OpenETran

An Open-Source Electromagnetic Transients Program

During the period from 1990 through 2002, EPRI funded the development of a Lightning Protection Design Workstation (LPDW), which was used by many utilities to assess the lightning performance of distribution lines. Since about 2002, this program has not been available. EPRI decided to release the simulation kernel of LPDW under the name OpenETran, with an open-source license (GPL v3), so it may be incorporated into IEEE Flash and other projects.

OpenETran can presently simulate multi-conductor power lines, insulators, surge arresters, non-linear grounds, and lightning strokes. It efficiently calculates energy and charge duty on surge arresters, and iterates to find the critical lightning current causing flashover on one or more phases. It is also suitable for use in substation insulation coordination. Capacitor switching, TRV, and other applications may be added.

EPRI originally had permission to use code from the Numerical Recipes book in LPDW. These routines have been removed in favor of the GNU Scientific Library (GSL), which also uses the GPL v3 license. As a result, the OpenETran package can be freely used and modified, but not commercialized.

There are few error checks on the input data, and no checks on whether the data is reasonable. It may be possible to "crash" the console-mode version of this program with inappropriate input data. However, a spreadsheet interface has been provided for more convenient input, plotting, and critical current estimates.

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1 INTRODUCTION

This program simulates the effect of direct lightning flashes to electric power distribution lines. The main application would be analysis of the effect of surge arresters, pole grounding, and insulation strength on the flashover rate from direct flashes to the line. A planned enhancement to the program will simulate nearby lightning flashes. Another application is the simulation of surges entering a substation from a shielding failure or backflash out on the line.

The solution algorithms are similar to those used in the "industry standard" Electromagnetic Transients program (EMTP) [1]. However, the program input and overall structure have been customized and simplified for this particular application.

Figure 1 shows the circuit structure analyzed for overhead lines. It includes a series of one or more poles, with each pole connected by a section of line with one or more conductors. One conductor, typically the neutral, may be grounded at selected poles or at all poles. Each line section must have the same span length and conductor configuration. Figure 1 also shows optional features, connected to some of the poles. These include:

1. Insulators
2. Surge arresters
3. Terminations, with optional D.C. voltage bias
4. Meters for plotted voltage output
5. Meters for arrester, pole ground, and service drop currents
6. Surge current to represent a direct flash to a conductor

The program can also simulate lumped resistors, inductors, and capacitors. However, it is not suitable for the study of switching transients. References [2-5] describe methods of simulating induced voltages from nearby lightning strokes. However, this has not been implemented in OpenETran yet.

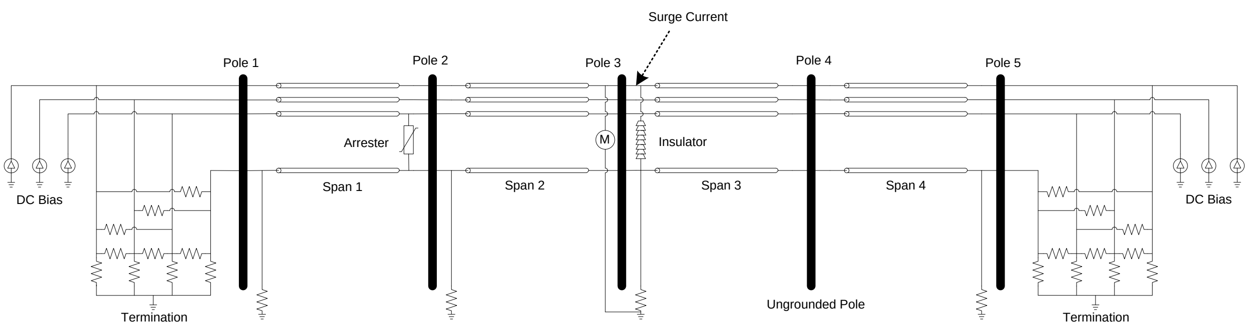

Figure 1 The Circuit Structure is a series of poles and line sections.

The rest of this manual covers the following topics:

1. Directions for installing and running the simulation and spreadsheet interfaces
2. Engineering assumptions and model characteristics
3. Input and output formats
4. Examples

2 INSTALLING AND RUNNING THE PROGRAM

This software requires Windows XP or greater, and Excel 2007 or greater to run the spreadsheet interface. The Output Processor (TOP) software can be downloaded from pqsoft.com and installed to plot binary waveform files. A text editor is also needed to create the input files. The mouse is not used. The software is a console-mode application that must be run from a command prompt.

To install the software, first create a subdirectory on the hard disk, such as ***c:\openetran***. Then unzip the contents of ***openentran.zip*** into that directory.

During execution, the program always writes a log file called ***openetran.log*** into the current directory. This may be useful for debugging model errors.

2.1 Console Interface – One-Shot Mode with Plot Files

The program in one-shot mode reads an input file, and creates one or two files for printed output and plot data. The command to execute one-shot mode is:

Command: ***openetran –plot elt overhead***

Reads: overhead.dat
Writes Plot Data File: overhead.elt
Writes Output File: overhead.out

Note that the program always uses file extension *.dat* for input files, *.out* for text output files, and *.elt* for binary plot output files. The program only creates plot data if the input file specifies voltage or current outputs. The complete plot file options include:

- ***-plot none*** to skip the creation of plot files
- ***-plot elt*** for a binary plot file with *.elt* extension
- ***-plot csv*** for a comma-delimited text plot file with *.csv* extension
- ***-plot tab*** for a tab-delimited text plot file with *.txt* extension

The binary voltage and current meter outputs may be plotted with The Output Processor (TOP) software. The file type to open in TOP is called "EPRI Lightning Transients" and the file extension is *.elt. See the TOP manual or on-line help for more information. The text files may be plotted in Excel, MatLab, or a variety of other programs.

2.1 Console Interface – Critical Current Iteration Mode

The program in critical-current mode reads an input file and creates one files for output. No plot data is created in this mode. The command to execute critical-current mode is:

Command: ***openetran –icrit pole1 pole2 wires… overhead***

Reads: overhead.dat
Writes Output File: overhead.out

Note that the program always uses file extension *.dat* for input files and *.out* for text output files. The command-line arguments for this mode are:

- ***pole1*** is the number of the first pole to hit, according to the numbering convention defined in the input file.
- ***pole2*** is the number of the last pole to hit, according to the numbering convention defined in the input file. If pole1 and pole2 are not equal, the program will average the critical currents for all poles numbered pole1 through pole2, inclusive. This averaging may not be what the user would want. Therefore, it is recommended to set pole2 = pole1, run the program separately for each pole, and handle the critical current output separately from each critical-current mode run.
- ***wires…*** are a sequence of integer flags, 0 or 1, identifying each wire (i.e. conductor) that should be considered for critical current analysis. The sequence of exposed wire flags must match the conductor sequence defined in the input file. If there are not as many flags as conductors, the remaining conductors are not included in the critical current analysis.

The output will include the critical stroke current that just causes flashover of any insulator in the model, constrained between 3 kA and 500 kA. For an example of using this mode, see the *run_icrit_tests.bat* and *test_icrit.dat* text files provided in the test sub-directory. The spreadsheet interface described in section 2.3 also supports critical-current mode.

2.3 Spreadsheet Interface

Figure 2 illustrates the Input worksheet in the *OpenETran.xlsm* spreadsheet interface. Macros must be enabled in order for the interface to work. In order to set up the interface and run it:

- **Area A** – edit the data so that it points to the installed location of the program, and a scratch file for writing the model data. The plot option may be *none*, *elt*, *csv*, or *tab*.
- **Area B** – edit the number of poles, number of conductors, time step, and maximum simulation time. The terminate left and right flags should usually be 1 for surge impedance terminations. When the first and last poles are not equal for critical current iteration, the program will run each requested pole separately, as suggested in the previous section.
- **Area C** – provide one row of conductor data, matching the number of conductors defined in Area B. This data block must be anchored in cell D5. See section 4 of this manual for details on the parameters. (Note: the first three conductors in Figure 2 are all exposed to direct strokes, but since conductors 1 and 3 are symmetrically placed and identical, we only need to Expose one of them for critical current iterations).
- **Area D** – provide one block of data for each type of component needed in the model. Consult section 4 of this manual for details on the parameters and component choices. The template provided in Figure 2 will cover most needs for lightning analysis of overhead lines. There must be a blank row between each block of data, and there must be a blank sub-column of cells to the right of each block. If you do need to add new blocks of data, the order of parameters must match that given in Table 3. (Note: the network input format is not supported yet.) The only restrictions on block sequencing are that conductors must come first, and meters should come last.
- The meter type choices are:
    - 0 for voltmeter
    - 1 for arrester current
    - 2 for pole ground current
    - 3 for customer house ground current
    - 4 for customer transformer X2 terminal current
    - 5 for pipegap discharge current

- Click the Run button to execute a single-shot simulation of the base case, with text outputs on the Output sheet and plot data on the Plot sheet. This action also runs a critical current simulation for each requested pole and exposed conductor, with results placed on the Icritical sheet.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Run	Program:	c:\openetran\test\openetran.exe									
2		File:	c:\openetran\test\test.dat				Area A					
3		Plot:	csv									
4												
5	Conductors	4		Conductor	H [m]	X [m]	r [m]	Vpf [V]	Label	Exposed?		
6	Poles	31		1	10	-1.5	0.00715	3854	A	0		
7	Span [m]	30		2	10.5	0	0.00715	-11097	B	1	Area C	
8	Terminate Left	1		3	10	1.5	0.00715	7243	C	1		
9	Terminate Right	1		4	8	0	0.00715	0	N	0		
10	Time Step [us]	0.02										
11	Stop Time [us]	25		Surge	Poles	N1	N2	Ipk [A]	Tf [s]	Tt [s]		
12	For Critical Currents:				16	1	0	-5.40E+04	3.83E-06	1.04E-04		
13	First Pole	16										
14	Last Pole	17		Insulator	Poles	N1	N2	CFO [V]	Vb	Beta	DE	
15					16	1	4	3.00E+05	0	5.42434	8.43E+21	
16	Area B				16	2	4	3.00E+05	0	5.42434	8.43E+21	
17					16	3	4	3.00E+05	0	5.42434	8.43E+21	
18												
19				Arrbez	Poles	N1	N2	Vgap	V10[V]	Uref	L [H/m]	d [m]
20					odd	1	4	0	39600	0.01	0	0
21					odd	2	4	0	3.96E+04	0.01	0.00E+00	0
22					odd	3	4	0	3.96E+04	0.01	0.00E+00	0
23												
24				Ground	Poles	N1	N2	R60	Rho	E0	L [H/m]	d [m]
25					all	4	0	85	250	4.00E+05	5.00E-07	10
26												
27				Meter	Poles	N1	N2	Type				
28					17	1	4	0		Area D		
29					17	2	4	0				
30					16	1	4	0				
31					17	1	4	1				
32					17	4	0	2				

Figure 2 Spreadsheet Interface to OpenETran

Each time you change data on the Input sheet and click Run, the output cells are cleared and refreshed. This action should automatically update any Charts that have been defined on the Plot sheet. However, if you changed either the Time Step or Stop Time, it may be necessary to expand or contract the Chart data selection.

The spreadsheet contains four other worksheets with data for different examples. In order to run those examples, you should select all data on the worksheet of interest, and copy it to the clipboard. Then you should **Paste/Special/Values** that data onto the corresponding cells of the Input sheet.

- Make sure you match cell A5 with A5, etc.
- Make sure you don't overwrite any Named Ranges that were defined on the Input sheet; Paste/Special/Values is certain to avoid that.
- Clean up any unused cells around the example data you just copied in.

3 ENGINEERING ASSUMPTIONS AND MODEL CHARACTERISTICS

The multi-conductor overhead line sections are subject to the following simplifying assumptions:

1. Earth return path has perfect conductivity.
2. Conductors have no resistance.

These assumptions produce the following self and mutual surge impedances for travelling waves:

$$Z_{ii} = 60 \ln \frac{2h_i}{r_i} \qquad \text{[ohms]}$$

$$Z_{ij} = 60 \ln \frac{D_{ij}}{d_{ij}} \qquad \text{[ohms]}$$

Where:

Where:	i, j	=	conductor #'s
	h	=	conductor height [m]
	r	=	conductor radius [m]
	d	=	distance between two conductors [m]
	D	=	Distance between conductor i and image (below ground) of conductor j [m]

The transmission line equations are then decoupled into single-phase modes. Because of assumption #1 above, travelling waves propagate at the speed of light in all modes. The travelling wave model is similar to EMTP's [1].

As an alternative to conductor data, the user may input the surge impedance and travelling wave velocity directly. This option is only available for uncoupled conductors. This option is useful for cables, which have lower surge impedances and travelling wave velocities than overhead lines. It can also be used for surge arrester leads.

All other model components are connected to poles. The solution of these lumped component models is also similar to EMTP's [1]. The following paragraphs describe model characteristics for these lumped components.

3.1 Bus Conductors

The typical kinds of bus conductor include:

1. **round tube**, described by outside radius R_0
2. **angle**, described by side lengths L and W, and wall thickness t
3. **IWCB**, also described by side lengths L and W, and wall thickness t

These bus conductor types are simulated by adjusting the input conductor radius. Round tubes are modeled the same way as stranded overhead line conductors. Because all high-frequency current is assumed to flow on the surface of the conductor, the round tube’s outer radius is input.

In both the angle and IWCB types, high-frequency currents tend to concentrate in the corners. Based on finite element simulations, it is apparent that currents in the angle bus concentrate on the two open edges, but not on the interior corner. Currents in the IWCB bus will concentrate on all four corners of the square or rectangle. The standard formulas for bundled conductors can approximate these distributions of current. The equivalent bus conductor radius is:

$$r_{equiv} = \sqrt[N]{NrA^{N-1}}$$

$$A = \sqrt{L^2 + W^2} \Big/ 2$$

where:

N	=	number of conductors in bundle, 2 for angle and 4 for IWCB
r	=	subconductor radius = t/2
t	=	bus wall thickness
L	=	one side length of angle or IWCB cross section
W	=	adjacent side length of angle or IWCB cross section
A	=	radius of circle through subconductor centers

There will be a slight error in using these equations for IWCB with rectangular rather than square cross sections.

For example, consider the self-impedance of a single bus conductor at height 10 meters. For a round tube, the outside diameter is 6 inches, or 0.1524 meters. For the angle and IWCB, the length and width are both 0.1524 meters, and the wall thickness is 0.5 inches, or 0.0127 meters. The equivalent radii and surge impedances are shown in Table 1.

Table 1 Bus Conductor Surge Impedances

Bus Type	N	r	A	r_{equiv}	Z
Round Tube	1	0.0762	N/A	0.0762	334.2
Angle	2	0.00635	0.1078	0.0370	377.6
IWCB	4	0.00635	0.1078	0.0751	335.1

The IWCB has nearly the same surge impedance as a round tube with similar outer dimensions, while the angle bus has higher surge impedance. There will be no effect on mutual surge impedances between bus conductors.

3.2 Surge Current

There are two surge current waveshape models in the program. The ***surge*** component uses a 1-cosine front. This component was used in EPRI's LPDW version 1.0 through 4.0, including the transmission line simulations in version 4.0. A ***steepfront*** component, with concave front, was added for EPRI's SDWorkstation.

3.2.1 1-cosine Front

The surge current waveshape has a 1-cosine front, and an exponential tail decay. As Figure 3 shows, this waveshape has a "toe" at the front and a relatively flat peak. For a direct flash to the line, a surge current should be connected from the struck conductor to ground. The program allows a delayed starting time for the surge, which would shift the waveshape in Figure 3 to the right.

3.2.2 Concave Front

Typical lightning current surges have a pronounced toe, flat peak, and maximum current steepness near the peak of the surge. Based on [11], the ***steepfront*** surge component uses Bezier splines to define a current front with maximum steepness at 90% of the crest value, with a flat peak and exponential tail. In contrast, the 1-cosine shape has maximum steepness at 50% of the crest value. Figure 4 shows a 30-kA surge, with 3.67-us front, represented by the two different surge models. The concave shape reaches its peak later, but its virtual zero based on the 30% and 90% points also occurs later. This difference in virtual zeros must be accounted for when constructing volt-time curves for insulators. Both shapes have the same front time, based on the 30% and 90% points. The concave shape is more realistic, and could produce higher voltages in arrester-protected systems, due to the higher maximum steepness.

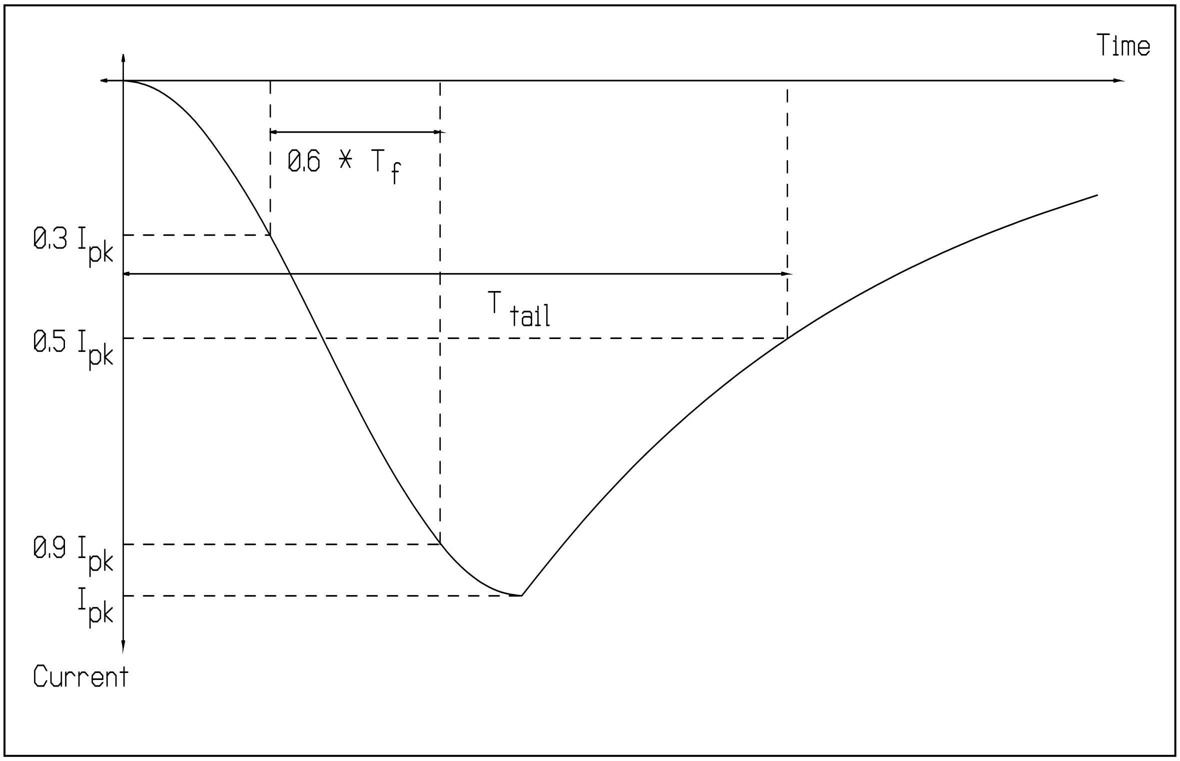

Figure 3 1-cosine Surge Current Parameters

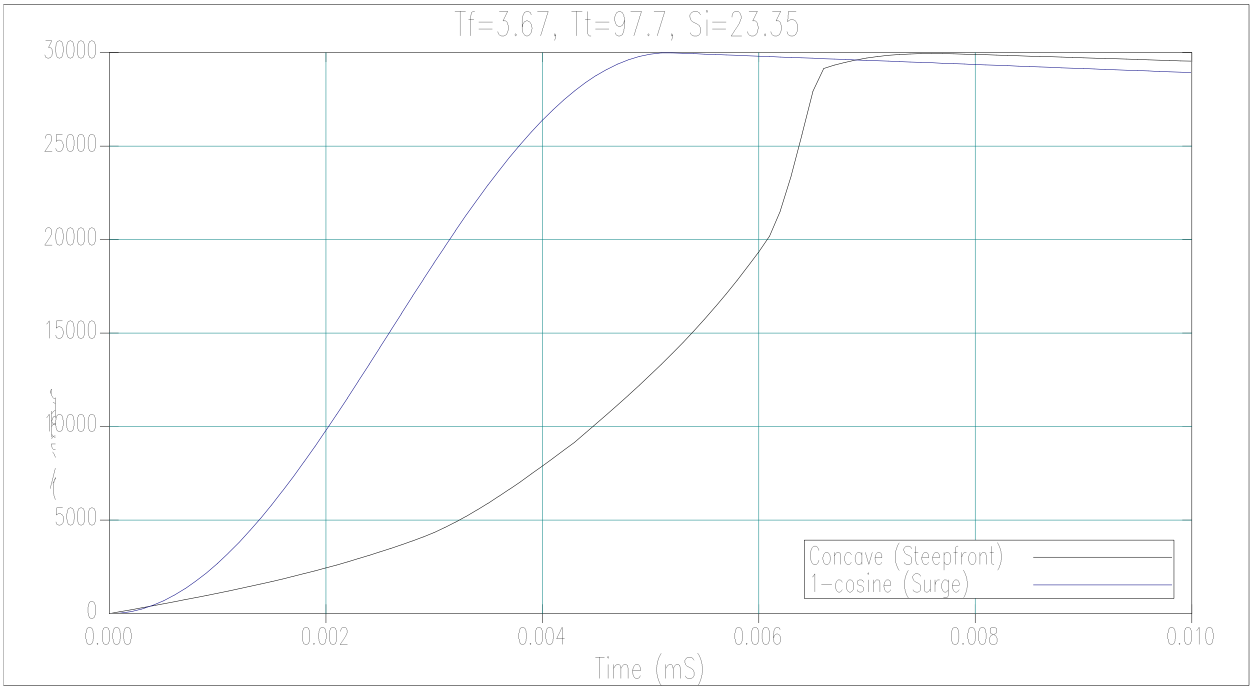

Figure 4 Typical Lightning Surge Current Parameters, surge vs. steepfront Models.

3.3 Insulators

Insulators may be connected between pairs of conductors, or between a conductor and ground. The typical phase insulator would be connected from a phase conductor to the neutral conductor, rather than from phase conductor to ground. There are two insulator models available. LPDW version 1.0 through 4.0 used the destructive effect model, while SDWorkstation and later versions of DFlash used the leader progression model.

3.3.1 Destructive Effect Model

The program integrates voltage across the insulator to determine a "Destructive Effect":

$$DE = \int (e - V_b)^{\beta} dt$$

where:	e	=	magnitude of voltage across insulator
	V_b	=	minimum breakdown voltage
	ß	=	exponent

When the DE exceeds a critical level, then the insulator flashes over. This equation simulates the volt-time curve, as illustrated in Figure 5. For an insulator with Critical Flashover Voltage of 100 kV, typical parameters are:

V_b	=	0.0
ß	=	5.42434
DE_{max}	=	8.4265E21

The program integrates DE only when the magnitude of "e" exceeds V_b. The program maintains both positive and negative polarity DE values, either of which may produce a flashover. If the voltage changes polarity, the DE value is maintained until the voltage changes polarity again. Thus, the DE values can never decrease during a simulation; they may only increase or remain constant. This crudely simulates the leader progression process.

Each insulator is an open circuit, not affecting the simulation, unless the destructive effect across the insulator exceeds the critical level. At that instant, the insulator becomes a short circuit, connecting the two conductors for the rest of the simulation.

If the insulator does not flash over, the program outputs a "per-unit severity index." The insulator would probably flash over if the voltage across the insulator were increased by a factor 1.0/SI, but kept the same waveshape.

3.3.2 Leader Progression Model

The leader progression model is based on the based on the physics of flashover [11], whereas the destructive effect method is more of a curve-fitting approach. The leader progression model generally gives more accurate results.

Only the leader propagation time is modeled; the corona inception time and streamer propagation time are ignored. The program keeps track of the remaining unbridged gap length in both positive and negative directions. The leader propagation velocity is:

$$dx/dt = Ke(t)\left[\frac{e(t)}{x} - E_0\right]$$

where K = propagation constant
E_0 = breakdown gradient
x = unbridged gap length
e(t) = voltage across gap

The unbridged gap length, x, starts at a value given by CFO / E_0. Two instances of this equation are integrated at each time step, one for positive e(t) and one for negative e(t). Only one leader can grow at each time step, and only if e(t) exceeds E_0.

For air-porcelain insulations, E_0 = 535.0e3 and K = 7.785e-7. For apparatus insulations, E_0 = 551.3e3 and K = 1.831e-6.

Whenever either the positive or negative leader's x reaches zero, the insulator flashes over. The program can also run in a mode where insulator flashovers are disabled. The waveshape across each insulator is saved in memory. At the end of the simulation, the saved waveshape is scaled up and down using the bisection method to determine the crest voltage that just barely causes flashover. This produces the severity index for each insulator. The severity index can be greater than one if insulator flashovers were disabled. If an insulator flashover occurs during the simulation, the output severity index is 1.0.

Figure 5 shows the volt-time curves for a 100 kV CFO insulation in air, using both insulator models. Each model was run with both 1-cosine and concave surge waveshapes for a 1.2 x 50 waveshape, but Figure 5 shows that the surge front model had little impact on the results. Figure 5 shows that the leader progression model takes longer to flash over at a given crest voltage.

At voltages below the CFO, Figure 6 shows that flashovers can still occur with the destructive effect model, which might be considered a defect. These flashovers can be eliminated by using a non-zero value for V_b, but then the curve fit isn't as good at higher voltages and lower flashover times. The leader progression model should work better over a wider range of crest voltages and times to flashover.

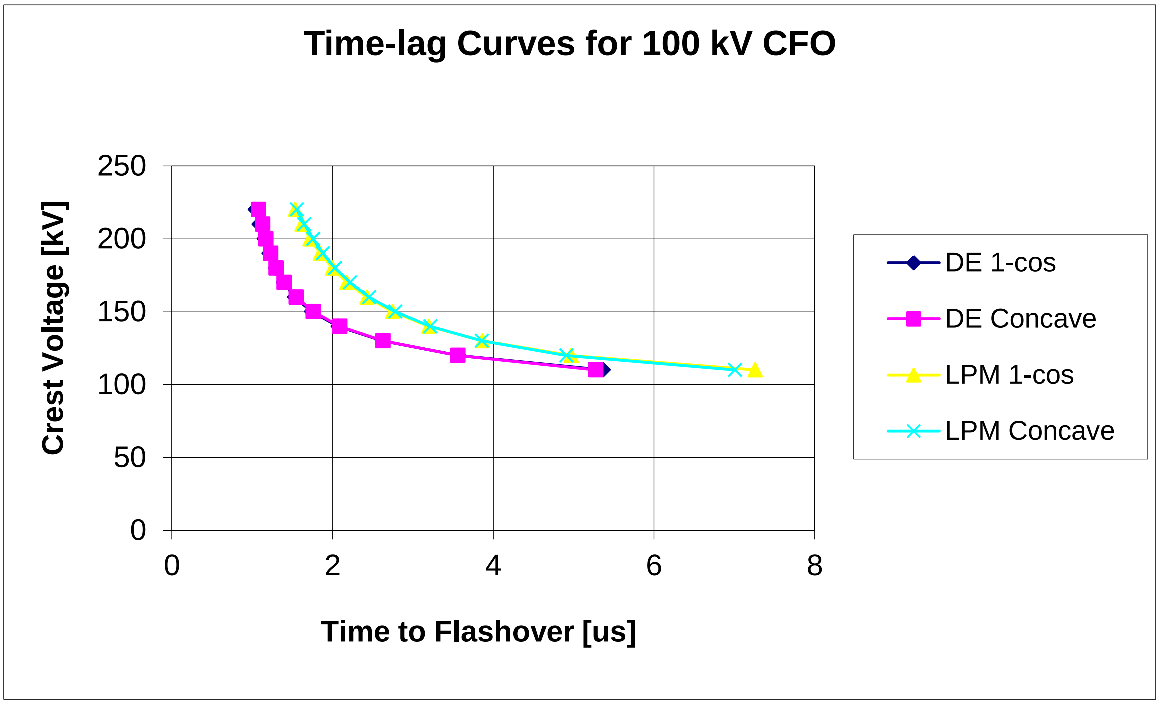

Figure 5 Air-Porcelain Insulator Volt-Time Curves, Destructive Effect and Leader Progression Models.

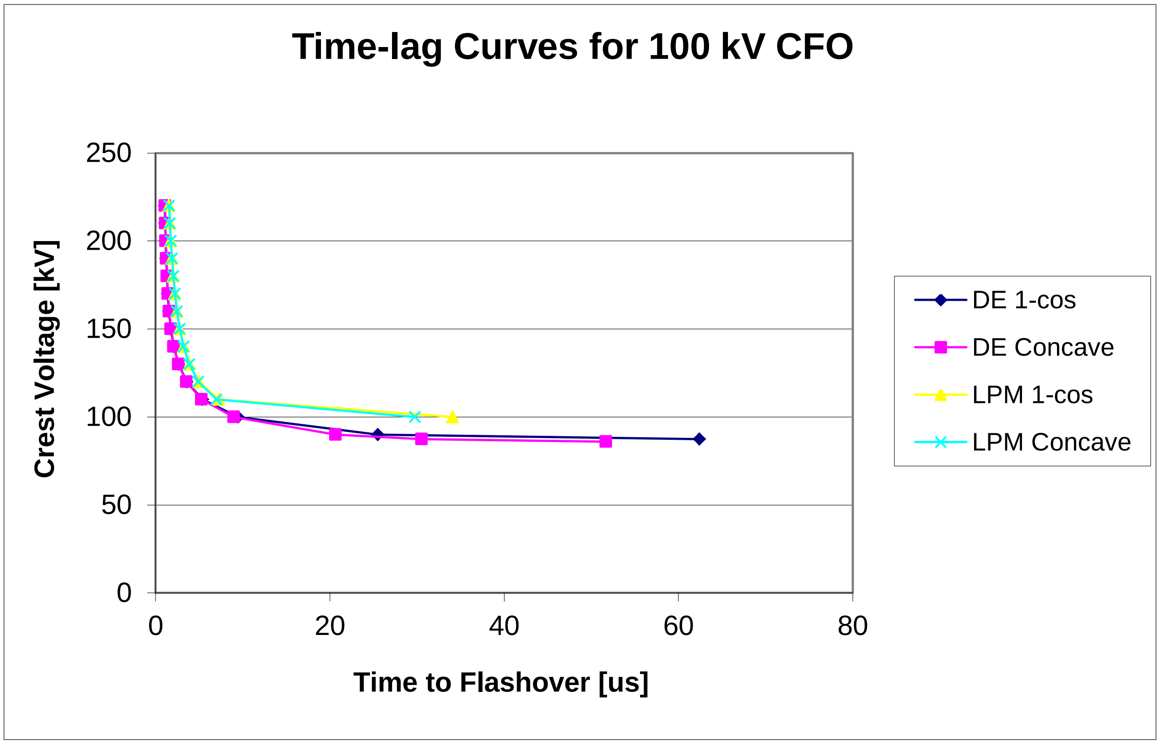

Figure 6 Volt-Time Curves Extended to Long Flashover Times

3.4 Surge Arresters

There are two surge arrester models available. Both models have optional built-in series gap and lead inductance. LPDW versions 1.0 through 4.0 used a simple switched model, with one linear segment for the discharge characteristic.

If the surge arrester gap sparks over, it will conduct until the voltage falls below V_{knee}. At that point, the gap recovers its full strength for voltage transients of positive or negative polarity.

The arrester model includes a built-in lead inductance, which may be input as zero. With a non-zero inductance, the output voltage at the arrester lead terminals will be increased for short impulses. However, the program keeps track of the actual arrester voltage for energy calculations.

On distribution lines, most surge arresters would be connected from a phase conductor to the neutral conductor.

3.4.1 Switch Model

A surge arrester includes a non-linear resistance designed to limit transient overvoltages. Some surge arresters have a gap that allows a higher peak transient voltage than the discharge voltage across the non-linear resistance. These characteristics are shown in Figure 7. In this program, the surge arrester switch model is an open circuit until the voltage exceeds V_{gap} or V_{knee}, whichever is greater. At that time, the discharge characteristic follows a single linear segment. Using this model, it is possible to fit two points on the discharge characteristic; LPDW versions 1.0 through 4.0 matched the 10-kA and 20-kA points.

3.4.2 Spline Model

There are two built-in 8x20 discharge characteristics, obtained from the data General Electric provides for its metal oxide arresters. Both characteristics are provided in per-unit of the 10-kA discharge voltage. One characteristic is for arresters rated 48 kV and below, or a 10-kA discharge voltage of 140 kV and below. The other characteristic is for arresters rated 54 kV and above. Both characteristics are shown in Table 2; the program selects one based on the input 10-kA discharge voltage.

Table 2 Built-in Surge Arrester Discharge Characteristics

I [A]	**V/V_{10}**	
	$V_{10} < 140e3$	**$V_{10} \geq 140e3$**
0.00	0.000	0.000
0.01	0.500	0.500
1.0	0.663	0.691
10.0	0.696	0.725
100.0	0.743	0.769
500.0	0.794	0.819
1000.0	0.824	0.847
2000.0	0.863	0.881
5000.0	0.937	0.946
10000.0	1.000	1.000
15000.0	1.069	1.061
20000.0	1.123	1.109
40000.0	1.288	1.251

Figure 8 shows the simulated arrester discharge characteristics for a 1.2 x 50 current discharge of 20 kA peak through both the switch and Bezier spline models. The 10-kA discharge voltage was input as 40 kV in both cases, but the spline model is more accurate over the whole range of currents. The Bezier spline technique ensures continuous first derivatives at the breakpoints given in Table 2 , with no oscillatory behavior between the breakpoints. However, the discharge voltages aren't exactly matched at the breakpoints. The error could be made arbitrarily small by choosing more tightly spaced breakpoints.

The simulation was repeated with a piecewise linear model. Figure 9 shows the region around the characteristic's knee, and the Bezier spline's error at the breakpoints is not significant.

For steep wavefronts, the surge arrester inductance plus lead inductance adds to the discharge voltage, primarily near the peak of the discharge current because the dI/dt is highest near the peak. Test results show that the discharge voltage peaks well in advance of the discharge current peak. This effect cannot be represented with just a series inductance.

The Cigre method [12] adds a turn-on conductance in series with the inductance and nonlinear discharge characteristic. The conductance starts at zero, and increases with time according to:

$$\frac{dG}{dt} = \frac{G_{ref}}{T}\left(1+\frac{G}{G_{ref}}\right)\left(1+\frac{G}{G_{ref}}\left(\frac{I}{I_{ref}}\right)^2\right)\exp\left(\frac{U}{U_{ref}}\right)$$

$$G_0 = 0$$

$$T = 80$$

$$G_{ref} = 34/U_{10}$$

$$I_{ref} = 5.4$$

$$U_{ref} = kU_{10}$$

where	U_{10}	=	10-kA discharge voltage, in kV
	U	=	voltage across the arrester, in kV
	I	=	current through the arrester, in kA
	k	=	constant ranging from about 0.03 to 0.05, depending on manufacturer

The effect is to delay the start of current conduction through the arrester, while the voltage continues to build up. Figure 10 shows a discharge characteristic with turn-on conductance, and with series inductance plus turn-on conductance. The upper part of the loop tracks the front of the wave, and the lower part of the loop tracks the tail. With just the turn-on conductance, the discharge voltage is increased only in the range from 0 to 5 kA on the wave front. This is caused by an effective delay in the start of conduction. With both turn-on conductance and series inductance, the discharge voltage is increased all the way up to the 20 kA peak on the wave front.

An IEEE working group has presented another model for these dynamics [13], using two nonlinear resistors, along with some linear resistors and inductors. The IEEE model can be implemented with off-the-shelf EMTP components, but requires iterative parameter adjustments to tune the model for each arrester. The Cigre model proved more convenient for this program, because the series inductance and time-dependent turn-on conductance could be built into the arrester model.

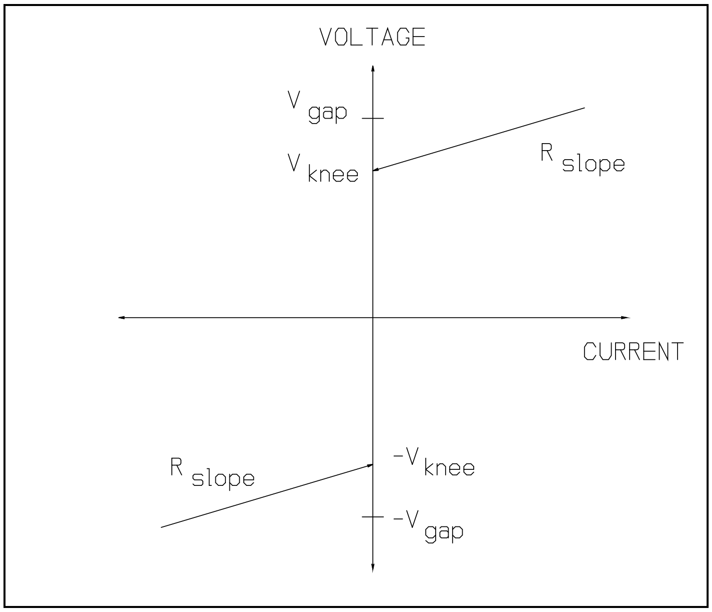

Figure 7 Surge Arrester Switch Model.

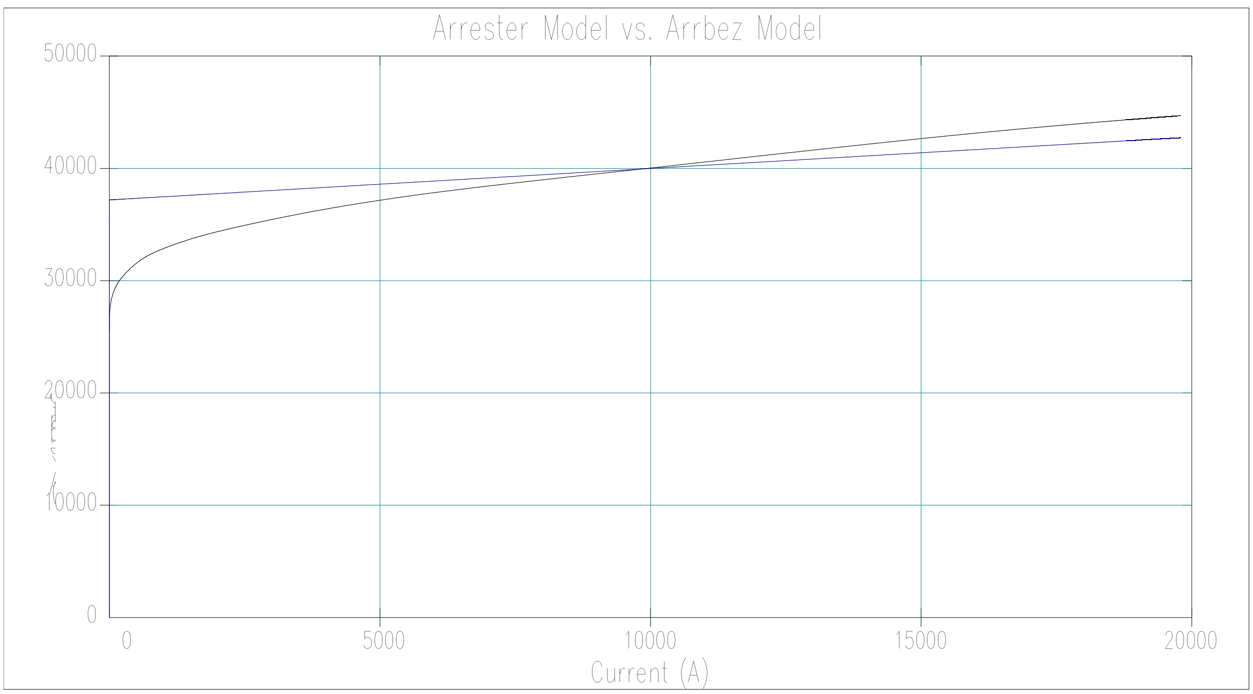

Figure 8 Arrester vs. Arrbez Model, 20 kA, 1x20 Discharge Current.

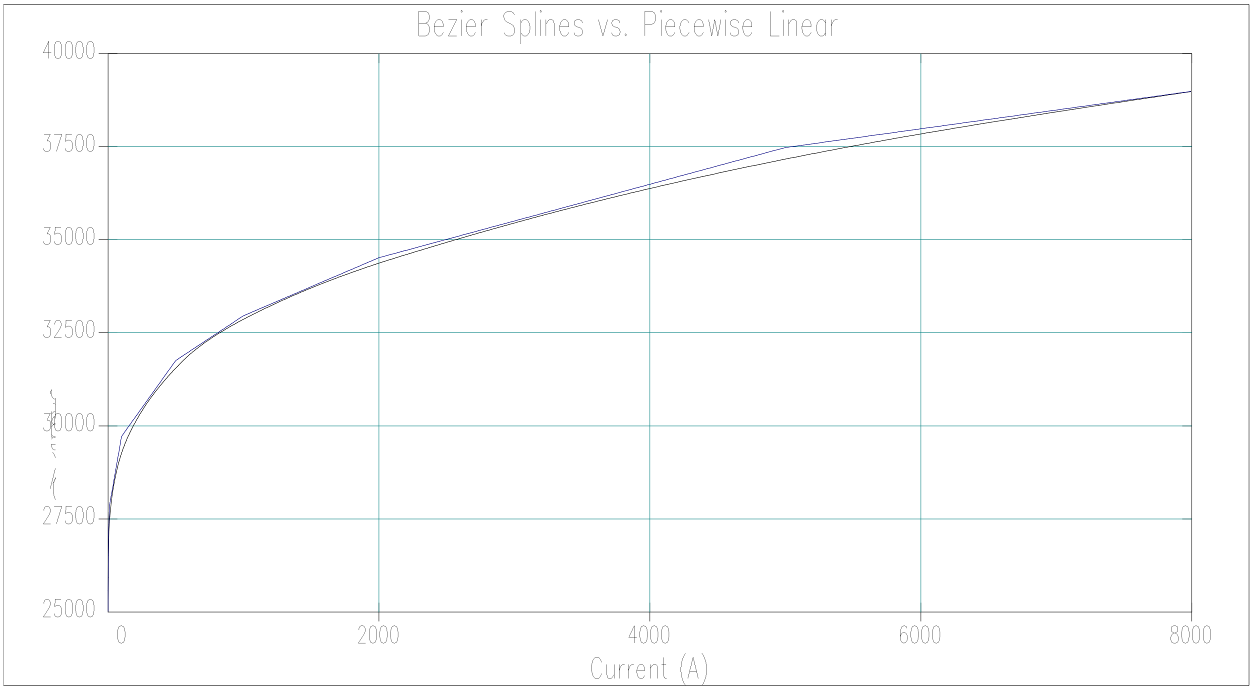

Figure 9 Bezier Spline vs. Piecewise Linear Characteristic, 20 kA, 1x20 Discharge Current.

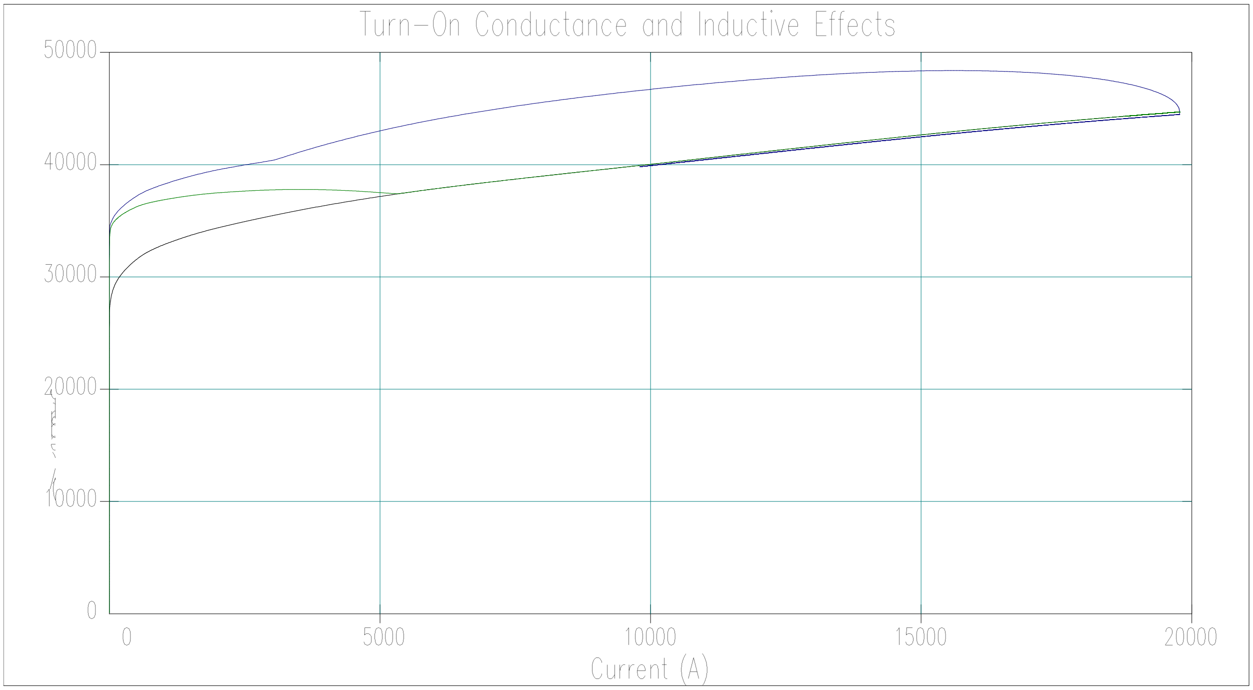

Figure 10 Arrbez Turn-On Conductance and Inductance Model, Uref = 0.051, L = 0.3 μH, 20 kA, 1x20 Discharge Current.

3.5 Pole Grounds

The neutral conductor at each pole, or at selected poles, is grounded through a resistance. The impulse ground resistance is less than the measured or calculated 60-Hz resistance, because significant ground currents cause voltage gradients sufficient to break down the soil around the ground rod. The following equations govern this behavior:

$$I_{brk} = \frac{\rho E_0}{2\pi R_{60}^2}$$

$$R_{ground} = \frac{R_{60}}{\sqrt{1 + \frac{I_{ground}}{I_{brk}}}}$$

Where: E_0 = soil breakdown gradient, typically 400 kV/m
ρ = soil resistivity [Ω-m]
R_{60} = measured or calculated 60-Hz ground resistance [Ω]

These equations assume that the pole ground consists of a single ground rod, which is typical of distribution lines. The program uses a supplemental current injection to model the decreasing resistance. The ground model includes a built-in pole downlead inductance, which may be input as zero. With a non-zero inductance, the output "ground" voltage will increase for steep current fronts. The model does not include capacitance in the pole ground.

3.6 Power Frequency Source

The program can automatically add a surge impedance termination at each end pole in Figure 1. This termination absorbs travelling waves, with no reflections back into the circuit model. The program calculates this termination to match the input conductor data. The program can also run with either or both end poles left open-circuited.

The program can also simulate a power frequency bias voltage on one or more conductors. The bias is modeled as a D.C. voltage, assuming the power frequency voltage will not change very much during the short time of interest for lightning transients.

Initial conditions for the line sections, plus any capacitors and inductors, are calculated to support this D.C. bias voltage. Injected currents are added to each end pole termination, to maintain the bias voltage across each surge impedance termination.

The bias voltage is input with the conductor data. First, convert the nominal line-to-line RMS voltage to peak volts line-to-ground. Then, select a phase A voltage angle. The conductor bias voltages for a 13.8-kV system, with instantaneous phase A voltage angle of 20 degrees, would be:

$$V_{peak} = 13{,}800\frac{\sqrt{2}}{\sqrt{3}} = 11{,}268$$

$$V_a = 11{,}268\sin(20°) = 3{,}854$$

$$V_b = 11{,}268\sin(20° + 240°) = -11{,}097$$

$$V_c = 11{,}268\sin(20° + 120°) = 7{,}243$$

$$V_n = 0$$

Because the bias voltage is D.C., any lumped inductors connected between phase conductors must include some series resistance. A pure inductance cannot support a D.C. voltage (V = L dI/dt = 0 for D.C.). Even with a series resistance, the solution for an inductor with D.C. bias would probably not be valid for the actual situation with an A.C. "bias." Lumped inductors should not be used in this program with a power frequency bias, unless the inductor is connected from neutral to ground (and the neutral has no power frequency voltage).

3.7 Pole-Top Transformer and Service Drop

The program can simulate the house ground current and transformer secondary terminal X2 current, according to a simplified model [6]. Normally, the transformer would be attached to a pole with a primary arrester and a pole ground. The program automatically adds a house ground with service drop inductance, and connects it to the pole.

Assuming the house load is shorted by gap sparkover in the service entrance meter, the X2 terminal current is:

$$I_{x2}(t) = k_1 I_{hg}(t) + k_2 \int V_p(t)dt$$

Where: I_{hg} = simulated house ground current
V_p = simulated transformer primary voltage

k1 and k2 are constant coefficients that depend on the transformer and service drop inductances [6]. k2 is zero if the transformer secondary winding inductances are balanced. k1 is much less for triplex service drops than for open-wire service drops. k1 increases somewhat if the transformer has interlaced secondary windings, which have lower inductances than non-interlaced windings.

3.8 Pre-Discharge Currents

Pre-discharge currents flow between two parallel conductors, or a pipe gap, when the voltage between them exceeds the insulation breakdown voltage [10]. Pre-discharge limits the voltage and delays final breakdown by a few microseconds or more. The effect can be modeled as a simple surge arrester connected between the conductors, with a knee voltage equal to the Critical Flashover Voltage (CFO), and a single slope resistance of 4300 ohm-feet, or 1311 ohm-meters. The resistance is lower, and more current flows, between longer conductors.

Pre-discharge currents only begin to flow when the voltage exceeds the pipe gap's CFO. It is possible to coordinate the pipe gap to protect substation equipment insulation. On an overhead line, however, the pole or tower insulation is the weak link, because its CFO is less than the CFO of the air gap between the conductors (which governs the flow of pre-discharge current). Figure 11 illustrates this coordination problem for a single-phase distribution line. Using an air breakdown gradient of 610 kV/m (186 kV/ft), the CFO between conductors is estimated at 744 kV. At the pole, the pin insulator and wood combine for an estimated CFO of 328 kV. The "protective level" provided by the pipe gap is over twice the CFO of the insulation to be protected.

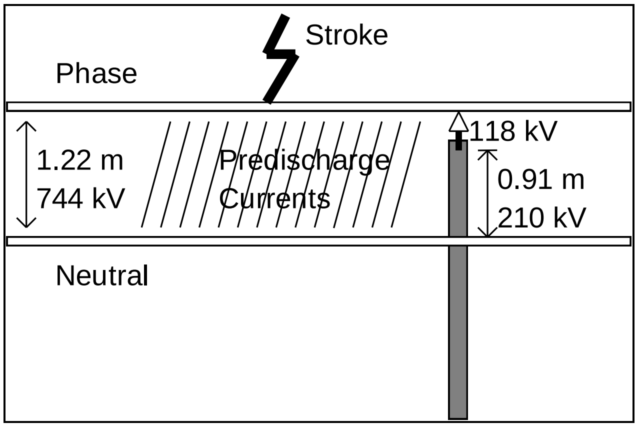

Figure 11 Pre-discharge Currents on a Single-phase Line.

Generally, the main effect of pre-discharge currents is to make midspan flashovers much less likely. Instead, flashovers occur at the pole. The PIPEGAPS.DAT, PAPERGAP.DAT, and PAPERARR.DAT test cases illustrate the use of this model. The OpenETran.exe screen output labeled "pipegaps" is the largest pre-discharge current through any of the line sections, in amps. Usually, this line section with maximum pre-discharge will be next to the stroke location.

3.9 Critical Current Iterations

Critical currents are determined for each requested pole and conductor, using the GSL Brent-Dekker root-finding method [14] on this function:

$$F(I) = SI_{\max} - 1 + (T_{\max} - t_{flashover})1e-5$$

I is the simulated peak stroke current. SI_{max} is the maximum severity index over all insulators in the model, which equals one if a flashover occurred. T_{max} is the requested simulation time and $t_{flashover}$ is the actual simulation stopping time; this is less than T_{max} if a flashover occurred. The function F(I) is negative if no flashover occurs, and it decreases in magnitude as insulators come closer to flashover. When a flashover occurs at exactly T_{max}, the function F(I) is zero, which is the desired root. When the flashover occurs more quickly, F(I) becomes more positive. This monotonic and smooth behavior of F(I) allows the root-finder to determine the critical current within 0.01 kA, usually within 10 iterations.

Based on [11], the critical current iterations are done with a fixed front time of 3.83 μs. The tail time (to half value) is fixed at 103.638 μs. For an exponential tail, this produces the median first-stroke charge of 4.65 C at the median first-stroke peak current of 31.1 kA.

4 INPUT AND OUTPUT FORMATS

The program input format for an overhead line is shown in Table 3. DFlash used this type of format. CFlash and SDW used an alternate form of input for network models, described in Section 4.7. The input must be created with a text editor and saved in a file before running the program.

The program uses SI (metric) units for input:

meters
seconds
volts
amperes
ohms
ohm-meters
henries
farads
volts per meter

Exponential notation may be used for numerical input:

1.0e-6	for 1 ms
-10.0e3	for -10 kA

Floating point input data may have a decimal point. Inputs that are defined as integers must not have a decimal point.

Text input may be upper or lower case, or a mixture, but the spelling of keywords must be correct. All model parameters must be provided in the correct order, and no missing parameters are allowed.

Inputs on the same line must be separated by one or more blanks or tabs. There may be any number of blank lines between the data entries in Table 3.

Comment lines begin with an asterisk (*).

Table 3 Transients Program Input Formats for Non-Network System

N_{cond}	N_{pole}	Span	l_term	r_term	dT	T_{max}		**(required)**
Conductor #	h	x	r	V_{bias}		**(N_{cond} entries required)**		
Conductor #	h	x	r	V_{bias}				
Node #								
ground		(-)R_{60}	r	E_0	L	d		
pairs								
poles								
surge		I_{peak}	T_{front}	T_{tail}	T_{start}			
pairs								
poles								
steepfront		I_{peak}	T_{front}	T_{tail}	T_{start}	S_I		
pairs								
poles								
arrester		(-)V_{gap}	V_{knee}	R_{slope}	L	d		
pairs								
poles								
arrbez		V_{gap}	V_{10}	U_{ref}	L	d	amps	
pairs								
poles								
insulator		CFO	V_b	β	DE			
pairs								
poles								
lpm		(-)CFO	E_0	K_L				
pairs								
poles								
meter	type							
pairs								
poles								
labelphase	N	C						
labelpole	N	name						
resistor		R						
pairs								
poles								
inductor		R	L					
pairs								
poles								
capacitor		C						
pairs								
poles								
customer	R_{hg}	r	E_0	L_{hg}	d	N	L_p	L_{S1}
	L_{S2}	L_{cm}	r_A	r_N	D_{AN}	D_{AA}	L	
pairs ...								
poles ...								
pipegap	V	R						

pairs ... poles ...

Notes for Table 3:

pairs ... =	one or more pairs of conductor #'s for component connections, at the specified poles. conductor 0 = ground limits: $0 \le$ conductor # $\le N_{cond}$
poles ... =	one or more pole #'s to connect components between specified conductor pairs. "poles all" means every pole "poles even" means all even-numbered poles "poles odd" means all odd-numbered poles limits: $1 \le$ pole # $\le N_{pole}$

Negative R_{60} or V_{gap} requests plotted current output for grounds and arresters, respectively.

Use "Meter" components to request plotted voltage or current output. Type = 0 (or blank) for voltage, 1 for arrester/arrbez current, 2 for pole ground current, 3 for customer house ground current, 4 for transformer X2 terminal current, 5 for pipegap current.

The "Customer" component produces plotted house ground and X2 terminal currents automatically.

For plotted arrester and pole ground current output, input the first numerical parameter with a negative sign ($-V_{gap}$ for arresters, $-R_{60}$ for grounds). For plotted arrbez currents, set “amps” to 1.

Negative CFO for the lpm component disables insulator flashover during simulation, but severity index is calculated at the end.

Negative V_{10} for the arrbez component causes piecewise linear rather than Bezier spline fit to VI characteristic.

The input file is divided into three subsections:

1. Required simulation control parameters
2. Required conductor or cable data
3. Optional pole component data

4.1 Required Simulation Control Parameters

These five parameters must be input on the first non-blank line in the file, in this order:

N_{cond} (integer): number of conductors
A three-phase line with neutral would have N_{cond} = 4.

N_{pole} (integer): number of poles in the circuit
The poles are numbered from 1 to N_{pole}.

Span (float): line section span length in meters
For distribution lines, the span length is probably between 20 and 100 meters.

lt (integer): 1 to terminate pole at left end, 0 to leave open

rt (integer): 1 to terminate pole at right end, 0 to leave open

dT (float): simulation time step in seconds.
As a rule of thumb, choose dT as the smallest of the following two values:

a. $dT = 0.1 * T_{front}$ (for a surge input)

b. dT = 0.2e-6 * (span / 300.0)

T_{max} (float): maximum simulation time in seconds
T_{max} should be at least three times T_{front} for the surge current input. To calculate surge arrester discharge duties, T_{max} should be at least two times T_{tail} for the surge current input.

4.2 Required Conductor Data

There must be one line for each conductor. The conductors are numbered in sequence from 1 to N_{cond}. In addition, conductor 0 is "remote ground."

Each line of conductor data begins with the "conductor" keyword, followed by data in the following order:

(integer): conductor number, from 1 to N_{cond}

h (float): conductor height above ground, in meters.
Use the height at the pole, or an average height accounting for sag.

x (float): conductor horizontal position, in meters.
Use the pole centerline as a reference, and enter conductors to "left" of the centerline with negative x, conductors to the "right" with a positive X.

r (float): conductor radius, in meters.

V_{bias} (float): instantaneous power frequency voltage, in volts to ground
See the previous section for equations to calculate V_{bias}. Enter 0.0 for conductors with no power frequency voltage.

The last "conductor" may be a pole node, with no physical conductor attached. This is entered in the form "node #". A typical usage is for arrester-protected lines with no grounded conductor. All arresters and phase-ground insulators are connected from phase to the pole node, and then the pole ground is connected from the pole node to 0.

A sample conductor configuration is shown in Figure 12.

Instead of the preceding "conductor" input, the alternative "cable" keyword may be used, followed by this data:

(integer): conductor number, must = 1

Z (float): surge impedance [Ohms]

V (float): travelling wave velocity, in meters per second

$\mathbf{V}_{bias}$ (float): instantaneous power frequency voltage, in volts to ground

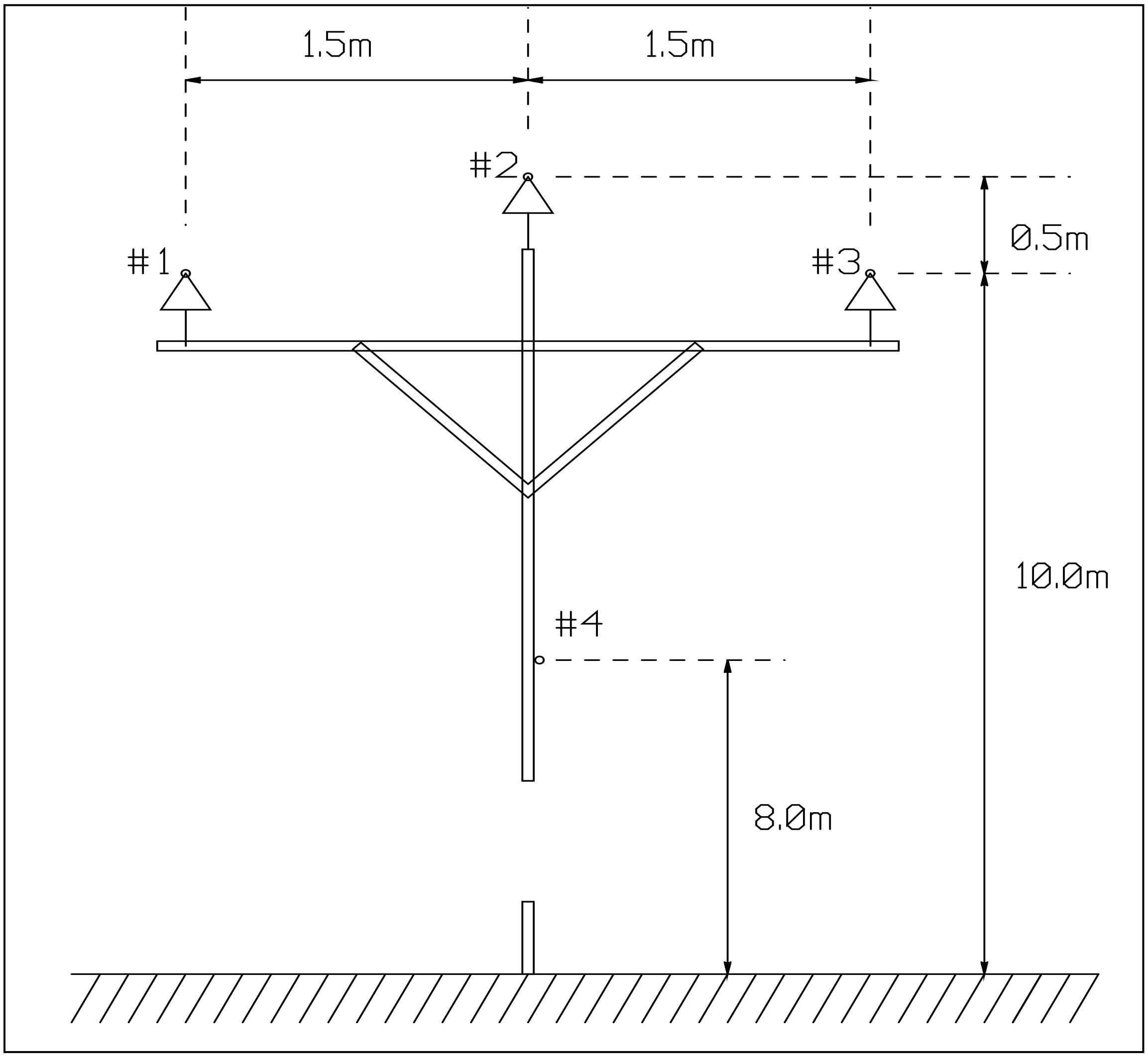

Figure 12 Example Conductor Configuration.

4.3 Optional Pole Components

Input for lumped components connected to poles must follow the required conductor data. Each section of optional input contains three lines, with no intervening blank lines, as follows:

1. Identifying keyword and component parameters
2. Conductor pair connections
3. Pole locations

These optional sections may be placed in any order in the input. A useful simulation case would include at least a "surge" input, but the program does not require this. An input file with no optional components would produce constant output voltages equal to the conductor bias voltages. Also, there would be no voltage output without some "meter" components.

There may be more than one input section for each type of optional component. For example, there might be two separate "insulator" components for the phase-to-ground and phase-to-phase insulation. There might also be two separate "arrester" components with identical characteristics, but one requests plotted currents at a selected pole, while the second places arresters at other poles and requests no plotted current output.

The optional component keywords and parameters follow:

ground parameters:	R_{60}	=	measured or calculated ground resistance, in Ω (If R_{60} is < 0, the ground current will be output for plotting.)
	ρ	=	soil resistivity, in Ω-m (typical ρ = 250.0)
	E_o	=	soil breakdown gradient, in volts per meter (typical E_o = 400.0e3)
	L	=	inductance per unit length of downlead
	d	=	length of downlead in consistent units (may be 0.0)

surge parameters:	I_{peak}	=	crest current, in amperes
	T_{front}	=	30-90 front time, in seconds
	T_{tail}	=	50% tail time, in seconds
	T_{start}	=	surge starting time after simulation time zero, in seconds (usually, T_{start} = 0.0)

steepfront parameters	I_{peak}	=	crest current, in amperes
	T_{front}	=	30-90 front time, in seconds
	T_{tail}	=	50% tail time, in seconds
	T_{start}	=	surge starting time after simulation time zero, in seconds (usually, T_{start} = 0.0)
	S_I	=	maximum current steepness, in per-unit of 30-90 steepness

arrester parameters:	V_{gap}	=	sparkover voltage for arresters that have gaps, in volts (use $V_{gap} \leq V_{knee}$ for gapless arresters) (If V_{gap} is < 0, the arrester discharge current will be output for plotting.)
	V_{knee}	=	"turn-on" voltage of the arrester's nonlinear discharge characteristic, in volts
	R_{slope}	=	slope of the arrester's non-linear discharge characteristic, in Ω
	L	=	inductance per unit length of arrester lead
	d	=	arrester lead length in consistent units (may be 0.0)

arrbez parameters	V_{gap}	=	sparkover voltage for arresters that have gaps, in volts
	V_{10}	=	10-kA, 8x20 crest discharge voltage from manufacturer's catalog, in volts. Negative V_{10} signifies piecewise linear characteristic, rather than Bezier spline fit.
	U_{ref}	=	reference voltage for dynamic turn-on conductance, in per-unit of V_{10}
	L	=	inductance per unit length of arrester lead
	d	=	arrester lead length in consistent units (may be 0.0)
	amps	=	use 1 to plot arrester current, 0 otherwise

insulator parameters:	CFO	=	critical flashover voltage, in volts (usually 95.0e3 $\leq$ CFO $\leq$ 500.0e3 for phase-to-neutral insulators)
	V_b	=	minimum voltage for destructive effect calculation at 100 kV CFO
	β	=	exponent for destructive effect calculation
	DE	=	minimum destructive effect to cause flashover when the CFO is 100 kV
lpm parameters	CFO	=	critical flashover voltage, or BIL, in volts. A negative number indicates these insulators will not flashover during simulation, but severity index will be calculated at the end. SDW runs in this mode.
	E_0	=	minimum breakdown gradient, in V/m. Use 535.0e3 for air-porcelain insulations, and 551.3e3 for apparatus insulations.
	K_L	=	Use 7.85e-7 for air-porcelain insulations, and 1.831e-6 for apparatus insulations.
meter parameters:	type	=	0 (or blank) for voltmeter 1 for arrester or arrbez current 2 for pole ground current 3 for customer house ground current 4 for customer transformer X2 terminal current 5 for pipegap discharge current
labelphase parameters:	N	=	wire number, from 0 to $\mathbf{N_{cond}}$
	C	=	character label for plots in TOP (eg., G, N, A, B, C)
labelpole parameters:	N	=	pole number, from 0 to $\mathbf{N_{pole}}$. For network input, N must correspond to one of the poles input with line data.
	name	=	location label for plots in TOP (eg., xfmr). No embedded blanks are allowed. For 16-bit versions of TOP, it is best to limit “name” to 5 characters.
resistor parameters:	R	=	resistance, in Ω
inductor parameters:	R	=	series resistance, in Ω
	L	=	series inductance, in henries
capacitor parameters:	C	=	capacitance, in farads
customer parameters:	R_{hg}	=	60-Hz house ground resistance, in Ω
	ρ	=	soil resistivity, in Ω-m
	E_0	=	soil breakdown gradient, in volts per meter
	L_{hg}	=	inductance per unit length of house ground downlead, in henries per meter
	d	=	house ground lead length, in meters
	N	=	transformer turns ratio
	L_p	=	transformer primary winding inductance, in henries
	L_{S1}, L_{S2}	=	secondary winding inductances, in henries

	L_{cm}	=	service drop common-mode inductance, in henries per meter (typical L_{cm} = 1.8 e-6)
	r_A, r_N	=	service drop phase and neutral conductor radii, in meters
	D_{AN}, D_{AA}	=	Service drop phase and neutral conductor spacings, in meters
	L	=	service drop length, in meters
pipegap parameters	V	=	the CFO between conductors, in volts (If V is < 0, the pipegap current will be output for plotting.)
	R	=	series resistance to pre-discharge currents, in Ω

Each optional component parameter line must be followed by two lines for "pairs" and "poles." These lines specify where the components are connected. Each component will have identical parameters. During the simulation, the program will track the status of individual grounds, insulators, arresters, and other components at each location.

4.4 "Pairs" Input

The keyword "pairs" is followed by pairs of integer conductor numbers specifying the component connections at each pole. Conductor #0 is ground. For example:

pairs 4 0	specifies connection from conductor 4 (neutral to conductor 0 (ground)
pairs 1 4 2 4 3 4	specifies three component connections, from conductors 1, 2, and 3 to 4

For a "customer" component, the <u>second</u> conductor in the pair will have the house ground attached. This should be the neutral conductor.

4.5 "Poles" Input

The keyword "poles" is followed by one or more integer pole numbers. The program also recognizes short-cuts "all", "even", and "odd" in place of the integer pole numbers. The specified poles and pairs are used to place components in the circuit model.

The following example places a ground at each odd-numbered pole, from conductor 4 to ground. The pole downlead has a 5-μH inductance:

```
ground   85.0   250.0   400.0e3   0.5e-6   10.0
pairs    4  0
poles    odd
```

The following example places a surge only at pole 16, from conductor 1 to ground:

```
surge  -10.0e3  1.0e-6  50.0e-6  0.0e-6
pairs   1  0
poles   16
```

4.6 Program Output

Certain portions of the input produce output, as shown in Table 4.

This output will appear on screen or in a file, according to the program execution commands described in the next section.

For meter, insulator, and arrester output, the individual components are identified by pole number and the conductor pair numbers.

The Output Processor (TOP) software may be used for plotting voltage and current waveforms from binary plot files.

4.7 Network System Input

Normally, the first line of text input specifies the number of poles and conductors. The program lays the poles out in series, and each span has the same length and conductor configuration.

An alternate form of input can be used for other topologies, including a substation network or feeder laterals. In this case, the first line of text input specifies the maximum number of conductors used in any span. In the next section of input more than one conductor geometry can be specified. Each of these input geometries will define a span type. These span types are referenced in a section of line inputs, in which poles are explicitly created as needed at the end of each line.

When using the network option, the first non-comment, non-blank text input line must be of the form:

"time" Ncond dT Tmax

time is a keyword, and the other three parameters are similar to those defined in Section 4.1

Following the time control card, one or more span definitions are input. These are similar to the conductor and cable inputs described in Section 4.2, with an additional span identifier before each span definition:

"span" Span_id

span is a keyword, and **Span_id** must be a unique integer. Whenever conductor geometry is input for a span definition, there can be no missing conductors. There must be **Ncond** lines of conductor input for the span definition, just as in Section 4.2. But when cable impedances are input, missing conductors are allowed. If the number of cable conductors for a span definition is less than **Ncond**, the span definition must be terminated with **"end"** on a single line of input. If **Ncond** cable conductors appear in the span definition, do not use the **"end"** terminator.

A single line of input with **"end"** terminates all span definitions.

Following the span definitions, one or more lines are input.

"line" From To Span_id Length Term_Left Term_Right

line is a keyword. ***From*** and ***To*** are integer pole numbers, which the program creates if they don't exist yet. The pole numbers do not have to be consecutive. ***Span_id*** refers to the conductor geometry or cable impedances entered previously. Note that the ***Span_id*** determines which phases are present in this line, and any power frequency offset voltage. If ***Term_Left*** or ***Term_Right*** are 1, a surge impedance termination is added at the From or To pole, respectively.

A single line of input with **"end"** terminates all line definitions.

Following the line definitions, any of the optional pole components may be input as described in Sections 4.3 through 4.5. Only those poles created in the line definitions may be used for these components. Some of these poles may have “missing phases”, if they are fed by spans that have less than **Ncond** cable conductors. These “missing phases” are solidly grounded in the simulation; they have no impact on the results because the cable conductors are uncoupled in this program.

See Table 6 and Table 7 for examples of network model input.

Table 4 Text Output

Input	**Output Generated**
Required Parameters	T_{max} and the current simulation time appear on the screen as a solution progress monitor.
Conductor Data	Surge Impedance Matrix, Z_p Modal Surge Impedances, Z_m[1] Modal Transformation Matrix, T_I[1]
Termination Flags	D.C. Bias Voltages, with Currents injected into surge impedance terminations
Meter	Peak voltage recorded Plot data file (voltage)
Insulator	If insulator flashes over: Time of flashover If insulator does not flash over Per-unit severity index
Arrester	If arrester operates: Time of sparkover or turn-on Time of peak discharge current Peak discharge current [Amperes] Energy discharged [Joules] Charge discharged [Coulombs] If V_{gap} input < 0: Peak current recorded Plot data file (current)
Ground	If R_{60} input < 0: Peak current recorded Plot data file (current)
Customer	Peak I_{hg} and I_{x2} Plot data file (I_{hg} and I_{x2})
Pipegap	Peak pre-discharge current If V input < 0: Plot data file (current)
"Black Box" Values	Highest per-unit severity index of any insulator Highest energy dissipated by any surge arrester Highest current discharged by any surge arrester Highest charge through any surge arrester Highest pre-discharge current through any pipegap

5 EXAMPLES

The software distribution includes over two dozen example text input files for execution from the command line, and four test cases for execution from the spreadsheet interface.

5.1 Console Mode Examples

The text input files are located in a “test” subdirectory of the OpenETran installation. All except “test_icrit.dat” may be executed from the “runtests.bat ” file. Each test case run this way produces a text output file and a binary output file.

The “run_icrit_tests.bat” script runs the “test_icrit.dat” file three times. The first run determines critical current for a stroke to pole without an arrester, producing an answer of 54.15 kA. The second run determines critical current for a stroke to pole with an arrester, producing an answer of 500 kA. The third run creates a plot file for a stroke approximately equal to the critical current on a pole without arrester.

The text input files include:

ABCIGLD	discharge test for Bezier spline arrester with turn-on conductance and lead inductance
ABCIGRE	discharge test for Bezier spline arrester with turn-on conductance
ABEZGAP	discharge test for Bezier spline arrester with series gap
ABEZLEAD	discharge test for Bezier spline arrester with lead inductance
ABGAPLD	discharge test for Bezier spline arrester with series gap and inductance
ARRBEZ	discharge test for Bezier spline arrester model
ARRESTER	discharge test for arrester switch model
ARRLEAD	discharge test for arrester switch model with lead inductance
ARRLIN	discharge test for piecewise linear arrester model
DESTEEP	destructive effect insulator model, 100 kV CFO, concave surge front
DESURGE	destructive effect insulator model, 100 kV CFO, 1-cosine surge front
DRIVENLT	sample run file from LPDW; three-wire line with top-phase arrester
EPRI138	incoming surge for the 138-kV substation example from the ICWorkstation training course (see Figure 14 and Table 7)
EPRI500	incoming surge for the 500-kV substation example from the ICWorkstation training course
HOUSE	single-phase overhead with transformer secondary model
LPMSTEEP	leader progression insulator model, 100 kV CFO, concave surge front
LPMSURGE	leader progression insulator model, 100 kV CFO, 1-cosine surge front
NO_FLASH	leader progression insulator model, 100 kV CFO, flashover disabled and severity index greater than one
OVERBEZ	4-conductor overhead line with Bezier spline arresters
OVERHEAD	4-conductor overhead line with arrester switch models (see Figure 1 and Table 5)
PAPERARR	add arresters and insulators to a three-phase line

PAPERGAP	three-phase line with predischarge currents
PIPEGAPS	single-phase lateral with predischarge currents
RISER	single-phase cable with riser pole arrester
SCOUT	4-conductor line with arresters feeding a single-phase cable with open-point arrester (see Figure 13 and Table 6)
SPANTEST	testing span/line input options with a single-phase cable terminated in surge impedance
STEEP	typical first-stroke current parameters, concave surge front
SURGE	typical first-stroke current parameters, 1-cosine surge front
TEST_ICRIT	overhead line with arresters every other pole, for testing critical current iterations

Table 5 shows the input data for a circuit similar to that shown in Figure 1. The time step of 0.02 μs was chosen to provide five steps for each line section. This also provides plenty of steps for the surge front.

The T_{max} of 5 μs is sufficient to determine the peak voltages at poles closest to the lightning flash. It is not sufficient to determine the energy discharged in any surge arresters that operate; that would require T_{max} = 200 μs or more.

Figure 12 shows the conductor configuration for this example. Conductors 1, 2, and 3 represent phases A, B, and C. Conductor 4 is the neutral. The number of poles might be increased if an insulator flashover occurs in the simulation, but 11 is recommended as a starting number. Other parameters in Table 3 were chosen to be typical of a 13.8-kV distribution line.

Table 6 shows example input for analysis of the scout arrester application, based on the circuit in Figure 12. The voltage at node 6 is of particular interest. With arresters at nodes 2 and 4, the peak voltages at nodes 6 and 7 are about the same. If the arresters at nodes 2 and 4 are removed, the peak voltage at node 6 is higher than the peak voltage at node 7.

Table 7 shows example input for a substation network model, illustrated in Figure 14. The EPRI ICWorkstation training manual discussed this example in detail. The severity index for this incoming surge is about 0.35 at all points, generally matching the results obtained by EMTP simulation in the OS/2 version of EPRI's ICWorkstation.

Table 5 Example Program Input for Overhead Line

```
4  31  30.0  1  1  0.02e-6   5.0e-6

conductor 1        10.0    -1.5       0.00715        3854.0
conductor 2        10.5     0.0       0.00715      -11097.0
conductor 3        10.0     1.5       0.00715        7243.0
conductor 4         8.0     0.0       0.00715           0.0

labelphase 0 G
labelphase 1 A
labelphase 2 B
labelphase 3 C
labelphase 4 N

ground 85.0 250.0 400.0e3 0.5e-6 10.0
pairs 4 0
poles all

arrester 42.4e3 36.8e3 0.28 1.0e-6 0.0
pairs 1 4  2 4  3 4
poles odd

insulator 300.0e3  0.0 5.42434 8.4265E21
pairs 1 4  2 4  3 4
poles 16

meter
pairs 1 0  1 4  2 4  3 4  4 0
poles 16 17

surge -10.0e3 1.0e-6 100.0e-6 0.0e-6
pairs 1 0
poles 16
```

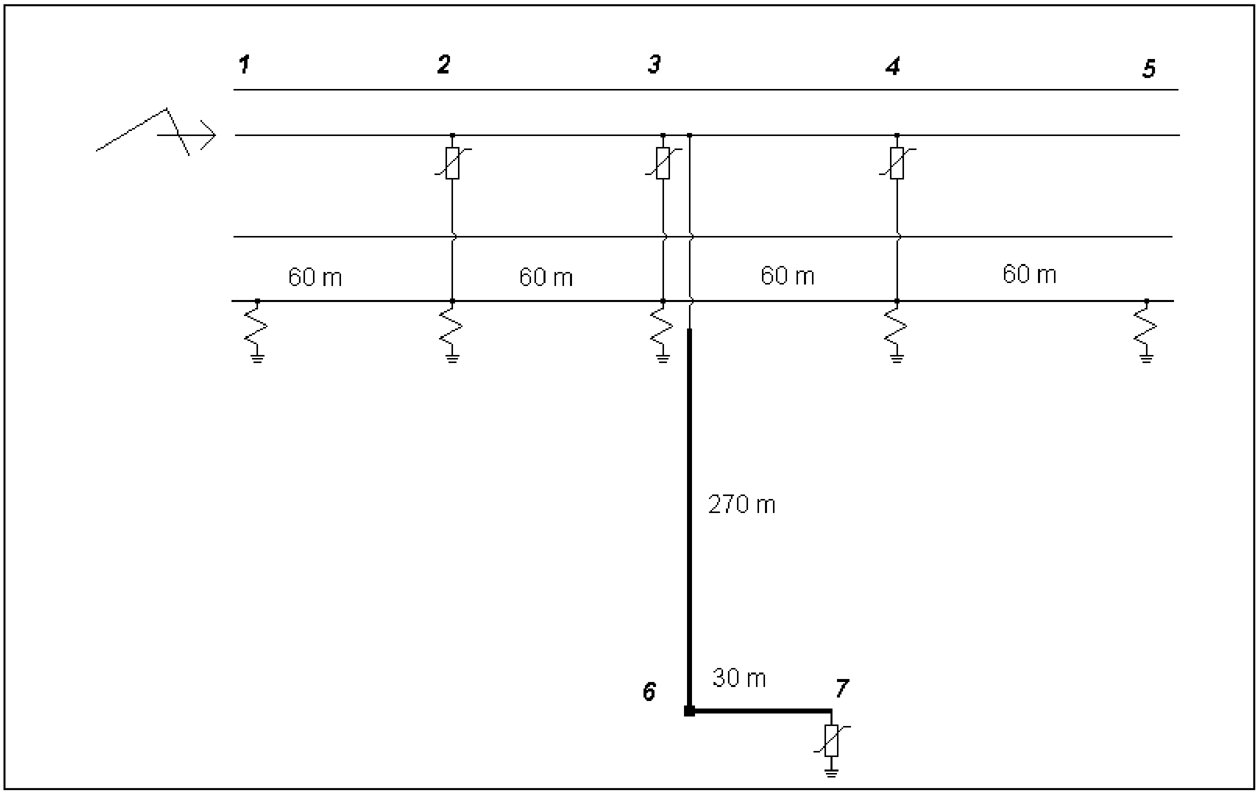

Figure 13 Scout and Cable Arrester Application

Table 6 Example Program Input for Scout Arrester Scheme

```
time 4 0.01e-6 15.0e-6

* overhead line geometry
span 1
conductor 1 10.0 -1.5 0.00715   3854.0
conductor 2 10.5  0.0 0.00715 -11097.0
conductor 3 10.0  1.5 0.00715   7243.0
conductor 4  8.0  0.0 0.00715      0.0

* single-phase underground attached to upper phase
span 2
cable 2 30.0 1.5e8 -11097.0
end
end

* overhead line spans
line 1 2 1 60.0 1 0
line 2 3 1 60.0 0 0
line 3 4 1 60.0 0 0
line 4 5 1 60.0 0 1
*underground spans
line 3 6 2 270.0 0 0
line 6 7 2  30.0 0 0
end

labelphase 0 G
labelphase 1 A
labelphase 2 B
labelphase 3 C
labelphase 4 N

labelpole 3 riser
labelpole 6 xfmr
labelpole 7 opntie

ground 85.0 250.0 400.0e3 0.5e-6 10.0
pairs 4 0
poles 1 2 3 4 5

* riser pole, scout, and open tie arresters
arrbez 0.0e3 40.0e3 0.0 0.0 0.0 0
pairs 2 0
poles 2 3 4 7

surge -10.0e3 1.0e-6 50.0e-6 0.0e-6
pairs 2 0
poles 1

meter
pairs 2 0
poles 3 6 7
```

Table 7 Example Program Input for 138-kV Substation

```
* incoming backflash for the EPRI 138-kV training example

time 1 6e-9 10e-6

* network definition

span 1
cable 1 472.0 3.0e8 -93.0e3
end

line 1 2 1 10.67 0 0
line 2 3 1 15.24 0 0
line 2 4 1  9.14 0 0
line 2 5 1  9.14 0 0
line 5 7 1  9.14 0 0
line 7 8 1  9.14 0 0
line 6 7 1 10.67 1 0
line 7 9 1 15.24 0 0
end

labelphase 0 G
labelphase 1 A

labelpole 1 ln1
labelpole 2 cb1
labelpole 3 xf1
labelpole 4 top
labelpole 5 tiebrk
labelpole 6 ln2
labelpole 7 cb2
labelpole 8 bot
labelpole 9 xf2

meter
pairs 1 0
poles all

* source equivalent

resistor 472.0
pairs 1 0
poles 1

steepfront 2.54e3 1.82e-6 9.7e-6 1.0e-7 1.0
pairs 1 0
poles 1

* transformers and arresters

capacitor 2e-9
pairs 1 0
poles 3 9

arrbez 0.0 296.0e3 0.051 1.57e-6 1.83 1
pairs 1 0
poles 3 9

* insulators

lpm 650.0e3 535.0e3 7.785e-7
* lpm 650.0e3 551.3e3 1.831e-6
pairs 1 0
poles all
```

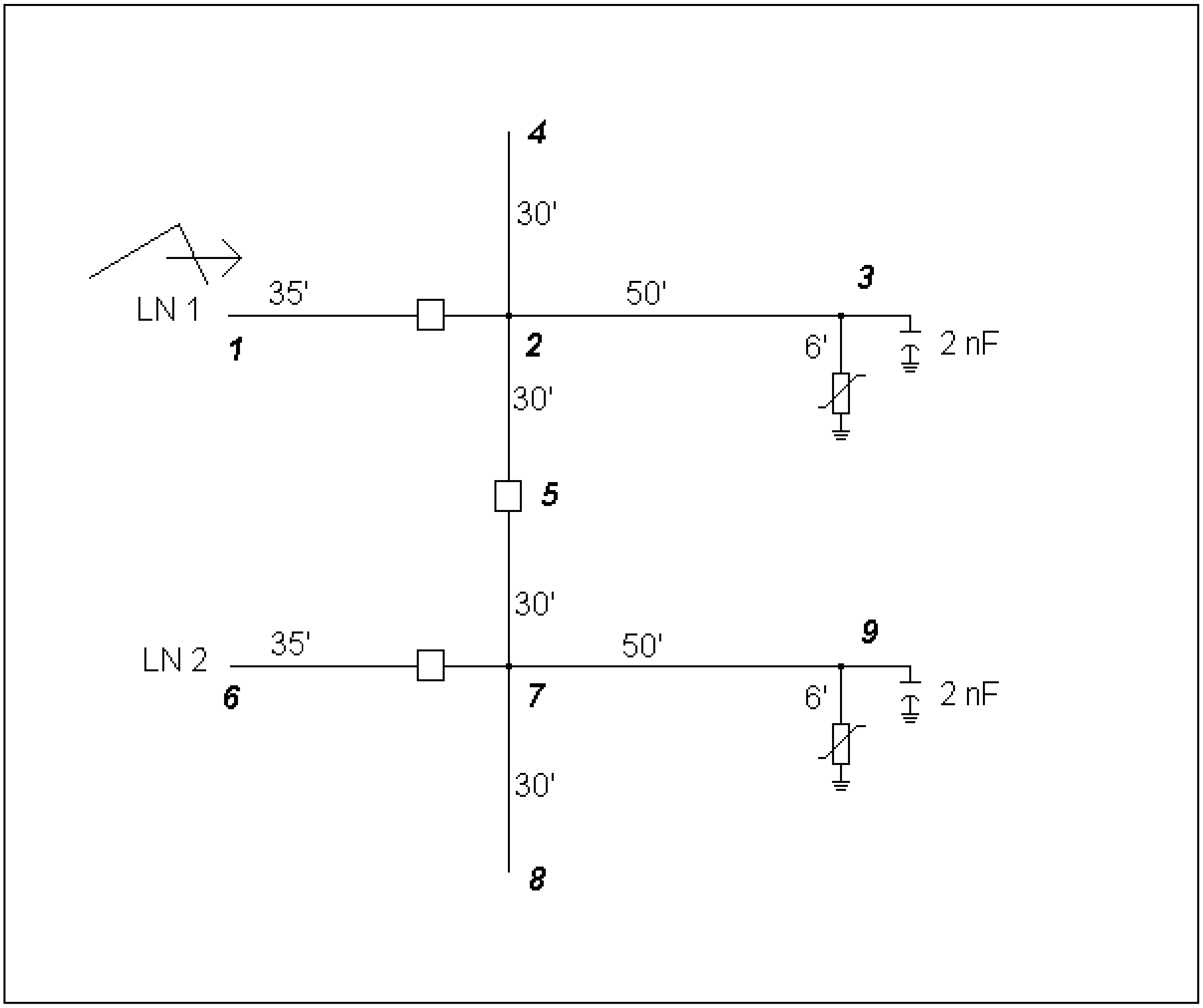

Figure 14 138-kV Substation Application

5.2 Spreadsheet Examples

The OpenETran.xlsm file contains four examples on separate sheets. Visual Basic for Applications (VBA) macros must be enabled. In order to run each example, copy-and-paste-special the **values** from the example sheet onto the Input sheet. Delete any unused values from the Input sheet before clicking the Run button. Please make sure the Input data is lined up as in , and take care not to delete any named ranges from the Input sheet.

The example sheets include:

1. Test – four-wire line with neutral and arresters every other pole. This example should give similar results to the *test_icrit.dat* console-mode example.
2. Std. 1410, 15-kV Line [15] – three-wire line with no arresters. The CFO is 152 kV on the middle phase and 268 kV on the outside phases. The critical current is 3 kA (i.e. the minimum value considered) and a simulated 1-kA stroke produces a flashover.
3. Std. 1410, 35-kV Line [15] – three-phase line with overhead shield wire, 180-kV CFO on each phase, 10-Ohm grounds, and no arresters. The critical current is about 48 kA, and the plotted result for a 49-kA stroke shows a flashover.
4. ARH, 13.9-kV Line [16] – three-phase line with neutral, arresters every other pole, 25-Ohm grounds, and CFO of 170 kV on each phase. The critical current is 408 kA for strokes to a pole with arresters, and 54 kA for strokes to a pole without arresters. The result for a 54-kA stroke is plotted.

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