g  n1g
n2a  n2b  n2c  n2g  n2g
336.4 ACSR
0.0  20.0
336.4 ACSR
4.0  20.0
336.4 ACSR
8.0  20.0
1ca3/8 steel
2.0  26.0
1ca3/8 steel
6.0  26.0
30.0
3000.0

z    5.0    0.0    n2g    gnd

parallel_line
5
n2a  n2b  n2c  n2g  n2g
n3a  n3b  n3c  n3g  n3g
336.4 ACSR
0.0  20.0
336.4 ACSR
4.0  20.0
336.4 ACSR
8.0  20.0
1ca3/8 steel
2.0  26.0
1ca3/8 steel
6.0  26.0
30.0
3000.0

z    3.0    0.0    n3g    gnd

parallel_line
5
n3a  n3b  n3c  n3g        n3g
qpa  qpb  qpc  qgrid      qgrid
336.4 ACSR
0.0  20.0
336.4 ACSR
4.0  20.0
336.4 ACSR
8.0  20.0
1ca3/8 steel
2.0  26.0
1ca3/8 steel
6.0  26.0
30.0
1000.0
```

```
source_z                         Power source at Radium plant
ra  rb  rc
rstar
12
0.0  3.6
0.0  0.0
-30.0


z   35.0   0.0   rstar  rgrid   star point of plant generator at Radium
z   2.2    0.0   rgrid  gnd     Radium ground resistance


three_cond_gnd                   cable from Y-delta transformer to Radium plant
1  1                             number of cables, number of ground wires
qsa  qsb  qsc  qgrid  qgrid      from nodes
ra   rb   rc   rgrid  rgrid      to nodes
0.0319  0.0818                   cable core GMR and Rac (750 MCM copper)
1.1  1.15  al                    sheath inside & outside radius & sheath metal
0.01579 0.278                    ground wire GMR & Rac (#4/0 copper)
60.0                             soil_resistivity
0.0  -1.0  1.0  -1.0             x,y locations of cable followed by ground-wire
300.0                            length metres


wye_delta                        transformer
qpa  qpb  qpc                    primary nodes
qsa  qsb  qsc                    secondary nodes
qgrid                            ground node
138.0                            primary voltage
12.0                             secondary voltage
20.0                             MVA
9.0                              %impedance


z   1.0  0.0  qgrid  gnd         substation ground resistance

end
```

Listing of results for a short circuit case:

Started at: Wed Aug 12 15:18:46 1998

TACLINK Visual C++ Windows 95/NT AC Version 1 Date: Aug 11 1998
Copyright: Ground-it.com Consulting Ltd.
Input File Name: C:\BCHProgs\Samples\Taclink\Tldemo1.dat. Calculation frequency: 60.0

```
Type        Real         Imaginary      From      To
  Z        0.001000       0.000000       QPC      QGRID
  I        0.000000   -9959.292144      MGRID      MA
  I    -8625.000000    4979.646072      MGRID      MB
  I     8625.000000    4979.646072      MGRID      MC
  Z        0.550000       0.000000      MGRID      GND
  Z        7.000000       0.000000       M1G       GND
  Z        4.000000       0.000000       M2G       GND
  Z        6.000000       0.000000       M3G       GND
  I        0.000000   -3983.716857      NGRID      NA
  I    -3450.000000    1991.858429      NGRID      NB
  I     3450.000000    1991.858429      NGRID      NC
  Z        1.300000       0.000000      NGRID      GND
  Z       10.000000       0.000000       N1G       GND
  Z        5.000000       0.000000       N2G       GND
  Z        3.000000       0.000000       N3G       GND
  I     -962.250449   -1666.666667      RSTAR      RA
  I     -962.250449    1666.666667      RSTAR      RB
  I     1924.500897       0.000000      RSTAR      RC
  Z       35.000000       0.000000      RSTAR      RGRID
  Z        2.200000       0.000000      RGRID      GND
  Z        0.000000      85.698000       QPA      @T1A
  Z        0.000000      85.698000       QPB      @T1B
  Z        0.000000      85.698000       QPC      @T1C
  Z        1.000000       0.000000      QGRID      GND
```

There are 15 impedances and 9 current sources in the model.

```
Transformer No: 1
Connected between nodes @T1A QGRID and QSA QSB - Ratio:      6.6395      0.0000
Transformer No: 2
Connected between nodes @T1B QGRID and QSB QSC - Ratio:      6.6395      0.0000
Transformer No: 3
Connected between nodes @T1C QGRID and QSC QSA - Ratio:      6.6395      0.0000

Matrix No:   1  Type: Y
 MGRID MGRID MGRID
   MA    MB    MC
 0.000000  -0.125000   0.000000   0.000000   0.000000   0.000000
 0.000000   0.000000   0.000000  -0.125000   0.000000   0.000000
 0.000000   0.000000   0.000000   0.000000   0.000000  -0.125000

Matrix No:   2  Type: Z
  MA  MB  MC MGRID
 M1A M1B M1C   M1G
 0.350751   1.670670   0.107834   0.754794   0.108558   0.649376   0.106420   0.754888
 0.107834   0.754794   0.352188   1.668889   0.109295   0.753003   0.107121   0.650735
 0.108558   0.649376   0.109295   0.753003   0.353674   1.667089   0.107834   0.588938
 0.106420   0.754888   0.107121   0.650735   0.107834   0.588938   9.689322   3.817546

Matrix No:   3  Type: Z
 M1A M1B M1C M1G
 M2A M2B M2C M2G
 0.876877   4.176676   0.269584   1.886984   0.271395   1.623441   0.266050   1.887220
 0.269584   1.886984   0.880469   4.172223   0.273237   1.882508   0.267803   1.626837
 0.271395   1.623441   0.273237   1.882508   0.884185   4.167723   0.269584   1.472346
 0.266050   1.887220   0.267803   1.626837   0.269584   1.472346 24.223305   9.543865

Matrix No:   4  Type: Z
 M2A M2B M2C M2G
 M3A M3B M3C M3G
 0.876877   4.176676   0.269584   1.886984   0.271395   1.623441   0.266050   1.887220
 0.269584   1.886984   0.880469   4.172223   0.273237   1.882508   0.267803   1.626837
 0.271395   1.623441   0.273237   1.882508   0.884185   4.167723   0.269584   1.472346
 0.266050   1.887220   0.267803   1.626837   0.269584   1.472346 24.223305   9.543865

Matrix No:   5  Type: Z
 M3A M3B M3C   M3G
 QPA QPB QPC QGRID
 0.876877   4.176676   0.269584   1.886984   0.271395   1.623441   0.266050   1.887220
 0.269584   1.886984   0.880469   4.172223   0.273237   1.882508   0.267803   1.626837
 0.271395   1.623441   0.273237   1.882508   0.884185   4.167723   0.269584   1.472346
 0.266050   1.887220   0.267803   1.626837   0.269584   1.472346 24.223305   9.543865
```

```
Matrix No:   6  Type: Y
 NGRID NGRID NGRID
   NA    NB    NC
  0.000000  -0.050000   0.000000   0.000000   0.000000   0.000000
  0.000000   0.000000   0.000000  -0.050000   0.000000   0.000000
  0.000000   0.000000   0.000000   0.000000   0.000000  -0.050000

Matrix No:   7  Type: Z
  NA  NB  NC NGRID NGRID
 N1A N1B N1C   N1G   N1G
  0.227119   0.834937   0.054336   0.364192   0.054323   0.311935   0.053699   0.330439   0.053691   0.308283
  0.054336   0.364192   0.227119   0.834937   0.054336   0.364192   0.053699   0.330439   0.053699   0.330439
  0.054323   0.311935   0.054336   0.364192   0.227119   0.834937   0.053691   0.308283   0.053699   0.330439
  0.053699   0.330439   0.053699   0.330439   0.053691   0.308283   4.844874   1.895817   0.053074   0.365768
  0.053691   0.308283   0.053699   0.330439   0.053699   0.330439   0.053074   0.365768   4.844874   1.895817

Matrix No:   8  Type: Z
 N1A N1B N1C N1G N1G
 N2A N2B N2C N2G N2G
  0.681356   2.504811   0.163008   1.092576   0.162970   0.935805   0.161097   0.991317   0.161073   0.924849
  0.163008   1.092576   0.681356   2.504811   0.163008   1.092576   0.161097   0.991317   0.161097   0.991317
  0.162970   0.935805   0.163008   1.092576   0.681356   2.504811   0.161073   0.924849   0.161097   0.991317
  0.161097   0.991317   0.161097   0.991317   0.161073   0.924849  14.534621   5.687450   0.159222   1.097303
  0.161073   0.924849   0.161097   0.991317   0.161097   0.991317   0.159222   1.097303  14.534621   5.687450

Matrix No:   9  Type: Z
 N2A N2B N2C N2G N2G
 N3A N3B N3C N3G N3G
  0.681356   2.504811   0.163008   1.092576   0.162970   0.935805   0.161097   0.991317   0.161073   0.924849
  0.163008   1.092576   0.681356   2.504811   0.163008   1.092576   0.161097   0.991317   0.161097   0.991317
  0.162970   0.935805   0.163008   1.092576   0.681356   2.504811   0.161073   0.924849   0.161097   0.991317
  0.161097   0.991317   0.161097   0.991317   0.161073   0.924849  14.534621   5.687450   0.159222   1.097303
  0.161073   0.924849   0.161097   0.991317   0.161097   0.991317   0.159222   1.097303  14.534621   5.687450

Matrix No:  10  Type: Z
 N3A N3B N3C   N3G   N3G
 QPA QPB QPC QGRID QGRID
  0.227119   0.834937   0.054336   0.364192   0.054323   0.311935   0.053699   0.330439   0.053691   0.308283
  0.054336   0.364192   0.227119   0.834937   0.054336   0.364192   0.053699   0.330439   0.053699   0.330439
  0.054323   0.311935   0.054336   0.364192   0.227119   0.834937   0.053691   0.308283   0.053699   0.330439
  0.053699   0.330439   0.053699   0.330439   0.053691   0.308283   4.844874   1.895817   0.053074   0.365768
  0.053691   0.308283   0.053699   0.330439   0.053699   0.330439   0.053074   0.365768   4.844874   1.895817

Matrix No:  11  Type: Y
 RSTAR RSTAR RSTAR
   RA    RB    RC
  0.000000  -0.277778   0.000000   0.000000   0.000000   0.000000
  0.000000   0.000000   0.000000  -0.277778   0.000000   0.000000
  0.000000   0.000000   0.000000   0.000000   0.000000  -0.277778

Matrix No:  12  Type: Z
 QSA QSB QSC QGRID QGRID
  RA  RB  RC RGRID RGRID
  0.033010   0.251621   0.017758   0.229430   0.017759   0.229430   0.017765   0.227158   0.017758   0.146527
  0.017758   0.229430   0.033010   0.251621   0.017759   0.229430   0.017765   0.227158   0.017758   0.147114
  0.017759   0.229430   0.017759   0.229430   0.033011   0.251620   0.017765   0.227158   0.017759   0.146816
  0.017765   0.227158   0.017765   0.227158   0.017765   0.227158   0.054604   0.226860   0.017758   0.146819
  0.017758   0.146527   0.017758   0.147114   0.017759   0.146816   0.017758   0.146819   0.069592   0.267527

Nodal voltages with respect to node GND:
 Node      Real         Imaginary        Magnitude
  QPC    2603.443035    2295.983699     3471.232747
QGRID    2597.853014    2291.406483     3464.012695
   MA   76592.102693    1607.532594    76608.970467
   MB  -43286.862756  -67085.184572    79838.427316
   MC  -20953.535667   45263.125268    49877.862484
MGRID   -1155.560213    -979.398506     1514.774188
  M1A   77301.376912     482.132978    77302.880442
  M1B  -42331.302562  -68467.067332    80496.450143
  M1C  -18190.878643   40230.420109    44151.950896
  M1G    -465.708950    -260.902563      533.811740
  M2A   79127.202265   -2466.838668    79165.645524
  M2B  -39899.583818  -72039.988947    82351.301121
  M2C  -11247.294491   27540.654354    29748.769313
  M2G       3.063303      -2.460676        3.929218
  M3A   80954.392325   -5414.528699    81135.262110
  M3B  -37466.659203  -75611.829433    84385.421146
  M3C   -4302.598142   14851.850321    15462.529183
  M3G     496.257480     248.388720      554.949045
  QPA   82725.459913   -8195.113606    83130.389177
  QPB  -35078.932728  -79038.028380    86472.778673
   NA   79083.718577   -2075.874685    79110.958784
   NB  -39569.903015  -71778.927258    81963.355367
```

```
    NC    -5200.559691   20551.925788   21199.704590
 NGRID    -2592.244913   -2040.008540    3298.691943
   N1A    79520.329699   -2800.871207   79569.640661
   N1B   -39027.991849  -72645.165504   82465.169732
   N1C    -4243.665895   18309.841369   18795.185320
   N1G    -1756.370400   -1183.133172    2117.697119
   N2A    80915.224619   -5163.194133   81079.788781
   N2B   -37313.266932  -75437.052109   84160.731461
   N2C    -1287.922954   11396.254756   11468.799763
   N2G     -137.775059     -77.572734     158.112289
   N3A    82320.545072   -7554.416209   82666.446309
   N3B   -35587.601207  -78258.753807   85970.401343
   N3C     1678.245521    4453.768993    4759.471217
   N3G     1331.006962     820.526566    1563.599494
    RA     7051.438897    1020.223344    7124.861134
    RB    -3199.867863   -1528.169569    3546.048022
    RC     4330.961206    6549.343779    7851.823286
 RSTAR     2727.510747    2013.799185    3390.383758
 RGRID     2727.510747    2013.799185    3390.383758
   QSA     6894.749495    1299.800518    7016.199255
   QSB    -3356.786228   -1271.413807    3589.499526
   QSC     4173.779982    6785.195592    7966.135736
  @T1A    70663.212476   19363.056229   73268.120925
  @T1B   -47401.552916  -51200.677973   69774.039898
  @T1C   -15468.100517   38711.841192   41687.753382

Transformer currents:

Trans (winding)       Real        Imaginary       Magnitude
T  1 primary      -321.573080     -140.752963      351.027980
T  1 secondary   -2135.093501     -934.533253     2330.660134
T  2 primary      -324.830806     -143.791223      355.233681
T  2 secondary   -2156.723262     -954.705862     2358.584006
T  3 primary      -424.932408     -210.874741      474.379287
T  3 secondary   -2821.350661    -1400.108767     3149.654602

 From    To  -------Impedance - ohms---------  -----------------Current - amps------------------
 Node   Node      Real         Imaginary            Real           Imaginary         Magnitude

 QPC QGRID      0.001000        0.000000        5590.020220      4577.216571      7224.903985
MGRID   GND     0.550000        0.000000       -2101.018569     -1780.724557      2754.134887
  M1G   GND     7.000000        0.000000         -66.529850       -37.271795        76.258820
  M2G   GND     4.000000        0.000000           0.765826        -0.615169         0.982305
  M3G   GND     6.000000        0.000000          82.709580        41.398120        92.491508
NGRID   GND     1.300000        0.000000       -1994.034549     -1569.237339      2537.455341
  N1G   GND    10.000000        0.000000        -175.637040      -118.313317       211.769712
  N2G   GND     5.000000        0.000000         -27.555012       -15.514547        31.622458
  N3G   GND     3.000000        0.000000         443.668987       273.508855       521.199831
RSTAR RGRID    35.000000        0.000000           0.000000         0.000000         0.000000
RGRID   GND     2.200000        0.000000        1239.777612       915.363266      1541.083527
  QPA  @T1A     0.000000       85.698000        -321.573080      -140.752963       351.027980
  QPB  @T1B     0.000000       85.698000        -324.830806      -143.791223       355.233681
  QPC  @T1C     0.000000       85.698000        -424.932408      -210.874741       474.379287
QGRID   GND     1.000000        0.000000        2597.853014      2291.406483      3464.012695

Matrix currents:
 From    To       Real         Imaginary          Magnitude
Matrix No. 1:
MGRID    MA     -323.366388     9718.457863       9723.836129
MGRID    MB     8263.223258    -5266.412818       9798.773524
MGRID    MC    -5780.315472    -2474.746932       6287.799244

Matrix No. 2:
   MA   M1A     -323.366388     -240.834280        403.195946
   MB   M1B     -361.776742     -286.766746        461.646594
   MC   M1C     2844.684528     2504.899140       3790.349557
MGRID   M1G      -58.522830     -196.573557        205.100182

Matrix No. 3:
  M1A   M2A     -323.366388     -240.834280        403.195946
  M1B   M2B     -361.776742     -286.766746        461.646594
  M1C   M2C     2844.684528     2504.899140       3790.349557
  M1G   M2G        8.007020     -159.301762        159.502864

Matrix No. 4:
  M2A   M3A     -323.366388     -240.834280        403.195946
  M2B   M3B     -361.776742     -286.766746        461.646594
  M2C   M3C     2844.684528     2504.899140       3790.349557
  M2G   M3G        7.241195     -158.686593        158.851722

Matrix No. 5:
  M3A   QPA     -323.366388     -240.834280        403.195946
  M3B   QPB     -361.776742     -286.766746        461.646594
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   M3C    QPC       2844.684528       2504.899140       3790.349557
   M3G QGRID         -75.468385       -200.084713        213.844265

Matrix No. 6:
NGRID     NA           1.793307       4083.798175       4083.798568
NGRID     NB        3486.945936      -1848.882905       3946.791096
NGRID     NC       -1129.596716       -130.415739       1137.100262

Matrix No. 7:
   NA    N1A           1.793307        100.081317        100.097383
   NB    N1B          36.945936        142.975524        147.671942
   NC    N1C        2320.403284       1861.442690       2974.767266
NGRID    N1G        -184.693827       -261.586073        320.217244
NGRID    N1G        -180.414151       -273.676118        327.792440

Matrix No. 8:
  N1A    N2A           1.793307        100.081317        100.097383
  N1B    N2B          36.945936        142.975524        147.671942
  N1C    N2C        2320.403284       1861.442690       2974.767266
  N1G    N2G         -96.875307       -202.429415        224.415893
  N1G    N2G         -92.595631       -214.519460        233.650486

Matrix No. 9:
  N2A    N3A           1.793307        100.081317        100.097383
  N2B    N3B          36.945936        142.975524        147.671942
  N2C    N3C        2320.403284       1861.442690       2974.767266
  N2G    N3G         -83.097801       -194.672141        211.665980
  N2G    N3G         -78.818125       -206.762186        221.275617

Matrix No. 10:
  N3A    QPA           1.793307        100.081317        100.097383
  N3B    QPB          36.945936        142.975524        147.671942
  N3C    QPC        2320.403284       1861.442690       2974.767266
  N3G QGRID         -304.932295       -331.426569        450.363492
  N3G QGRID         -300.652618       -343.516614        456.503736

Matrix No. 11:
RSTAR     RA         275.993289       1201.091153       1232.392897
RSTAR     RB         983.880209      -1646.494058       1918.062291
RSTAR     RC       -1259.873499        445.402906       1336.287761

Matrix No. 12:
  QSA     RA         686.257160        465.575514        829.282490
  QSB     RB         -21.629761        -20.172608         29.576692
  QSC     RC        -664.627399       -445.402906        800.070827
QGRID RGRID         735.791644        554.621214        921.408723
QGRID RGRID         503.985969        360.742051        619.787612


Main matrix storage locations used: 300 out of maximum 1275 =   23.5 %
Completed at: Mon Apr 29 16:09:19 1996
Compute time: 0 hr. 0 min. 3 sec.
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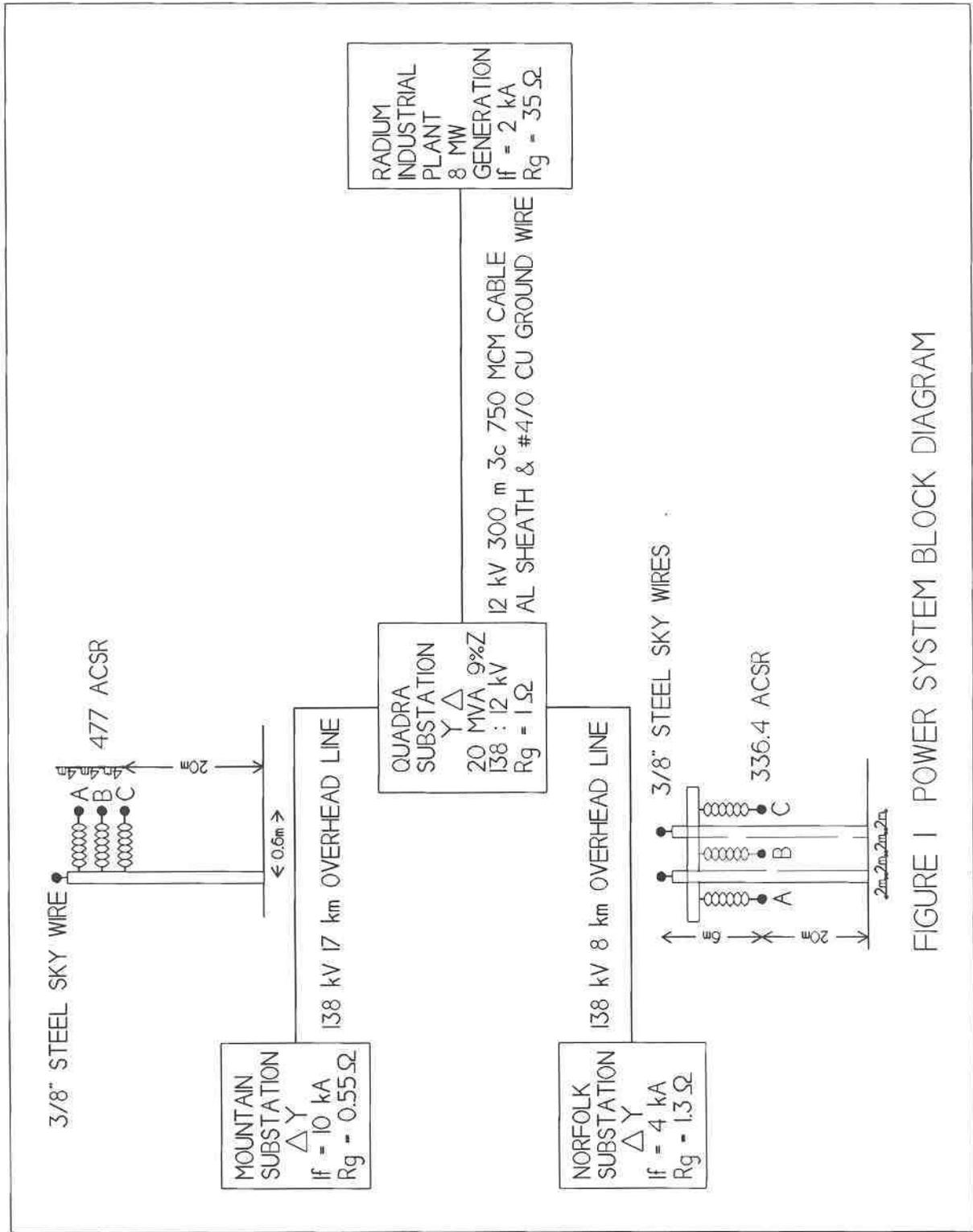
Figure 1 Block Diagram of Sample Power System
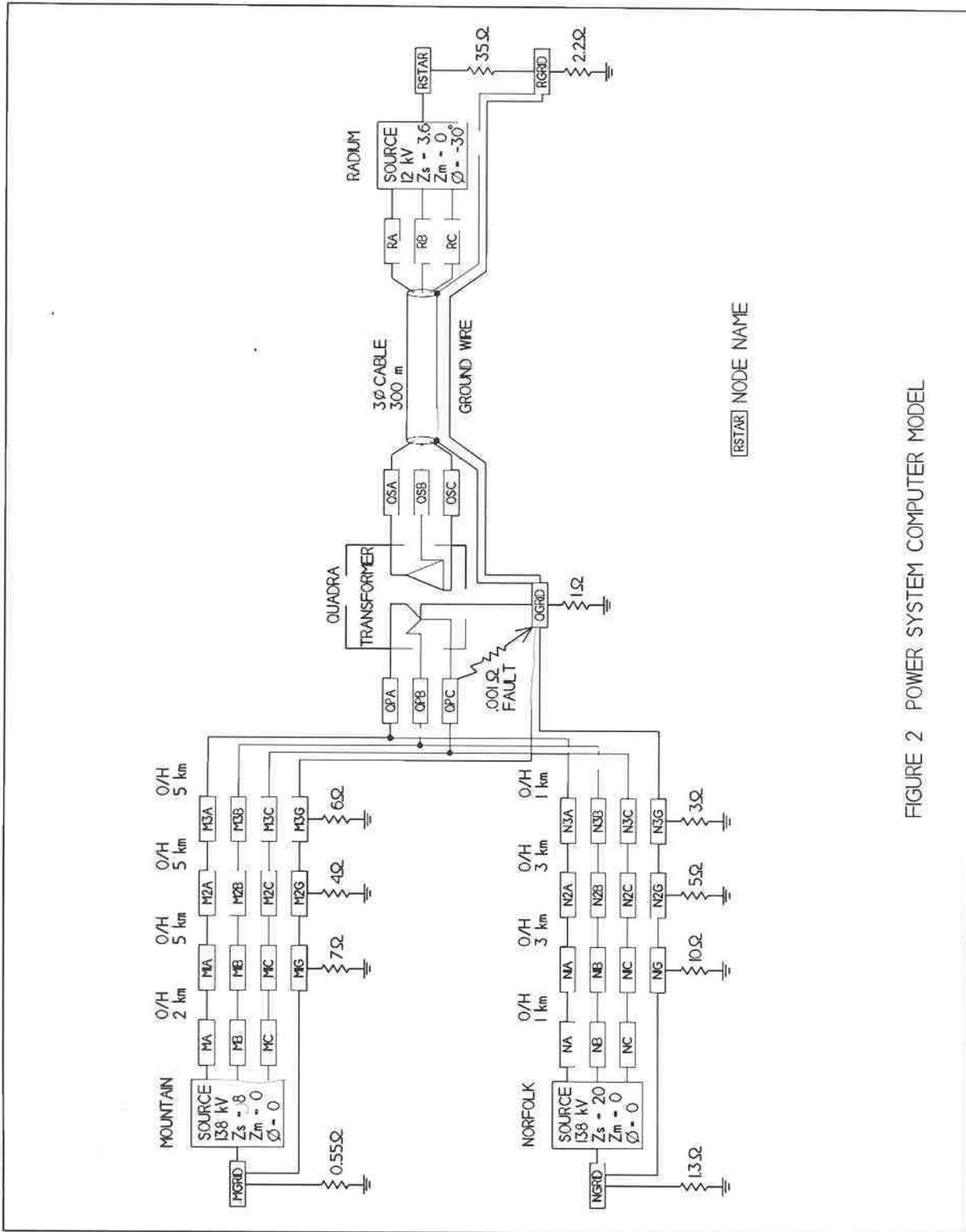
Figure 2 Nodal Diagram of Sample Power System