KWIKGRID®

Ground Electrode Analysis Computer Program

REFERENCE MANUAL

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1. OVERVIEW

KWIKGRID is a ground electrode analysis computer program.

KWIKGRID represents a ground electrode as a series of straight conductor segments buried in soil that may be uniform or horizontally layered, with two layers of differing resistivity. The electrode may be any buried metallic structure whose internal resistance is small compared with its resistive contact with the soil. Examples of ground electrodes are:

Substation ground electrodes that may consist of a combination of horizontal grid conductors at various angles and vertical ground rods.

Ground rods at power poles, padmount transformers, switching kiosks and consumer premises.

Metallic footings of transmission towers. These may be direct buried or concrete encased.

Building footings. Reinforcing steel rods in concrete footings and slabs that can be simulated as ground electrodes.

KWIKGRID is mostly used to analyze the effects of ground faults when current will flow into the soil from the buried electrode conductors. However, other effects such as constant current flow from induced voltages in transmission or distribution conductors and intentional current flow such as from impressed current cathodic protection systems and dc transmission earth return electrodes may also be analyzed.

The results of KWIKGRID calculations may be used directly to obtain the ground resistance and voltage rise or to plot graphs or contour maps of potentials. For example, a contour map of touch potentials in a substation can be plotted to indicate areas where touch potentials may exceed hazardous levels.

Due to resistive contact between the electrode and soil, a potential rise will occur on the electrode and in the surrounding soil when current flows from the electrode to the soil. In reality, the current that flows into the soil, returns to one or more remote sources, often at great distance from the electrode being examined.

KWIKGRID can analyze multiple electrode cases with or without impedance bonds between the individual electrodes. Remote ground impedances may also be added. This ability enables more complex problems to be analyzed. Examples are described in case studies in Appendix A are:

1. A fall-of-potential resistance measurement has been carried out under less than ideal conditions. Due to urban development, the current return electrode had to be placed too close to the ground grid. KWIKGRID can be used to model the measurement configuration and to determine the correction required to compensate for the non-ideal measurement configuration.

2. A substation with ground grid has the first few towers bonded to the substation by overhead sky-wires. Safety around the towers must be assessed. KWIKGRID can be used to model the substation ground grid and the inherent electrodes of the tower footings, with

the towers connected to the substation by ac impedances calculated for the sky-wires. Step and touch potentials can be calculated around the towers.

3. A ground fault at a tower near a substation where the substation has grounded Y transformer connections. In this example, current will flow from the tower into the soil. Some current will return to the substation ground grid and some will flow to other remote grounded points of the transmission system. KWIKGRID allows the direction of the current flow to be specified. The current flowing from the tower can be specified with a positive direction and the current returning to the substation with a negative direction. Soil potentials between the tower and substation will then be accurately computed.

4. A substation has a perimeter fence that is not grounded. Safety around the fence must be assessed. KWIKGRID can be used to model the fence as a separate electrically floating electrode consisting of short ground rods representing the part of each fence post that is buried. Touch potential contours can be calculated around the fence and any hazardous areas can be identified.

When current is injected into the ground system, the core functions of KWIKGRID calculate the potential rise of the electrode/s, the effective resistance or impedance and soil potentials anywhere on or below the surface of the soil, as specified by the user.

To use KWIKGRID, it is necessary to provide all the data needed to form a computer model of the system being analyzed. This includes all or some of the following:

1. Soil resistivity with layering if applicable.

2. Co-ordinates of the ends and radii of every straight conductor element forming the electrodes.

3. Injected or returned currents.

4. Locations where soil potentials are to be calculated.

2. DEFINITIONS

The following terms are used in this manual:

complex	The complex number format $a + jb$ where a is the real part and b is the imaginary part of a complex number. This notation is used for ac impedances and vector voltages and currents.
electrode	One or more buried conductors that may be wires or vertical rods that make up a ground electrode. Often this is called a ground grid. All such conductors will have zero internal resistance so that the potential on all conductors in an electrode is the same.
injected current	The current that flows into a ground electrode. One or more electrodes in a model may have injected current.
model	Means a computer model of a real life ground grid or electrode.
potential	Used to refer to electrical potentials. In many cases, the term voltage could also be used.
radius	The radius of a conductor segment = ½ diameter.
segment	A buried segment of a ground electrode consisting of a straight length of cylindrical conductor with a given radius.

3. 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 following discussion applies to both the dc and ac versions. The only differences between the two are that the ac version has the added features and requirements:

- interconnecting separate electrodes with ac impedances.

- adding a remote ground impedance to one or more electrodes.

- the injected current must be specified with both a real and imaginary parts.

In fact, a dc model without interconnecting impedances, can be analyzed with the ac program, providing the injected current is specified with real and imaginary part. More memory will be required and the calculation will take longer than if the dc version is used, because calculations are done with complex numbers.

The KWIKGRID package of programs are standard windows 95/NT and later operating system programs. This means that they can be started by double clicking on the icon for each program or on the program file name (e.g. **KWIKR.EXE**) in the File Manager. The user can also drag a data file from the File Manager onto the program icon and it will be immediately loaded.

It is necessary to have data or calculation results files available before the programs 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 a word processor such as Wordpad, Word Perfect or Word for Windows is used, the files must be saved in text mode.

If the programs have been installed as instructed, there should be a set of icons on the computer desktop. Use the File Manager to drag the file **SAMPLE1.KDA** onto the icon for **KWIKR**.

Providing there are no errors in the data, the file should be loaded and a plot of the ground electrode model should appear on the screen. The file **SAMPLE1.KDA** contains data for the small substation ground grid shown in Figure 1.
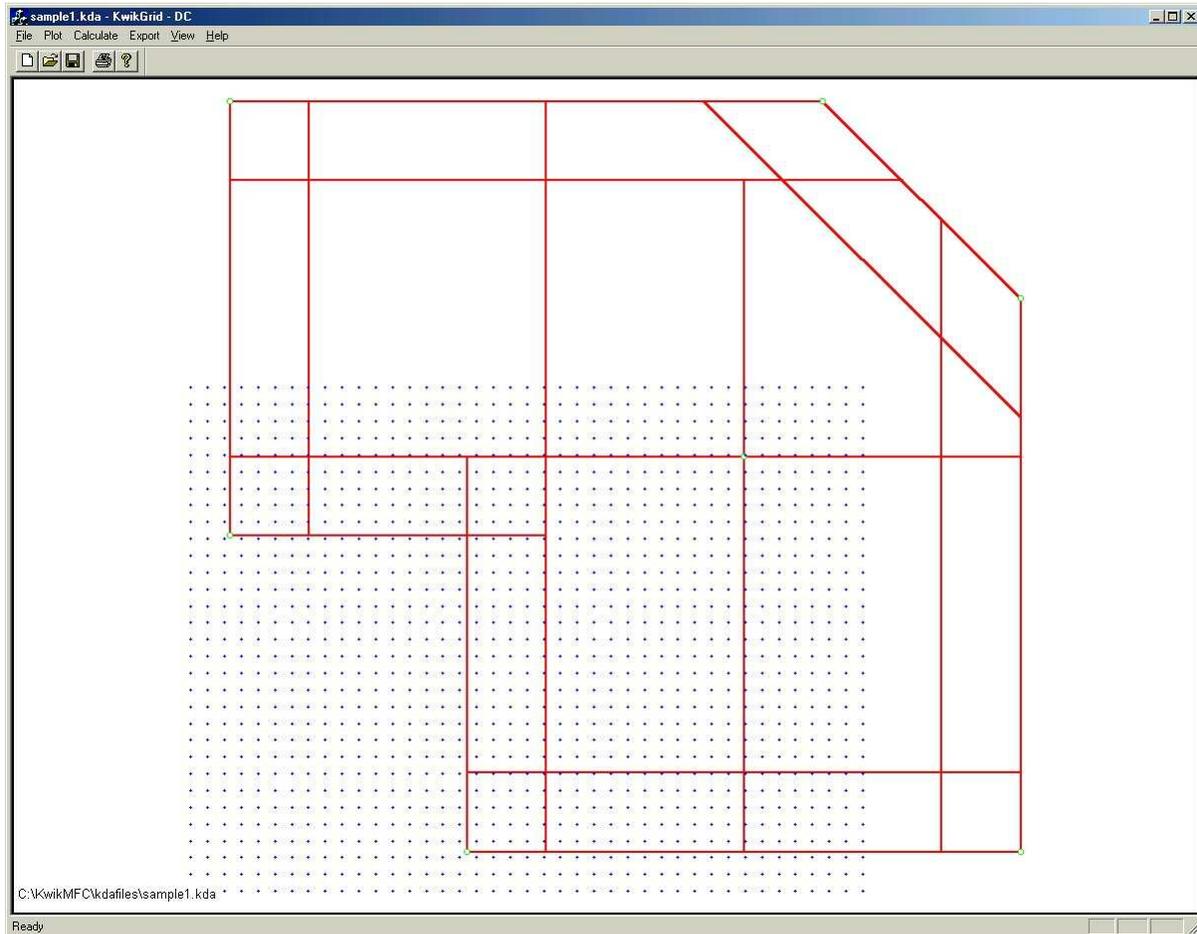
Figure 1 Ground Grid Example

The current version of the program does not allow the file to be saved, edited or renamed, as is usually possible with Windows 95/NT programs. These options will be included in later versions. Also, the calculation results are not automatically saved. The input data files must be generated using a text editor as discussed above. Normal printing with print-preview of the graphical plots is possible using the **File** menu selection. If **File|Print** is selected, the ground electrode model will be printed.

The **Calculate** menu selection will initiate the calculation of the ground resistance and soil potentials for this model. Progress bars at the top left of the screen indicate the progress of the calculation. The first bar is displayed during the calculation of the elements in the matrix. The second bar shows the progress of the matrix solution. A third bar is only displayed if there are soil potential calculations. It shows the progress of the potential calculations. In the present version, the display will be frozen while calculations are taking place. If, possibly due to an error, the calculation is taking too long to finish, the user can stop it by invoking the Task Manager in Windows NT or using Ctrl+Alt+Del keys in Windows 95/ME, selecting the program and ending the process.

The speed of matrix element and soil potential calculation is dependent on the soil model, number of non-orthogonal[1] conductors and number of conductor segments. In the case of soil potential calculations, the speed is also dependent on how many potential points are calculated. If an **area** of soil potentials is being calculated to plot contour lines, there may be many points to calculate and most of the execution time may be spent doing these calculations. The matrix solution time is only dependent on the size of the matrix, which is related to the number of conductor segments and separate structures in the model.

When a calculation is finished, the results should save using the **Export|Results** menu selection. The results are not affected by selection of different plots. If the results are saved, contour plots can be generated later without re-running the calculation. This could save time for large models[2].
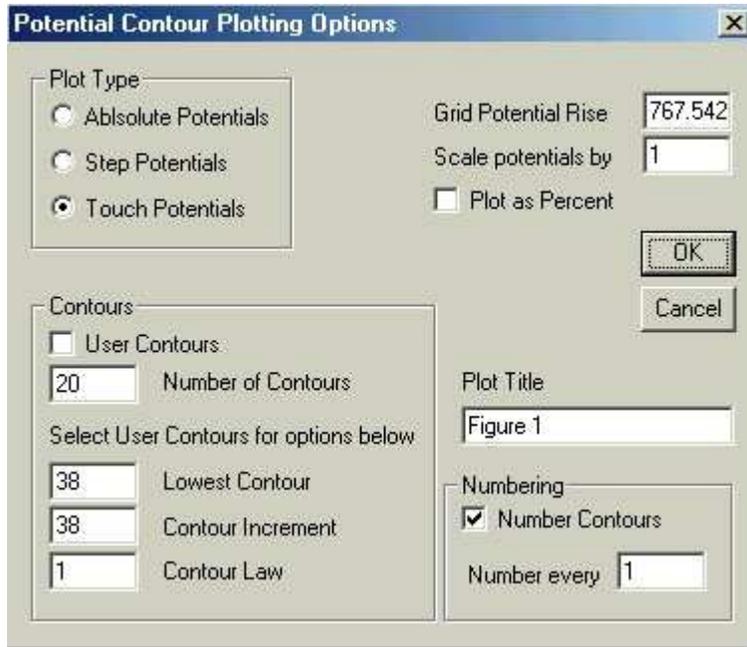
Figure 2 Plotting Dialog Box

When the program is started for the first time and before any calculation is done, it will default to displaying a plot of the complete electrode model in plan view. Vertical conductors (ground rods) are shown as small circles and locations where soil potentials will be calculated are shown as small + symbols. If there is a data error in the input file, an error message will be displayed and there will be no plot. Errors must be corrected before calculations can proceed.

The drop-down menu **Plot|Plot Grid** can be used to modify the plot. The current version of the program has a dialogue box with options to plot in plan or isometric view and to rotate the plot 90 degrees to better fit the printer paper. The plot title can be edited and positioned at any of the four corners of the plot. The second menu selection **Plot|Plot Contours** will only be active after a calculation with a plotable area has been completed.

---

[1] Orthogonal conductors are conductors that are at right angles to each other. Typically and in most grid models, conductors that run north-south, east-west and vertical (rods) are orthogonal. A simpler, faster algorithm is used in the mutual resistance calculation than when conductors are angled to each other.

[2] In the present version, the output file will have the same name as the input file, but the name extension is changed to .OUT. The output file will overwrite any existing file with the same name.

Once the calculation is complete, the **Plot|Plot Contours** menu selection can be made. A dialogue box for contour plotting options will be displayed as shown in Figure 2. This contains the following selections:

1. **Plot Type**.

   Absolute Potentials plots contours of soil potential rise relative to remote ground, where the potential is zero. These are the real soil potentials that could be measured relative to a reference electrode located far away. The Ground Potential Rise (GPR) entered in the dialogue box has no effect on this plot.

   Step Potentials will calculate step potentials from the array of soil potentials calculated and plot contour lines of step potentials. The GPR entered in the dialogue box has no effect on this plot.

   Touch Potentials will plot contours of touch potential based on the GPR entered in the dialogue box. The default value will be the GPR of the first electrode in the model. Touch potentials are the difference between the electrode potential rise and the soil potential rise.

   If it is a multi-electrode model, for example a substation ground grid with a fence that is not bonded to the grid and the fence has been entered as a separate electrode, touch potentials along the fence must use the GPR of the fence. This value must be obtained from the **detailed program output** and entered in the dialogue box. **Detailed program output** can be sent to a text file using the menu selection **Export|Results**. This should be done without ending the KWIKRID program (or recalculation will be required) and the results should be viewed using a text editor in another window, to read the required GPR, which can then be entered in the dialogue box.

2. **Ground Potential Rise**. This will contain the GPR in volts, of the first electrode in the model. In the present version, if the model is loaded from a results file, the GPR must be manually entered. Any value can be entered and will be used to calculate touch potentials as a difference between this value and the calculated soil potentials.

   Note that when **Scale Potentials by** is set to something different from 1, only the soil potentials are increased or decreased. The GPR is not changed. This must be done manually for touch potentials to be calculated properly.

3. **Scale Potentials by**. This is a factor that can be useful where plots are required for different injected currents. For example, the calculation can be done for 1000 amps ground current and plots for 2500 amps can be produced by setting **Scale Potentials by** 2.5. The default value is 1.

   Note that when **Scale Potentials by** is set to something different from 1, only the soil potentials are increased or decreased. The GPR is not changed. This must be done manually for touch potentials to be calculated properly.

4. **Plot as Percent**. If this box is checked, all contours will be given values in percent of the GPR. The default is for the box to be unchecked.

5. **Contours.**

   User Contours. If this is unchecked (the default), the plot will be for the **Number of Contours** specified (default 20), using linear increments between the contour levels to cover the whole range of step, touch or absolute potentials in the plotted area. This will usually produce odd contour levels e.g. 113 volts. It enables a quick plot to be done, after which a better series of contour levels can be selected.

   If **User Contours** is checked, contours will be plotted using the parameters specified by **Lowest Contour**, **Contour Increment** and **Contour Law** for the contour plot. This enables selecting reasonable values for contour lines so that they are not spaced too close together and are, for example, in easy to understand steps of 100 volts.
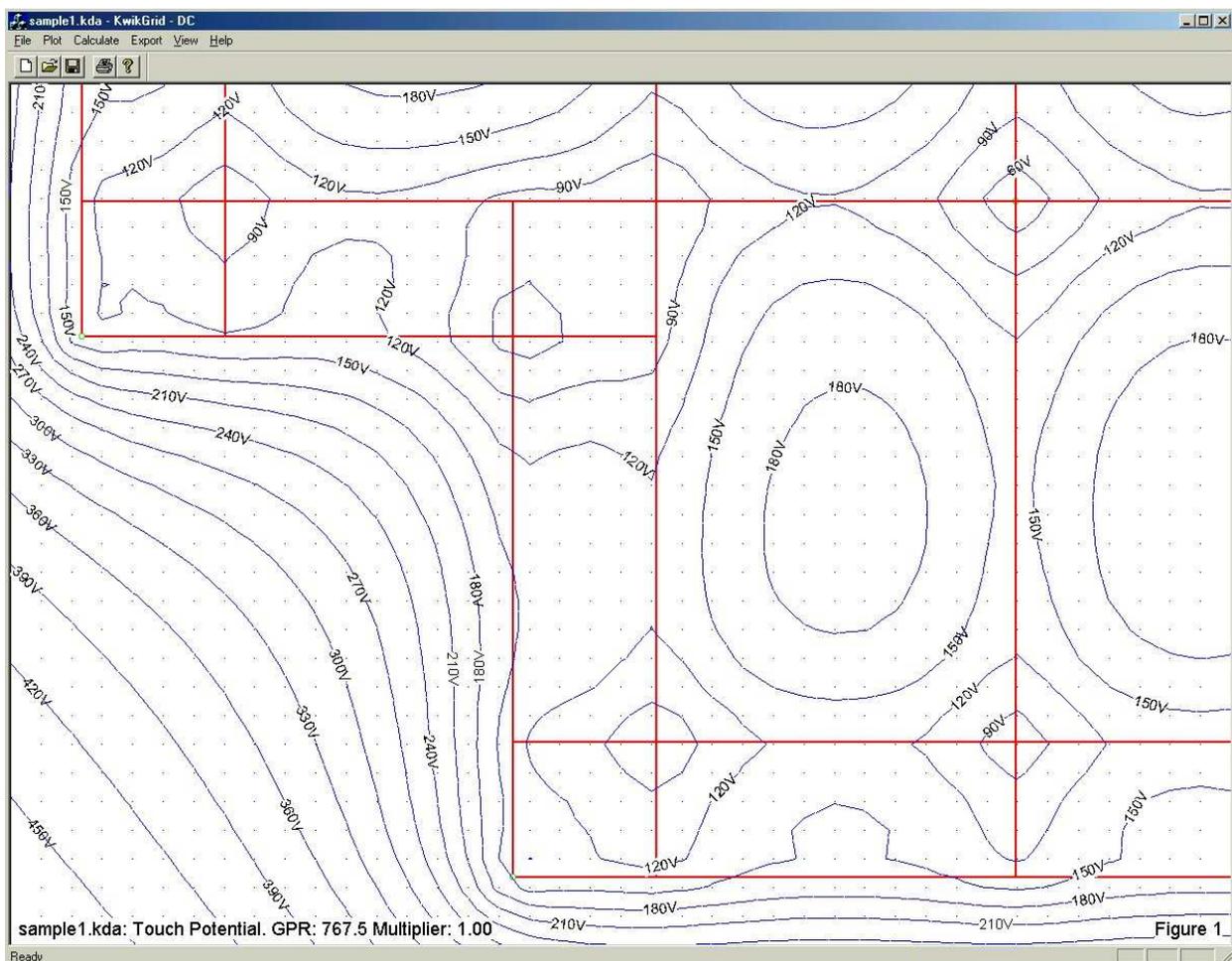

Figure 3 Plot of Touch Potential Contour Lines

Note that only the **Number of Contours** selected, will be plotted. If a plot of the whole area is required, enough contours must be selected or parts of the plot will not have contour lines. Also, it is possible to select a combination of parameters that results in nothing being plotted. It is therefore best to first plot with **User Contours** not checked to see the range of contours. **User Contours** can then be checked and used to produce easier to read plots with practical contour steps. Sometimes it is useful to plot just a few contours showing a critical step, touch or absolute potential level. Areas to one side of this contour are within the tolerable level and to the other side exceed it. It is possible to plot only one contour. For example, if it is known that the tolerable touch potential is 373 volts, only that contour will be plotted by setting the lowest contour to 373 and the contour increment to 100000 or some other very high number.

Number of Contours. This defaults to 20 and sets the number of contour lines that will be used. Valid entries are 2 - 500 contours

If **User Contours** has been checked:

Lowest Contour. Set the value of the lowest contour in the plot. Valid entries are -10,000,000 to +10,000,000 volts or percent.

Contour Increment. Sets the step increment between each contour. Valid entries are 0.001 to +1,000,000 volts or percent.

Law. The default value of **Law** is 1. Contours will be plotted with uniform difference between adjacent contours. Selecting a **Law** of between 0.1 and 5 distorts the difference between contour levels so that, for example, contour increments can be made larger for the higher potentials. This is sometimes useful where the contour lines are very dense near part of an electrode and widely spaced elsewhere. The contour lines will have odd values when **Law** is activated. Some experimentation is required.

1. **Numbering**

    Number Contours. The default is for this box to be checked. Every contour has a number representing voltage or percent printed at intervals along it.

    Number every enables limiting the amount of contour numbering. If **Number every** is set to 5, for example, only every 5th contour will be numbered.

    Contour numbering is in volts **V**, kilo-volts **kV** or percent **%**. The switch to **kV** notation occurs if the highest contour to plot exceeds ±32,000 volts.

Figure 3 shows a plot of touch potential contour lines from the input data file **SAMPLE1.KDA** using a contour increment of 30 volts.

The **Export** menu selection has two sub-menu items that become active after a calculation has been completed.

Export|Saved Data produces an output text file with the extension **.SAV**, that is similar to the input file, but has the following differences:

> If the conductor segments were specified to be subdivided or crossed the interface between upper and deep soil layers in a two-layer soil analysis, the conductor information will list the segments after they have been subdivided.

> Each line of conductor information will contain the leakage current for that conductor, in the first column. For **KWIKZ**, there will be two such columns representing real and imaginary parts of the leakage current.

> The keyword **READ** will be added to instruct KWIKGRID to read the conductor segment current and not to repeat the main matrix calculation.

> All * comments will be at the start of the file.

The purpose of this file is to enable a second calculation to be done without wasting time redoing the main matrix development and solution. Some time can be saved this way. The **Saved Data** file is used as input, with a different plotted **AREA**.

The menu selection **Export|Results** will produce a text file with the same name as the input file, but the extension **.OUT**, containing all details of the calculation. **Note**: if this menu selection is not made, the calculation results will be lost when the program is terminated or a new file is opened.

If the file **SAMPLE1.KDA** is used for input, calculated and the results are exported, a file named **SAMPLE1.OUT** will be created. The following lines will be found in this file:

```
Electrode #1  Main. Injected Current:  1000.0000 amps
Potential Rise:   767.5424 volts, Resistance:    0.7675 ohms
```

KWIKGRID has calculated the ground resistance to be 0.7675 Ω. The resistance is the ground resistance with reference to remote ground. Because the ground fault current was 1000 amps, the GPR is 767.5 volts.

Utility|IEEE 80 is a utility that will calculate tolerable step and touch potentials from input data provided by the user. Selection will open a dialog box in which the following parameters can be entered:

> Body resistance in Ω.
> Radius of a plate that represents a human foot in metres.
> Resistivity of a top layer of crushed rock in Ω-metres.
> Thickness of the crushed rock layer in metres.
> Resistivity of the underlying soil in Ω-metres.
> Fault duration in seconds.
> Person's body weight in kg.

The input data dialog and results that would be calculated when the button "Calculate Step and Touch" are shown below.
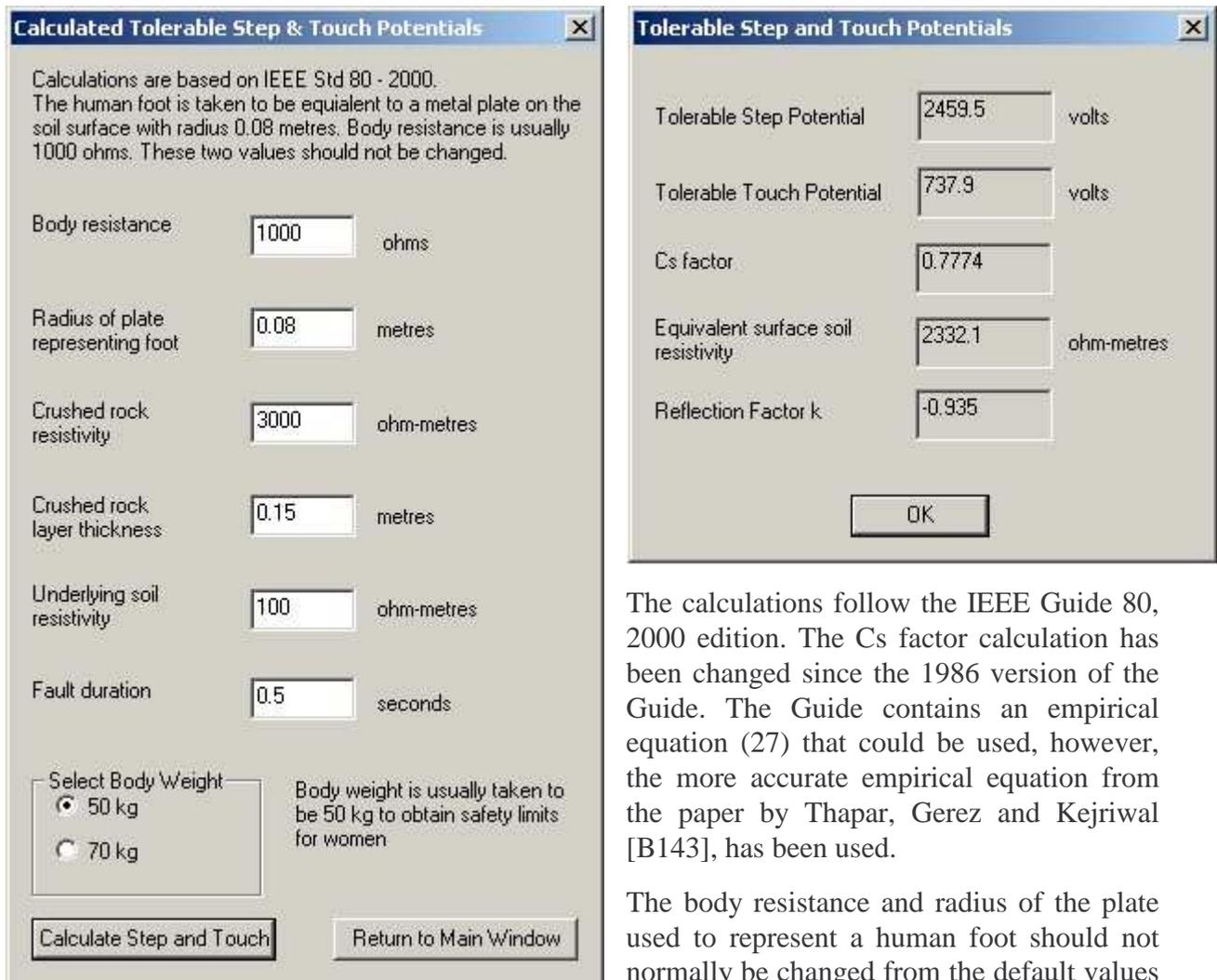
The calculations follow the IEEE Guide 80, 2000 edition. The Cs factor calculation has been changed since the 1986 version of the Guide. The Guide contains an empirical equation (27) that could be used, however, the more accurate empirical equation from the paper by Thapar, Gerez and Kejriwal [B143], has been used.

The body resistance and radius of the plate used to represent a human foot should not normally be changed from the default values provided by the program. The dialog box will not allow entry of values outside the valid range for each parameter.

3.1   Planned Improvements

3.1.1   Avoiding Recalculation

The current version of KWIKGRID requires that calculations be done before plotting potential contours. If contours must be plotted at a later time, perhaps using different plotting parameters, the calculations must be redone, even if the calculation results have been saved to a file. This may take considerable time for large models and high ratios of upper to deep layer soil resistivity.

3.1.2 Saving AREA Specification in Saved Data File

The current version of KWIKGRID saves the **AREA** specified for potential contour plotting as a series of **PROFILE** statements. If the saved data is read into KWIKGRID, it will not be possible to plot contours as the program will not read the **AREA** keyword.

A new version will be developed that includes the **AREA** specification in the saved data file.

Work-Around. Delete the **PROFILE** information and enter a new **AREA** specification.

4. MODEL DATA FORMAT

KWIKGRID uses and produces normal ASCII text files. Data is prepared in a text file for reading by the program.

4.1   DC Version KWIKR

The input data file for the sample ground electrode **SAMPLE1.KDA** is on disk. It is a standard text format file and can be viewed and modified with any text editor such as NotePad or a word processor such as Word for Windows **in text mode**.

The file format makes use of keywords that are interpreted by the program. Keywords can be in upper or lower case or a combination of upper and lower case.

There are a number of "comment" lines at the start of the file:

```
* FILE: SAMPLE1.KDA
* Created on March 12, 2001 by Ian Simpson
* Example of a 19 x 20 m ground grid with rods and angled conductors in
* two layered soil
* Lines starting with an * are comments - ignored in the calculation
* Calculation assumes metric units, otherwise use keyword english
* for english, resistivity is still in ohm-metres.
```

Any line starting with an * is merely a comment and is ignored by the program. Comment lines can be added in most, but not all areas of the file.

The soil resistivity is specified by the keyword **SOIL**, followed by the resistivity of the top layer, resistivity of the deep layer and thickness of the top layer. Here the top layer resistivity is 47 Ω-metres, deep layer resistivity is 28 Ω-metres and the thickness of the top layer is 1.3 metres:

```
soil
47
28
1.3
```

For uniform soil, the two layers are given the same resistivity and the depth can be any value.

The next line has the keyword **electrode** followed, on the same line, by an optional name for the electrode. This signifies the start of data specifying an electrode. For multiple electrodes, there will be more blocks of data headed by the **electrode** keyword. A comment has been added on the line following.

```
electrode Substation
* Perimeter conductors
```

The program interprets each line of data after the **electrode** keyword as representing a conductor segment in the model. The ends of each conductor are specified as x,y,z co-ordinates based on a reference point. z = 0 is the soil surface and z is +ve in a downward direction. The x =

0, y = 0 reference is at the bottom left of the grid. All values must be in metres, including the radius of the conductor, except if the keyword **english** is used, when all values, including the conductor radius, must be in feet.

Each conductor "runs from point x,y,z at its origin to point x,y,z at its extremity. Tab or space characters can be used to separate entries on a line of data.

Note: comments should <u>not</u> be added after lines of conductor segment data or the program may try to interpret the comment as an "abc" type data entry. Use the asterisk * method with comments on a separate line.

The first block of lines is rather cryptic, but is an alternative, shorthand way of entering the conductor data, which may be more efficient in some cases. It illustrates the "abc" method. The more conventional conductor data entry method is described later and the reader can ignore this alternative method and skip to the next item:

```
* These are entered using the intelligent format
a0 b19 c.6 x15 s3 r.006
x20 y14 s1
y0 s3
x6 s1
y10
a8 b8 x0
y19
```

Each conductor is specified to run from a,b,c to x,y,z, where a corresponds with x, b with y and c with z of the conductor origin.

The *first* principle is that each conductor extremity is assumed to be the origin of the next conductor, unless modified. Of course, the first conductor has no previous one to specify its starting point, so all the data must be given. The *second* principle is that the co-ordinates of the extremity of a conductor are the same as its origin, unless modified. Looking at the first conductor above: `a0 b19 c.6 x15 s3 r.006` one can see that this conductor starts at **x = 0 y = 19 and z = 0.6**, corresponding with the numbers next to a, b and c. The extremity is only specified by **x = 15**, therefore, y and z remain the same at the extremity. The required sub-division **s** is **3** and the radius **r** is **0.006**. The next conductor starts at the end of the first one, has different x and y co-ordinates at its extremity and a different sub-division, therefore three parameters are required to specify it: `x20 y14 s1`

If the order of entry of conductors is chosen carefully, many conductor segment entries are reduced to only one letter and number. It is much quicker to prepare the data in this way, but it is more difficult to make changes later than if the full specification is used. Both this format and the more conventional format described below, can be used and can be intermixed in the data blocks.

The keyword **CURRENT** is used to specify the current injected into an electrode. This is illustrated in the following lines in the file, the first one being a comment line and ignored by the program:

```
* Injected current
```

```
current
1000.0
```

A current of 1000 amps will be injected into electrode Main. If there were other separate electrodes, +ve or -ve current could be injected into them as well. When the separate electrodes are bonded by impedances and the ac version of the program, **KWIKZ** is used, the injected current must be complex e.g. `1000.0 200.0`. In fact, the complex current can be used with **KWIKR**, the dc version of KWIKGRID. the imaginary part of the current will be ignored. It is therefore possible to run ac models with the dc program providing all the **IMPEDANCE** bonds are deleted from the input data.

Every model must have at least one current injection, but each electrode in the model can have only one current injection. The **CURRENT** keyword followed by the injected current, can be anywhere in a block of electrode data.

The conventional data format is used for the rest of the conductor segments:

```
18.0   16.0   0.600   18.0   0.0   0.6   0.006  3
```

The above line specifies a conductor segment that runs from $x = 18$, $y = 16$, $z = 0.6$ to $x = 18$, $y = 0.0$ and $z = 0.6$. The last two numbers on the line, specify that the segment should have a radius of `0.006` metre and the program should subdivide the segment into `3` pieces. The conductor runs from north to south in the model and the full length is 16 metres because the x co-ordinate does not change and the y co-ordinate changes from 16 at one end to 0 at the other. Its is buried horizontally at a depth of 0.6 metre.

A spreadsheet program can often be used to prepare the block of conductor data, which can be saved in text format.

The conductor data for the electrode continues until the keyword **AREA**:

```
area
-1  -1  17
```

This specifies a rectangular area on the soil surface where soil potential calculations are required. The area is specified by the x and y co-ordinates of the bottom-left corner of the area and the width. In this case, the bottom-left corner is at $x = -1$, $y = -1$ and the required width is `17` metres. The program will generate a two dimensional array of soil potentials covering this area. By default, there will be 41 points in the x-direction and 31 points in the y-direction.

The number of points in the x-direction can be altered by adding the required number of points to the end of the line following the keyword **AREA**. For example, if 81 points were required in the x-direction, the line after **AREA** would be: `-1  -1  17  81`. The program will develop a 3:4 aspect ratio and calculate 61 points in the y direction.

The ratio between the number of points in the x-direction and y-direction should be 4 to 3 as this will produce "square" plots when step and touch potential contours are plotted from the soil potentials.

The last keyword is **END**. This signifies the end of the data. The program will not read the file any further.

Other keywords are used for soil potential calculation below the soil surface.

4.2   AC Version KWIKZ

This is the same as the dc version **KWIKR**, but allows impedance bonds between separate electrodes to be included in the model and addition of remote ground impedances. The calculation becomes complex in that all voltages and currents will have real and imaginary parts. This doubles the size of the matrix and slows the calculation time to some extent. Therefore, **KWIKZ** should not be used for models that do not have impedance bonds.

The user must enter the impedance bond data in the input data file using the keyword **IMPEDANCE**.

The following is an example:

```
IMPEDANCE
1   3    0.196     0.224
```

This will add an impedance of 0.196 + j0.224 Ω between the first and third electrodes in the model. This could represent a sky-wire between a substation ground grid (first electrode) and tower footing (third electrode). There can be more similar lines. The keyword only needs to be used once.

It is up to the user to ensure that the impedance is correctly assigned to the two electrodes. The electrode numbers 1 and 3 in the example, relate strictly to the order in which the electrodes were specified in the model. Of course, and **impedance** cannot be connect to a non-existent electrode, for example, between **3** and **10**, if there are only 4 electrodes in the model.

The **REMOTE** keyword may also be used with **KWIKZ** models. It enables adding a known remote ground impedance value to a ground electrode. This can be useful as illustrated by the following examples:

- Substation feeding a large distribution system network with neutral/ground wires having a known impedance.

- Substation supplying power to an oil pump station that is bonded to an oil pipeline. The ground impedance of the pipeline can be included.

Note: The block of **IMPEDANCE** or **REMOTE** information may not be within a block of electrode or other data. The information must also be given after all the electrodes are specified.

4.3   Reviewing the Results of the Calculation

If **Export|Results** was selected, the file **SAMPLE1.OUT** will have been created. This can be viewed using a text editor.

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

```
Start: Tue Mar 13 15:36:49 2001

KWIKGRID DC Version 1.2. Compiled on: Dec  4 2000
Copyright: Ground-it.com Consulting Ltd.
-------------------------------------------------------------
* FILE: SAMPLE1.KDA
* Created on March 12, 2001 by Ian Simpson
* Example of a 19 x 20 m ground grid with rods and angled conductors in
* two layered soil
* Lines starting with an * are comments - ignored in the calculation
* Calculation assumes metric units, otherwise use keyword english
* for english, resistivity is still in ohm-metres.
* Perimeter conductors
* These are entered using the intelligent format
* Injected current
* Other conductors
* These are entered using the basic x,y,z format
* rods
* Following lines specify the area for plotting potentials

Upper layer resistivity:    47.0000 ohm-meters, depth:     1.3000 meters

Deep layer resistivity:    28.0000 ohm-meters.

Calculation accuracy selected: 0.001000 used: 0.001000

METRIC units of measure.
```

The above block repeats all the comments made in the input file, soil resistivity and accuracy for the two-layer calculation. As no accuracy was selected, the default value of 0.001 p.u. was used. This number is used to stop the calculation of many infinite series when sufficient accuracy has been achieved. The infinite series is only used for two-layered calculations. The use of metric measure is also confirmed.

The next part of the results file is a repeat of input data as interpreted by the program. There will be more conductors than in the input data, as each conductor will be subdivided into the selected number of sub-segments and for ground rods, where they cross the interface between the upper and deep soil layers.

```
Electrode: Substation
Injected current  1000.0000 amps
  #    X origin  Y origin  Z origin  X extrem  Y extrem  Z extrem   Radius
 ---   <-------><-------><-------><-------><-------><-------><------->
   1      0.000    19.000     0.600     5.000    19.000     0.600     0.006
   2     15.000    19.000     0.600    20.000    14.000     0.600     0.006
```

The original conductors will be found truncated in length and new conductors will be added at the end of the original block. For example, conductor #1 was originally from **x = 0** to **x = 15**. It was subdivided into **3** pieces. In the above block of results, conductor #1 now goes from **x**

= 0 to **x = 5** and there are two new conductors #30 and #31 (not listed above) that go from **x = 5** to **x = 10** and from **x = 10** to **x = 15**.

The number of terms in the infinite series that were used, the potential rise and resistance of the electrode is given at the end of the block of subdivided conductor data:

```
Maximum number of series terms required 5
Average number of series terms used 3

Electrode  Main. Injected Current:  1000.0000 amps
Potential Rise:   767.5424 volts, Resistance:    0.7675 ohms
```

The number of terms of the infinite series used, depends on the soil model and accuracy selected. Widely differing soil resistivities and requests for higher than 0.001 p.u. accuracy will result in more terms being required and can slow the calculation considerably. The program incorporates code that determines the maximum number of terms required to obtain the required accuracy – 5 in the above example. As the evaluation of the infinite series proceeds, it is able to predict when sufficient terms have been calculated and will stop the infinite series evaluation at that point. This leads to the statement: **Average number of series terms used 3.**

If there are multiple electrodes, the injected current and potential rise of each will be given.

The next part of the results file gives information on the flow of current out of each conductor segment into the soil. By going through this table of results, one can see that more current flows from the parts of the ground rods that are in the bottom layer of the soil. Other effects, such as the way current flow is distributed around the electrode, can also be determined. The total of all current flow to the soil equals the injected current of 1000 amps.

```
Cond #  length     amps/meter    amps to soil     cum amps
    1   5.000      5.03070788     25.1535394      25.153539
    2   7.071      4.29068813     30.3397467      55.493286
    .
    .
   42   5.667      3.44274261     19.5088748     977.639919
   43   5.667      3.94589668     22.3600812    1000.000000
```

When the ac version of the program is used and there are impedance bonds between electrodes and remote ground impedances connected to one or more electrodes, there will be additional lines like the following:

```
Impedances:
From Electrode  To Electrode   Real           Imaginary
       1              2         0.340000        0.133000
       2              3         0.340000        0.133000

Remote Grounds:
From Electrode      Real          Imaginary
       2        3.900000       1.000000
```

This repeats the input data for the impedances between electrodes and impedances to remote ground.

The last block of information in the results file is the series of potential profiles that cover the selected **AREA**. These have the following format:

```
Soil Potential Profile No. 2

   x              y              z             Soil Potl
   -1.000         11.325          0.000        519.3699
   -0.575         11.325          0.000        561.3220     .
   .
   .
   15.575         11.325          0.000        616.2648
   16.000         11.325          0.000        617.8615


Average number of series terms used 4
```

Each profile covers a line across the area and consists of 41 potential points. The x,y,z co-ordinate and soil potential of each point is listed. The average number of terms of the infinite series that were used, is given at the bottom of each potential profile. The potential calculation is similar to the mutual resistance calculation in that sufficient terms of an infinite series must be evaluated to meet the accuracy requirements.

```
End: Wed Aug 12 10:07:44 1998
Calculation time: 1 sec.
```

The calculation time is given at the end of the results file. The sample file took 1 seconds to calculate. Models with many conductor segments, two layered soil having a high ratio between the upper and deep layer resistivity values and many soil potential points, can take many minutes to calculate.

5. CALCULATION METHODOLOGY

Sunde [2] gives an equation for the voltage produced at a point P in the earth by a point source of I amps. He states that the voltage produced is:

$$V = \frac{I\rho}{4\pi}\left(\frac{1}{r} + \frac{1}{r'}\right)$$

where ρ is the resistivity of the soil, r is the distance between P and the source of current and r' is the distance between P and the image of the source of current. The image is an imaginary second source of current located directly over the current source as far above the surface as the current source is below the surface.

This equation forms the basis of the program.

A technical paper by R.J. Heppe [1] expands the basic equation. It develops equations for:

- Calculating the voltage at points in the soil due to a thin conductor segment that discharges current uniformly along its length.

- Calculating the mutual resistance between two conductor segments. The term "mutual resistance" means that for a pair of conductor segments with a given mutual resistance R, the flow of 1.0 amp from one conductor segment in the pair will produce a potential of R x 1.0 volts on the second one. The mutual resistance calculation considers the first conductor as an infinite number of small current sources. Each current source produces a potential at every point along the second conductor. Double integration is used to integrate the potentials along the second conductor, for all the current sources on the first.

- Accounting for the effect of soil layering where there are two distinct layers of soil with differing resistivity. The mutual resistance calculation becomes the summation of an infinite series of mutual resistances between the segment and images of the segment. The image locations are determined by the interface between the soil layers. Fortunately the series converges and a method is developed for determining how many terms are needed to ensure that the mutual resistance is calculated to within a given per-unit accuracy.

The equations developed by Heppe closely simulate the real world, providing the conductors segments are thin compared with their length. This is normally the case with ground electrode wires and rods.

They assume that the flow of current from a conductor segment is uniform along its length. This is referred to as a current density in units of amps/metre. In the real world, the current flow is not uniform. As an example, if a single horizontal conductor segment is considered, the current density will be higher at the ends than in the middle. The calculation can be made to compensate for this effect to some extent by sub-dividing the conductor segments into smaller pieces. If this were done for the single conductor example, the parts that are near the ends could have a higher current density.

KWIKGRID models ground electrodes as a set of conductor segments that are related by their mutual resistances. In the KWIKGRID analysis, every conductor segment has a mutual resistance with every other segment. When current flows into (or out of) the soil from the conductor segments, it produces a potential rise at all segments, including itself, that is determined by the mutual resistances between the segment pairs. The self resistance of a conductor segment is the mutual resistance between its centre and a second parallel and equal length conductor radius distance away.

Given a ground electrode configuration and ground current, one could analyze it as follows:

Calculate all the mutual resistances between every possible pair of segments and the self resistance of each segment.

Divide the ground current by the total length of all the segments to obtain a uniform current density.

Calculate the potential rise of all segments.

This process suffers from two problems. First, the conductor segments will probably have different potentials which is not possible if the electrode has all segments interconnected as in a ground grid. Second, the current density is known to vary from segment to segment and it has been forced to be the same in each segment.

In KWIKGRID, the analysis is done by developing an equation for each conductor segment. In each equation, the potential rise of the segment is calculated from the current flowing out of every segment, including itself and the mutual resistance with that segment. The currents are unknowns in the equations. The potential rise is also unknown, but the interconnection of the segments ensures that all the segments have the same potential rise. So there is one more unknown in the set of equations.

For a single electrode with N conductor segments, there will be N simultaneous equations with N+1 unknowns. An extra equation can be written by recognizing that the sum of all the individual segment currents equals the total ground current. KWIKGRID uses this method to develop N+1 equations with N+1 unknowns. In KWIKGRID, Gaussian Elimination [3] is used to solve the equations and to determine the potential rise and ground resistance of the electrode and the current flow from every conductor segment.

With the conductor segment currents known, potentials are calculated at any location on or below the soil surface by summing the effect of the current flow from every conductor segment.

Separate and interconnected electrodes are considered as a large system comprising all the conductor segments, but with differing potential rise for each electrode. When there are ac impedances between separate electrodes, the whole calculation is carried out using complex math. Injected currents can be specified in complex format with implied phase angle. Conductor segment currents, electrode potential rise and soil potentials, will have complex values.

KWIKGRID analyses assume the following:

1. Conductor segments are thin compared with their length.

2. Parallel conductor segments are not too close to one another. Crossing conductor segments can touch and ends of segments can meet and can be co-linear or at angles.

3. Current density is constant along each conductor segment.

4. Soil is perfectly uniform in resistivity or perfectly layered.

Of the above items, a reasonable model can usually be created to satisfy Items 1 and 2. Item 3 can usually be accepted by increasing subdivision of long conductor segments. Item 4 is usually the most difficult to determine with accuracy.

6. PROGRAM KEYWORDS

The KWIKGRID input data format makes use of keywords. Keywords can be in upper or lower case or a mix of upper and lower case. A keyword must be the first word on a new line. Except for the keyword **ELECTRODE**, everything after the keyword is ignored. Therefore, comments can be added after keywords as reminding notation. In the case of the keyword **ELECTRODE**, a descriptive comment should be added as it will be printed out in the calculation results. This can be helpful in models with many separate electrodes, where each can be given a name:

```
ELECTRODE Fence
ELECTRODE Tower 1
ELECTRODE Ground Grid
```

Each keyword is followed by the required data. The data can be entered in free format with columns spaced by spaces and/or tab characters.

KEYWORDS:

*   Start of a comment line that is ignored by the program. Can be anywhere in the file. Text on comment lines will be stored and included in the output as a record or commentary about the run. Comments are usually placed at the beginning of the data file to describe the case.

ACCURACY   This keyword only has effect for two-layered soil cases where the program calculates mutual resistances and soil potentials from truncated infinite series. The number entered is the per-unit accuracy of the infinite series calculation. For example, if 0.001 is entered, the infinite series terms will be calculated until within 0.001 per-unit of the value that would be obtained after an infinite number of terms.

            The line following must have the desired per unit accuracy of the infinite series calculation. The accuracy cannot be larger than **0.1** or less than zero. In the first case it will be set to **0.1** and in the second to **0.001**. If **ACCURACY** is not specified, it will default to **0.001**. This is a reasonable value for most models. Using a higher accuracy will result in more terms of the infinite series and slower calculations.

            Example:

```
ACCURACY
0.003
```

AREA   Indicates an area calculation of soil potentials. The soil potentials will be calculated on the soil surface. For below surface potential calculations, **PROFILE** should be used. With **PROFILE**, it is possible to specify potential calculations anywhere on or below the soil surface. **AREA** can only be used once in a model and cannot be used with **PROFILE** in the same model.

The next line must have the x and y co-ordinates of the bottom left corner of the area to be calculated, the width and number of potential points across. If the number of points across is omitted, the program will use 41 points across and 31 up from the specified bottom left corner to make a rectangular plotted area with a width/height aspect ratio of 4/3. This aspect ratio produces "square" plots in the graphical output where the scale is the same in the x and y directions. Whatever number of points is chosen, the y direction will use as close to ¾ the number of points as possible and they will be spaced to produce a 4/3 aspect ratio.

The following example shows how to specify a rectangular array of 60 x 45 potential points with corners at x,y = (0,0) (12,0) (12,9) and (0,9):

```
AREA
0    0    12    60
```

CURRENT   Indicates that current is injected into this **ELECTRODE**. The next line has the current value +ve or -ve. In the ac version, the current must be given in complex format. There must be at least one **CURRENT** statement. It can be anywhere in a block of **ELECTRODE** data. There may only be one **CURRENT** statement in a block of electrode data. The example below is for the ac version **KWIKZ** with real and imaginary parts of the current. Any vector value can be used. For the dc version, **KWIKR**, only the real part of the current will be used, but it can be positive or negative, which allows current return electrodes to be modelled.

```
CURRENT
1000.0  -300.0
```

END   This keyword must be placed at the end of the file. Nothing will be read after this keyword. If it is not provided, the program will stop with an error message.

ELECTRODE Name   Indicates the data about an electrode follows. "Name" can be any description of one or more words that will be associated with this electrode. There must always be at least one electrode in a model. There can be more than one. **ELECTRODE** must be followed by a block of conductor segment data. The conductor data format is given later. The keyword and conductor segment data is referred to elsewhere as a "block of **ELECTRODE** data".

Example:

```
ELECTRODE Main Ground Grid
33.4    92.5    0.6    33.4    12.8    0.6    0.0096    2
33.4    12.8    0.6    14.9    12.8    0.6    0.0096    2
```

The format of the data following **ELECTRODE** is described later.

ENGLISH   This indicates that all model dimension data are in feet rather than metres, including the conductor radius and soil layer height. However, the soil resistivity is al-

ways in Ω-metres. Internally, the program always uses metric (metres). If **ENGLISH** is specified, it will convert the x, y, z co-ordinate, and radius data and the soil depth from feet to metres, do the calculation and convert them back to feet at the end of the calculation. This keyword does not have any subsequent data. If it is not used, the program will assume metric units apply. There is no keyword for metric measure.

IMPEDANCE Used for the ac version only. Indicates that the data following describes impedances that exist between different pairs of electrodes. On each subsequent line, the data must be specified as follows:

<from electrode> <to electrode> <real> <imaginary>

where:

<from electrode> is the number of one of the electrodes
<to electrode> is the number of the other electrode.
<real> is the real part of the ac impedance connected between the two electrodes
<imaginary> is the imaginary part of the impedance.

The following example shows how three electrodes could be specified to be interconnected by an impedance of 1.79 + j3.44 Ω between electrode #1 to #2 and 0.44 + j1.88 Ω from #1 to #3.

The user must associate the numbers of the electrodes with the order in which the electrode data was entered. If the results are exported, the electrode numbering and correct connection of impedances can be confirmed:

```
IMPEDANCE
1     2     1.79     3.44
1     3     0.44     1.88
```

Note: More than one impedance can be specified between the same pair of electrodes. The program will add them in parallel. The impedance values can also be negative or positive, but not zero. If the effect of zero impedance is needed, a very small value such as 0.00001 +j0.0 Ω can be used. If the keyword is not used and there is more than one electrode in the model, the electrodes will not be connected in any way other than through the soil and will be electrically "floating".

PROFILE Indicates potential profile data follows. On each following line the data must be specified as:

<number of points> <x-origin> <y-origin> <z-origin> <x-increment> <y-increment> <z-increment>.

The **PROFILE** keyword can be used more than once, but the results will all be grouped together in the output file. **PROFILE** is used for calculating one or more

potential points along any line on the surface or below the surface of the soil. x and y use the conventional x and y co-ordinate system. z is positive downwards and is equivalent to depth.

While **PROFILE** can be used to calculate points over an area, it is easier to use **AREA** for this. See **AREA** for specifying an array of potential calculations on the soil surface to cover a given area. **AREA** cannot be used for below the surface.

The following example shows how to specify the calculation of a single potential at $x = 12.8$, $y = -1.2$, $z = 0$ and a series of 5 potential points starting at $x = 3$, $y = 8$ and $z = 1.5$, spaced 1 metre apart, increasing in the x-direction. The first point will be on the soil surface. The 5 points will be 1.5 metres below the surface along a straight line.

```
PROFILE
1  12.8  -1.2  0    0    0  0
5  3     8     1.5  1.0  0  0
```

READ   Indicates that the data file contains saved information from a previous calculation. The user will not normally create a data file with the **READ** keyword from scratch and will only modify the potential **PROFILE** or **AREA** part of the file.

When **READ** is used, each line of conductor segment data in each electrode has a leakage current added to the start of the line. This format is produced when the **Export|Saved Data** menu item is selected. For ac models using KWIKZ, the leakage current has two parts - real and imaginary. The leakage current is the current that flows from each conductor to the soil.

The **READ** option is used to avoid having to recalculate the main matrix. This can save time when different areas need to be plotted as the saved data file can be used with a new **AREA** statement. Other data in the saved file should not be changed or the calculation will become meaningless.

The keyword **READ** must appear on a line by itself before any electrode information is listed in the input file.

REMOTE   Used for the ac version only. It indicates that the data following describes impedances that exist between one or more electrodes and remote ground.. On each line, the data must be specified as follows: <from electrode> <real> <imaginary> where:

> <from electrode> is the number of one of the electrodes.
> <real> is the real part of the ac impedance connected from the electrode to remote ground.
> <imaginary> is the imaginary part of the impedance.

The **REMOTE** keyword is useful for models where there is an external ground electrode, for which the impedance is known. An example of this is an oil or gas pipeline that extends for many km and is bonded to a ground electrode that is being modelled. The ground impedance of the pipeline can be added to the ground grid model.

The following example shows how an impedance of 1.79 + j3.44 Ω between electrode #2 and remote ground can be specified. The user must associate the number of the electrode with the order in which the electrode data was entered. The impedance will be added to the second electrode specified:

```
REMOTE
2      1.79      3.44
```

Note: More than one impedance can be specified from the same electrode to remote ground. The program will add them in parallel.

SOIL   Soil resistivity. This must be followed by the upper layer resistivity, deep layer resistivity and height of the upper layer on separate lines. If not specified, soil will default to 100 Ω-metres uniform. Uniform soil is specified as the same resistivity for upper and deep layers, in which case the height is ignored.

Example:

```
SOIL
145
388
4.3
```

For two-layer soil, the ratio between the upper and deep layer resistivity and the height of the upper layer, affects the number of terms of the infinite series that must be calculated to achieve a given accuracy in the mutual resistance and potential calculations. See **ACCURACY** above. Calculations can become quite slow when the ratio of soil resistivities is in the order of 10:1 or higher. The height of the upper layer has a smaller effect on the number of series terms.

6.1   Conductor Segment Data Entry Format

There are two conductor data segment formats that can be used. The first is a fundamental format in which the co-ordinates of the ends of the conductor segments and the conductor radii and sub-division are specified. The second is an "intelligent" simplified data format that is quicker to use while setting up the model, but it is more difficult to modify later.

In both formats, a conductor segment is considered to go from "origin" at one end to "extremity" at the other. The radius is the conductor radius in metres (or feet if **ENGLISH** units are being used). A sub-division entry is provided for each segment. It instructs the program to subdivide

the segment into the specified number of smaller segments. The sub-division process implemented, is discussed later.

Fundamental Format

For the fundamental format, each conductor "runs from point x_1, y_1, z_1 at its origin to point x_2, y_2, z_2 at its extremity". As an example, a conductor segment could be specified as:

```
20   14   .6   20   0   .6   .006   3
```

The origin is specified by the first three numbers: `x₁ = 20, y₁ = 14, z₁ = 0.6` (down) and the second three numbers specify the extremity**: `x₂ = 20, y₂ = 0, z₂ = 0.6`** (down). The last two numbers on the line are the conductor radius of `0.006` metres and the required conductor sub-division of `3`. All entries are required, or the program will stop with an error message.

A spreadsheet program such as Excel, can be used to facilitate data entry. For example, if a series of conductor segments are equally spaced, the spreadsheet copy function can be used to calculate the changing co-ordinates. Once a table has been prepared, it can be copied to a text file using a cut and past operation.

Intelligent Format

The intelligent format uses a simplified shorthand entry format. Here the conductor is specified to run from origin a, b, c to extremity x, y, z, where 'a' corresponds with 'x', 'b' with 'y' and 'c' with 'z'.

The *first* principle is that each conductor extremity is assumed to be the origin of the next conductor, unless modified. Of course, the first conductor in an electrode has no previous one to specify its origin, so all the data must be given for the first conductor.

The *second* principle is that the co-ordinates of the extremity of a conductor are the same as its origin, unless modified. The following is an example of this type of data entry:

```
a0 b19 c.6 x15 s3 r.006
x20 y14 s1
```

Looking at the first conductor above: `a0 b19 c.6 x15 s3 r.006` one can see that this conductor starts at `x = 0 y = 19` and `z = 0.6` (down), corresponding with the numbers next to a, b and c. The extremity is only specified by `x = 15`, therefore, y and z remain the same at the extremity. The required sub-division 's' is `3` and the radius 'r' is `0.006`. The next conductor starts at the end of the first one, has different x and y co-ordinates at its extremity and a different subdivision, therefore three parameters are required to specify it: `x20 y14 s1`

If the order of entry of conductors is chosen carefully, many entries are reduced to only one number. It is much quicker to prepare the data in this way, but it is more difficult to make changes later than if the fundamental format is used.

Note: There cannot be any spaces between the letters a, b, c, x, y & z and the associated numbers. There must be a space between letter number pairs.

Both types of entry can be used in the same model and can be intermixed in electrode data blocks.

6.2   Sub-Division Process

Where conductor segments are vertical or angled to cross the interface between the upper and deep soil layers in models with two-layer soil, each will automatically be divided into at least two sub-segments, one in each layer, meeting close to the interface between the layers, even if a sub-division of 1 is specified. If a subdivision greater than 2 is specified, the program will apportion the sub-segments between the layers to have similar length sub-segments in each layer.

The sub-division process proceeds from the first conductor in a block of electrode data. If the soil is two-layered and the conductor crosses from the upper to the deep layer, it will be subdivided into at least two parts. If the sub-division entry specifies more than two, it will be sub-divided further. The original conductor entry remains in the same location in the block of data, with its extremity co-ordinates changed to make it shorter. The new segments are added to the end of the block of electrode data.

The calculation only starts after the conductors have all been sub-divided and it is as if the user entered the data as a number of smaller segments. The results will contain the sub-divided conductor segments.

A note on sub-division

The theory behind KWIKGRID is based on the assumption that current flows into the soil uniformly from each conductor. This is referred to as a current density in units of amps/metre or amps/ft. In the computer model, the rate of flow is the same at all points on a particular conductor segment. In reality, conductors that cross an electrode, will have a higher current density at the ends near the edges of the electrode than in the centre. Some compensation can be made by subdividing conductors. When this is done, the program splits the conductor segment into the specified number of shorter conductor segments, placed end-to-end. Each sub-segment will now have a different current density (barring symmetry in the model).

When sub-division is activated, the number of conductor segments is increased and the model will take longer to solve. Experience has shown that the end result of determining soil potentials in an area or calculating the ground resistance, is not affected much by improving the accuracy through sub-division of conductors segments. The user should carry out trial runs with different amounts of sub-division to determine the effect.

7. ERROR MESSAGES

The program can generate many error or warning messages to report on input data errors. Most are self-explanatory. Use the error message to identify where the data error has occurred and make appropriate changes to the input data file.

The following are a few of the messages that can appear:

7.1   Errors

ERROR in abc... method in line: Followed by the line where the error occurred. As well as for errors in the data format, this error message occurs when a KWIKZ file, which is an ac file with some **IMPEDANCE** information, is dropped onto the dc KWIKR program. KWIKR does not recognize the keyword **IMPEDANCE.**

ERROR: IMPEDANCE node number is out of range. This can occur if an **IMPEDANCE** is specified connected between say electrode 6 and 3 and there are only 4 electrodes. It can also occur if the **IMPEDANCE** keyword is used before all the electrode data in the file. KWIKGRID reads the data from the top of the file to the bottom and determines how many electrodes there are while the data is being read. If, for example, the **IMPEDANCE** is connected between electrodes 3 and 5 and the data for electrode 3 is given after the **REMOTE** keyword, KWIKGRID will only have counted up to 2 electrodes in the model.

ERROR: REMOTE Impedance node number is out of range. This error can occur for similar reasons to the previous error message.

Conductor segments too short after subdivision. This may happen when conductors cross the interface between upper and deep soil layers and start too close to the layer interface. Either make the conductor longer so that the pieces are not too short, or change it so that the short piece is eliminated. Usually the short piece will have hardly any effect on the analysis result and can be deleted.

Conductor 6 in electrode 3 crossing upper/deep interface is too short or too close. As for the previous message.

Plot width 0.3 too narrow to calculate 1 metre steps. Step potentials plots require a plot area at least 1.2 metres wide so that step potentials can be interpreted from the soil potential data up to the area edges. Make the plot area wider.

Plot height 0.7 too short to calculate 1 metre steps. Step potentials plots require a plot area at least 1.2 metres high so that step potentials can be interpreted from the soil potential data up to the area edges. Make the plot area higher.

7.2 Warnings

Subdivision may be too high in this line: Followed by the line. Occurs when the subdivision is set to > 100.

No impedances specified - You may not need to use the impedance version of the program. Displayed when KWIKZ is used to calculate models without impedance bonds.

Electrode #1 Original Conductor #23 length:rad is 6.34:1 after subdivision. The conductor is so short that the concept of a thin filament is being violated. The ratio of length to radius should be at least 10:1.

8. REFERENCES

1. R.J. Heppe, "Computation of Potential at Surface Above an Energized Grid or Other Electrode Allowing for Non-Uniform Current Distribution", IEEE Trans. on Power Apparatus and Systems Vol. PAS-98, No. 6 Nov/Dec 1979.

2. E.D. Sunde, "Earth Conduction Effects in Transmission Systems", D. van Nostrand Co. Inc., 1949.

3. W.H. Press, B.P. Flannery, S.A. Teukolsky, W.T. Vetterling, "Numerical Recipes in C", Cambridge University Press 1989.

This appendix contains some hypothetical case studies that illustrate how KWIKGRID can be used to solve certain grounding analysis problems.

A1. FALL-OF-POTENTIAL MEASUREMENT ADJUSTMENT

The ground resistance or impedance of a ground grid is often measured using the fall-of-potential test method. To use this method, a current return electrode is located some distance away from the ground grid being measured. A test current is applied to the ground grid using the current return electrode for the return path. Another test probe is used to measure the GPR of the ground grid. For the conventional fall-of-potentia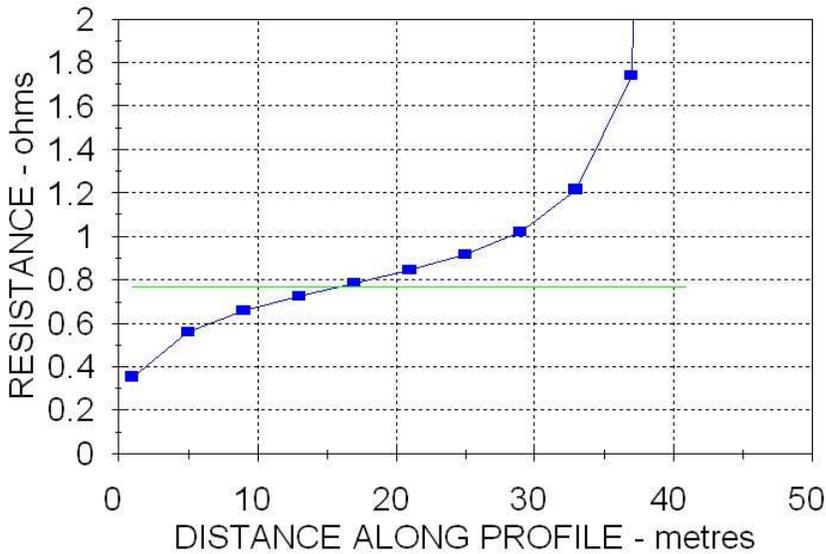l test, the potential test probe is moved out towards the current return electrode and the voltage is measured for each location.

If the voltage is divided by the current for each probe location, a curve as shown in Figure 4 may be obtained. In this measurement, which has been simulated by a computer model, the distance to the current return electrode is 41 metres from the edge of the ground grid.

If the distance towards the current return electrode is much greater than the size of the electrode, it can be shown that the correct ground resistance will be measured at a distance of 61.8% of the total distance from the ground grid to the current return electrode. In the above case, this would be at 25.3 metres where the measured resistance is about 0.92 Ω. The correct resistance is 0.7675 Ω, which is given at a distance of about 15 metres.

Figure 4 Fall of Potential Plot

Most fall-of-potential resistance measurements are carried out under less than ideal conditions. Due to urban development, the current return electrode often has to be placed too close to the ground grid. KWIKGRID can be used to model the measurement configuration and to determine the correction required to compensate for the non-ideal measurement configuration.

The method can be illustrated using the substation model shown in Figure 1 in the body of the manual. The calculated ground resistance was 0.7675 Ω. Data file SAMPLE2.KDA is the same as SAMPLE1.KDA, but a return electrode consisting of a single ground rod has been added at a distance of 41 metres from the west side of the ground grid. This is achieved by adding the following lines to the input data file:

```
* The next electrode is the fall-of-potential return electrode
electrode return
-41  12  0.1  -41  12  3.1  0.009 1
* Returning current
current
-1000.0
```

A return current has also been added for this new electrode that is named "return". The current is –1000 amps and is negative because it returns to that electrode. The current flowing into the Substation ground grid remains the same at 1000 amps (positive). Also, the **AREA** specification in file **SAMPLE1.KDA** has been replaced by the following:

```
profile
11  -1  12   0.1  -4  0   0
```

This specifies points along a line between the Substation and the current return electrode where KWIKGRID should calculate soil potentials. There are 11 points starting at $x = -1$, $y = 12$, $z = 0.1$. The increment is $x = -4$. y and z are not changed. The first point will be 0.1 metre deep at 1 metre from the edge of the ground grid, the next one at 5 metres away, then 9, 13, 17.......up to 41 metres, at the return electrode rod location.

When this file is analysed, the following lines are printed in the output:

```
Electrode #1  Main. Injected Current:  1000.0000 amps
Potential Rise:   680.2629 volts, Resistance:     0.6803 ohms
```

and:

```
Soil Potential Profile No. 1
```

x	y	z	Soil Potl
-1.000	12.000	0.100	413.4795
-5.000	12.000	0.100	206.9817
-9.000	12.000	0.100	109.8086
-13.000	12.000	0.100	41.9621
-17.000	12.000	0.100	-16.4807
-21.000	12.000	0.100	-76.4974
-25.000	12.000	0.100	-149.3252
-29.000	12.000	0.100	-254.9799
-33.000	12.000	0.100	-448.0344
-37.000	12.000	0.100	-971.6320
-41.000	12.000	0.100	-7703.0568

The first few lines above state that the ground potential rise of the Substation is now 680.3 volts whereas it was 767.5 volts without the current return electrode. The effect of the current return electrode is to reduce the "absolute" potential rise of the ground grid being measured. Elsewhere in the results file, the GPR of the return electrode has been calculated to be –10463 volts. This is very high due to the use of 1000 amps. Usually a much smaller test current would be used.

The next group of lines is the potential profile along the line starting 1 metre from the ground grid and running all the way to the current return electrode.

The fall-of-potential plot that would be measured, is calculated by taking the difference between the Substation GPR of 680.3 and the soil potential at each point and dividing the result by 1000 to get the resistance reading. This is exactly what is plotted in Figure 4.

By doing this analysis, it is possible to pick the point on the fall-of-potential curve at which the correct ground impedance will be read, when the test conditions are not ideal. Sometimes it can be as little as 8% of the distance if the Substation is bonded to a remote ground system by a pipe-line or distribution system neutral/ground wires or underground cable sheaths.

A2. TOWERS BONDED BY SKY-WIRES

This case study shows how a series of transmission line towers that are bonded to the Substation by overhead sky-wires, can be modelled and the safety around the towers can be calculated. The modelling correctly includes the additional grounding effect of the tower footings in reducing the ground impedance at the Substation and the GPR for a 1000 amps ground fault current.

Figure 5 shows the computer model of the Substation ground grid and two transmission towers to the south-west of it. For KWIKGRID, only the underground parts are shown. The input data file is **SAMPLE3.ZDA**. Note that the file name extension is **.ZDA**. The file contains impedance bonds and the ac version of KWIKGRID must be used for this calculation.

Each tower ground is simulated by four ground rods. The ground electrode at each tower could be more complicated, for example, the effect of adding gradient control loops of wire to reduce touch potentials next to the towers, could be investigated. One of the towers is hidden under the blue crosses that show an **AREA** to be plotted around the tower.

The towers are modelled as separate electrodes, but are connected to the Substation by impedances that represent the impedance of an overhead ground wire or sky-wire. A 3/8 inch steel sky-wire has been used. The impedance of the sky-wire must be calculated with ground return, as is done for transmission line conductor impedances. The impedance of one type of 3/8 inch steel sky-wire can be calculated to be $4.85 + j1.90$ Ω/km. In the model, the distance between towers is about 70 metres. The impedance will be $0.340 + j0.133$ Ω. The sky-wire impedances are added to the model using the following lines of data in file **SAMPLE3.ZDA**.

```
* Impedance between substation and towers
* 3/8 inch steel 70 metres long
impedance
1     2      0.340 0.133
2     3      0.340 0.133
```
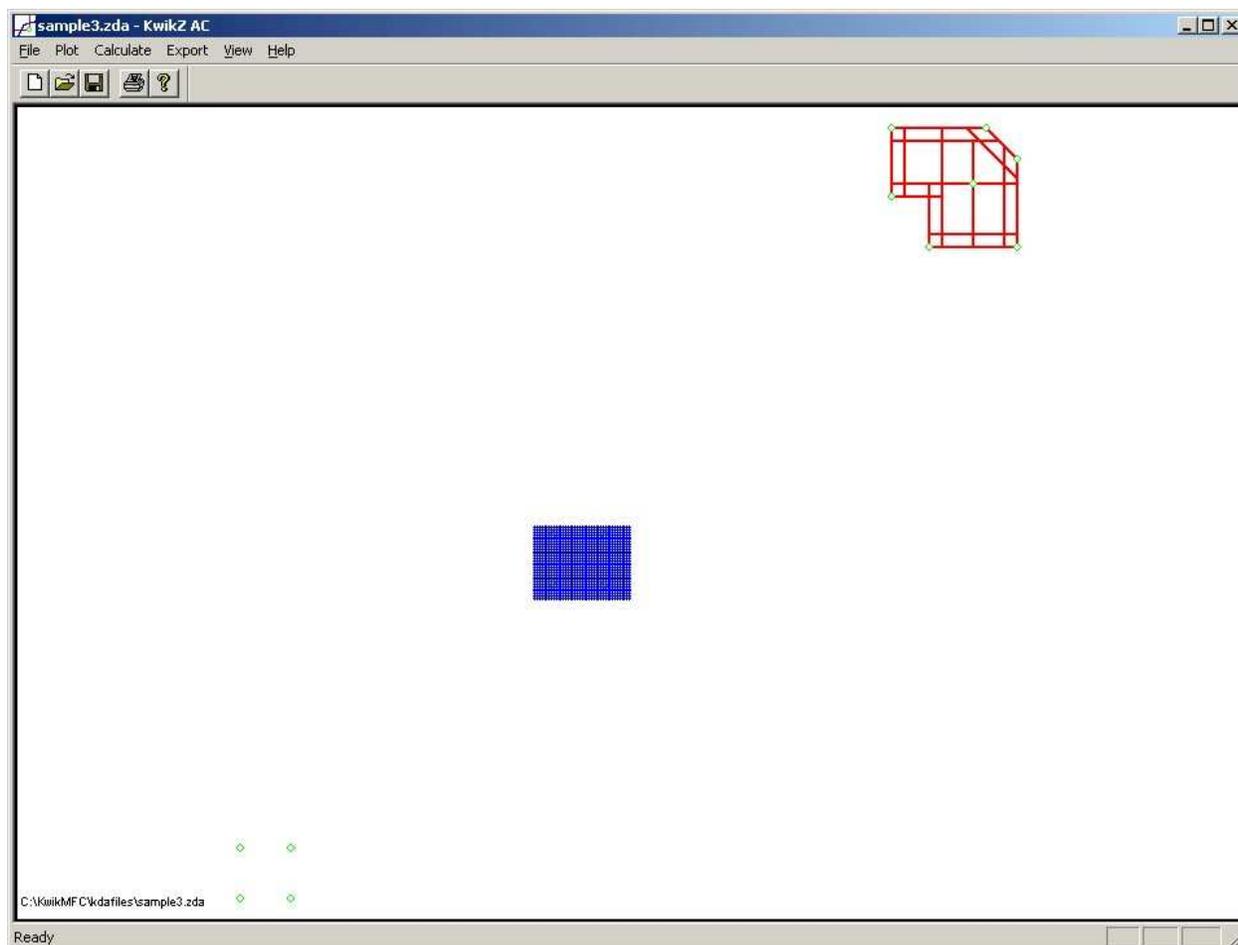
Figure 5 Model of Substation and Transmission Line Towers

The results file SAMPLE3.OUT shows that the ground impedance of the Substation has decreased to the value given in the lines below. This is really the combined impedance of the Substation and tower footings:

```
Electrode #1  Substation. Injected Current:  1000.0000     0.0000 amps
Potential Rise: |   567.6420|   567.5049 j   12.4747 volts
    Impedance:        0.5675 j     0.0125 ohms
```

The GPR has also decreased from 768 volts to 568 volts, due to the extra grounding of the connected towers. Further on in the results file, it can be seen that the GPR of Tower #1 is 472 volts and 426 volts for Tower #2.
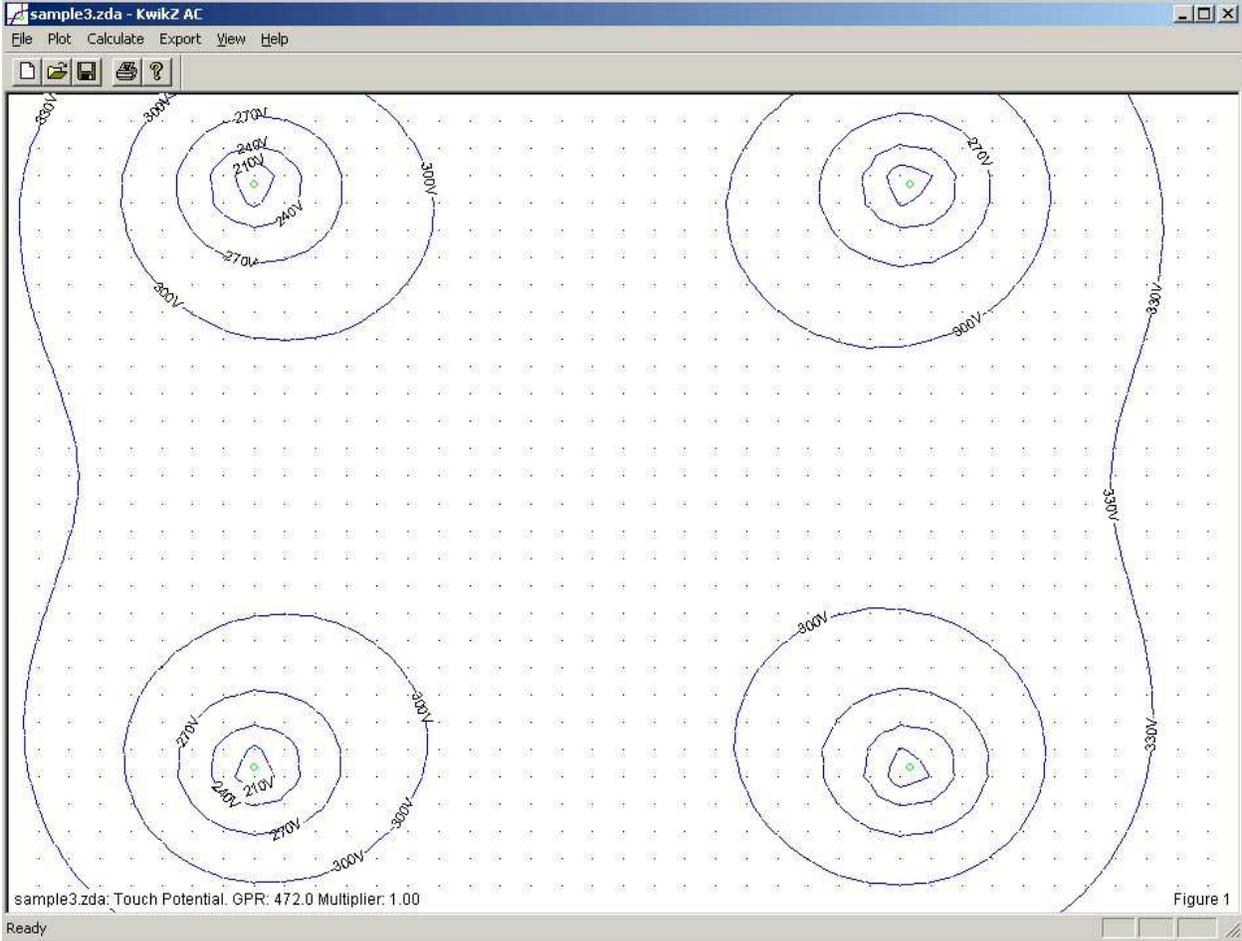
Figure 6 Touch Potentials Around First Tower

Figure 6 shows a plot of touch potentials around the first tower. To plot these contours, the GPR in the KWIKGRID Potential Contour Plotting Options dialog box, must be changed to the GPR for the tower. KWIKGRID will automatically put the GPR of the first ground electrode in the model. Figure 7 shows the dialog box with the GPR changed to the Tower GPR of 472.0 volts.
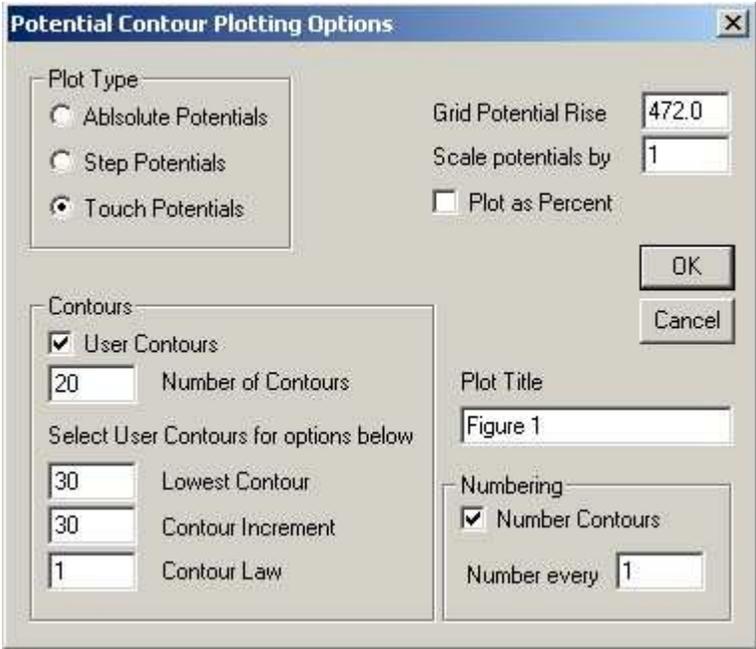
Figure 7 GPR of 472.0 volts for Tower Must be Used

This model could be used to calculate step and touch potentials in other areas and to calculate the effect of ground faults at the towers.

A3. SUBSTATION WITH GROUNDED Y TRANSFORMER

This case is similar to the case in Section A2, in that the Substation and towers are the same, however, the towers are now not bonded to the Substation (They could be). There is a 1000 amp ground fault at the first tower and, because there is a Y-Δ transformer with the Y primary side grounded to the Substation ground grid, 400 amps returns to ground through the star point connection.

The actual current split must be calculated using network analysis such as Ground-it's TACLINK program. One way to do this is to first calculate the ground resistances of the tower and Substation and use them in a TACLINK network model that includes the transformer. The TACLINK results will give the current flowing to ground at the tower and the transformer star point. The currents will likely be complex (r + jx) values. Simple values of 1000 amps at the tower and – 400 at the Substation have been used.

The input data file is **SAMPLE4.KDA**. It is a dc file because there are no impedance bonds and the currents are not complex. If complex currents needed to be analysed, the file could be changed to ac by changing the name extension to **.ZDA**.

The results file **SAMPLE4.OUT** shows the following:

- The Substation GPR is –255 volts and the ground resistance is 0.6365 Ω. The ground resistance is lower than in the base model described in the body of the manual, because of the proximity of the grounded towers.

- The GPR of the first tower is 2960 volts and its ground resistance is 2.96 Ω.

- The GPR at the second tower is about 52 volts. This seems strange as there is no fault at that tower and it is not connected to anything by sky-wires or other means. The reason is that the soil potential around that tower is elevated by the fault at the first tower. The ground resistance is not given because there is no injected current at the second tower. The detailed segment current listing shows that there are small currents that flow into and out of the tower, but the cumulative total current ("cum amps") is zero.

```
Electrode #3  Tower #2:
Potential Rise:    51.7436 volts

Cond #  length     amps/meter    amps to soil     cum amps
    27   1.190     0.09858939      0.1173707       0.117371
    28   1.190     0.00642032      0.0076434       0.125014
    29   1.190    -0.11332910     -0.1349183      -0.009904
    30   1.190     0.00637235      0.0075863      -0.002318
    56   1.791     0.17704166      0.3169931       0.314675
    57   1.791     0.01260183      0.0225636       0.337239
    58   1.791    -0.20086506     -0.3596489      -0.022410
    59   1.791     0.01251615      0.0224102      -0.000000
```

Soil potentials could be plotted around the Substation or towers and step and touch potential contours could be calculated, but care must be taken to use the correct GPR for the touch potential calculations.

A4. SUBSTATION FENCE ANALYSIS

Substations are usually enclosed by a wire mesh fence. Often the fence is grounded to the substation ground grid. Sometimes it may be thought that it would be better not to ground the fence and to let it "float electrically". What will happen then is that the fence will pick up an averaged soil voltage, that is most likely lower than the Substation GPR. Touch potentials are now referenced to the fence GPR.

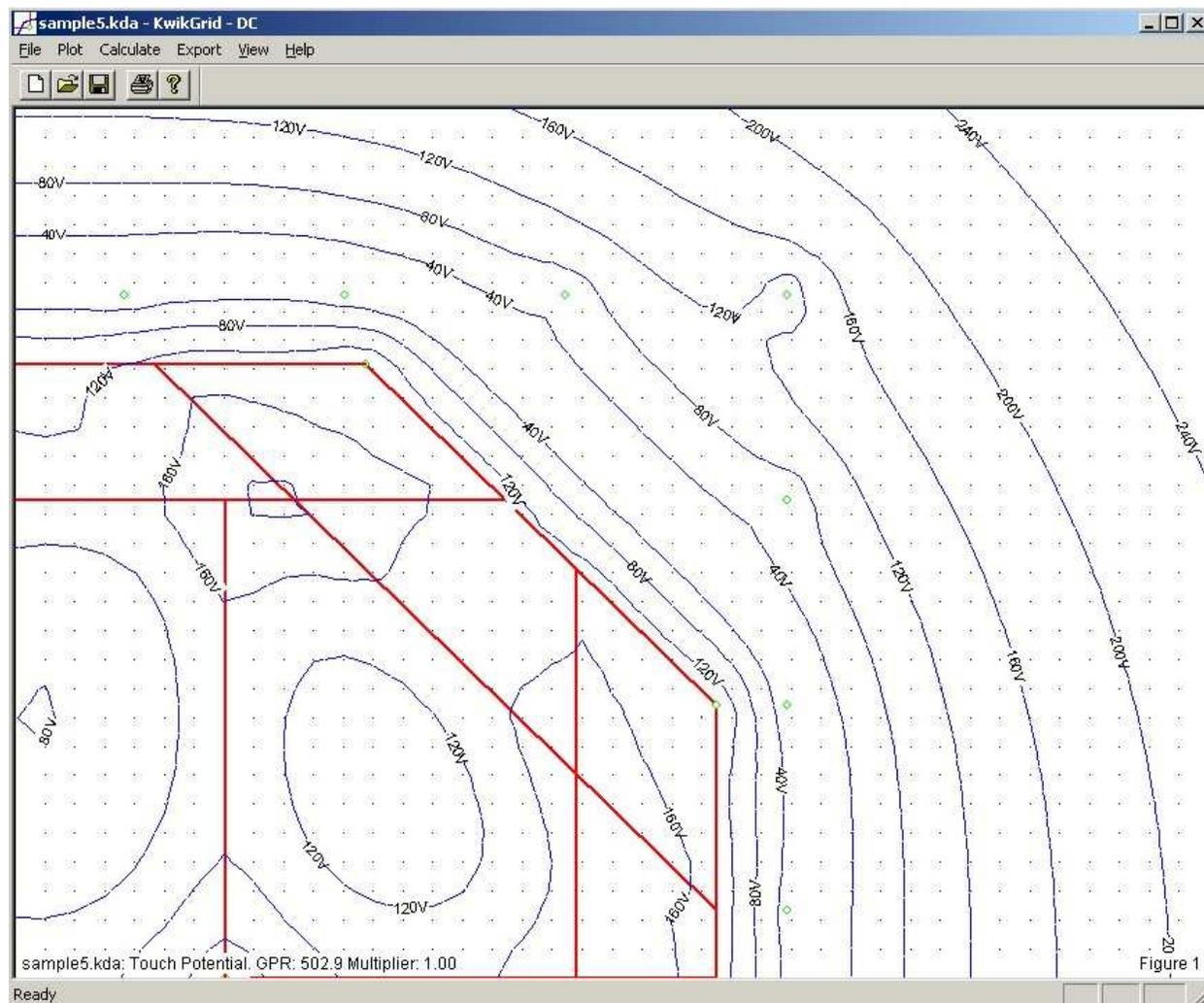KWIKGRID can be used to obtain a definitive analysis for an isolated fence.

Figure 8 Touch Potential Contours Relative to Fence – Fence GPR of 502.9 volts is Used

File **SAMPLE5.KDA** illustrates the addition of the fence. A series of fence posts has been simulated by adding short ground rods with a radius of 0.03 metres and length 0.3 metres. They are in a separate electrode named Fence.

Figure 8 shows the results of the calculation for the north-east corner of the Substation. The Substation GPR is 766 volts and the ground resistance is 0.7661 Ω. It is slightly lower than the resistance of the model without the fence, which was 0.7675 Ω. The fence GPR is 502.9 volts. This value of GPR must be used for plotting touch potentials relative to the fence. The plot in Figure 8 must not be used for touch potentials relative to the Substation equipment. The contour line marked 120V that is inside the Substation ground grid is the difference between the fence GPR of 502.9 volts and the soil potential along that contour.

The plot shows that the touch potential is about 160 volts at the corner of the fence. The fence can easily be grounded to the Substation ground grid by making it part of the Substation electrode and the change in touch potential can be calculated for comparison.