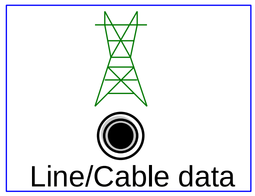
Line/Cable Data



Jesus Morales, Jean Mahseredjian, Haoyan Xue, Ilhan Kocar 06/06/2022 18:47:00.

1 Introduction

This device is used to calculate input parameters for line and cable models available in EMTP. There are two data input tabs. The first tab is for entering conductor data and the second tab is for making line or cable model selections.

2 Conductors tab

The *Conductors* tab in the mask of the Line/Cable Data device is for entering geometrical and electrical data of conductors.

2.1 Main selection

At first the Line/Cable Data device requires a main selection depending on the line/cable system to be modeled. The **Geometrical data and materials** dropdown menu allows selecting:

- **Overhead line**: allows entering data for single-wire and/or bundle of conductors.
- **Insulated cable**: allows entering data for single-core and/or pipe-type cables.
- **Combined line and cable**: allows entering data for a transmission system composed of both overhead lines and insulated cables.
- **Load p.u.l. parameters from file**: allows selecting a file containing the per-unit-length (p.u.l.) series impedance and shunt admittance matrices calculated from an external source.

The options listed above are further explained in the following sections.

2.2 Overhead line

The **Overhead line** option permits modeling aerial bare conductors considering single-wires and/or bundle of conductors. Note that modeling a bundle of conductors is equivalent to modelling individual single-wires and grouping them. The advantage of using the bundle representation is that less input data is required and only the phase pin becomes accessible for connection to the surrounding network.

The options available after selecting the **Overhead line** option from the main menu are shown in Figure 1. In this figure, the **Conductor characteristic** is set to be represented by its DC resistance, alternatively the conductor **Resistivity** can be selected. Also, the **Midspan height** of each conductor can be entered as input data when available. If at least one conductor is tubular, the **Hollow conductors** option must be checked to allow entering conductor's inner radius.
After entering the number of conductors and selecting the required options in the menu shown in Figure 1, the corresponding tables are generated to enter necessary data for each individual conductor.

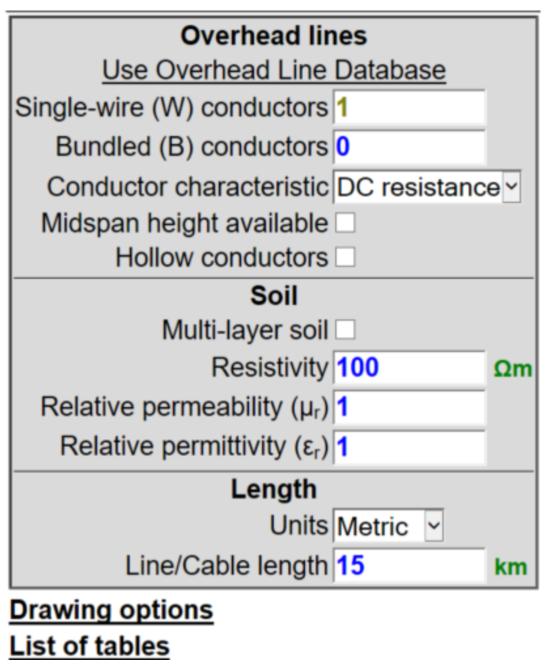


Figure 1 Overhead line options.

2.2.1 Single-wire (W) conductors

This section shows how to model a transmission line consisting of single wires only.

Figure 2 illustrates an example of a three-phase overhead transmission line with two shield wires. The necessary input data in is shown in Figure 3.
Note that after entering a non-zero value in the "Single-wire (W) conductors" input, the system of units (Metric or English), the line length, and soil modeling options become available as shown in Figure 3. Also, a table with the necessary rows for entering the conductor positions and material properties is generated.

The column Phase presents the numbering of conductors in the actual model from top down. When a Phase is given the number 0, then it is not accessible in the actual line model. Note that in the data table of Figure 3, the ground wires are given a zero value in the column Phase. This allows the reduction of ground wires in the output model, such that the resulting model will have only three connection pins at each remote end of the transmission line.
The line geometry (cross-section) is drawn in the box on the right of Figure 3. The conductors are clickable and hovering over conductors allows highlighting corresponding data rows.

The **Drawing options** allow showing wire names and distances between wires.
The option **Set minimal conductor size** sets the conductors radius to a predefined value (only in the drawing box) for better visualization. This option does not modify actual data entered in tables.

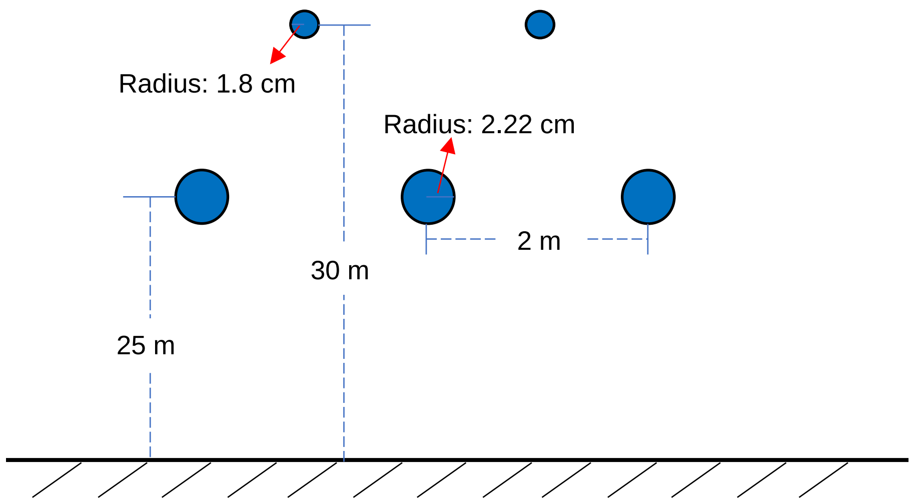
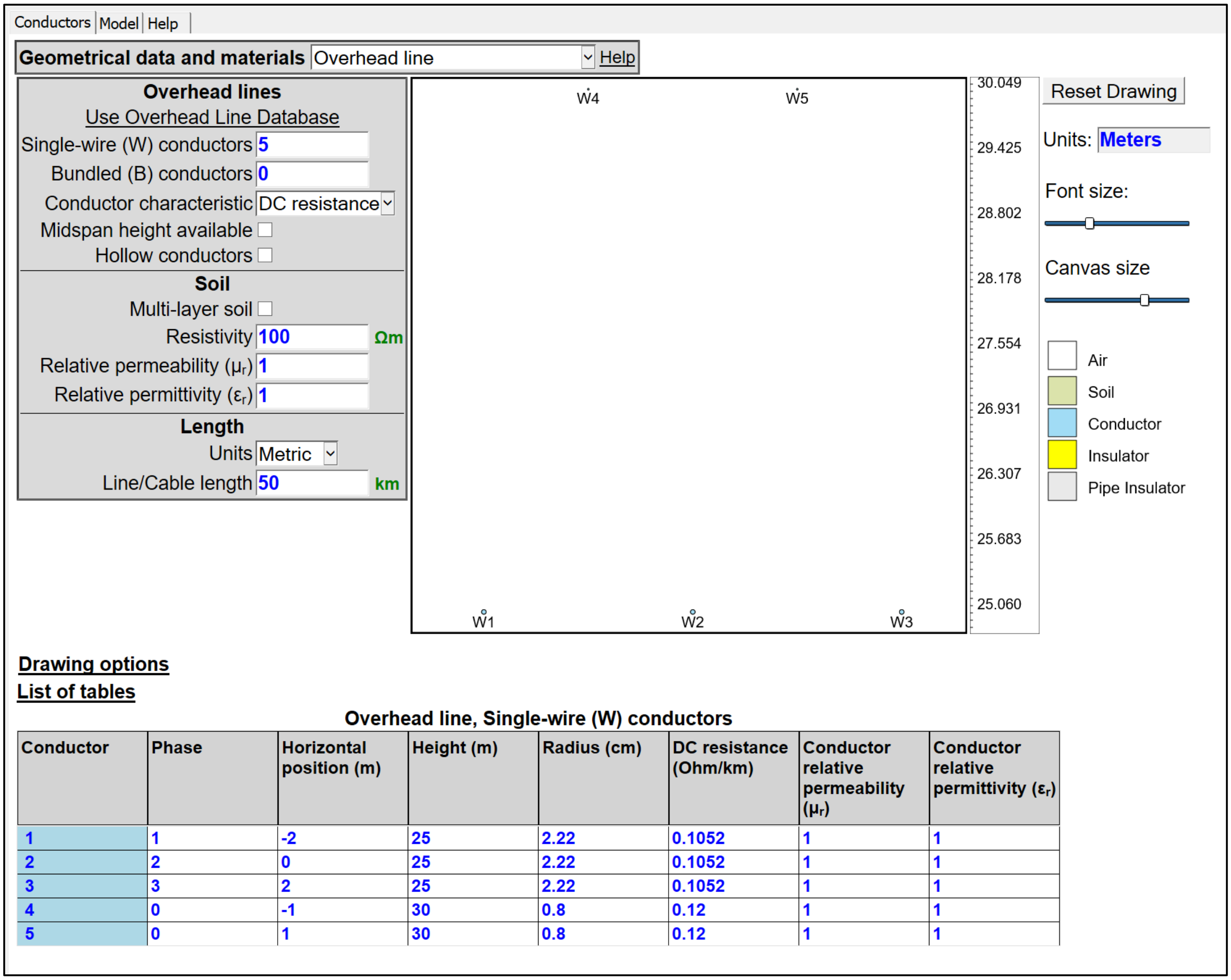


Figure 2 Three-phase overhead line with ground conductors.



Conductor	Phase	Horizontal position (m)	Height (m)	Radius (cm)	DC resistance (Ohm/km)	Conductor relative permeability (μ_r)	Conductor relative permittivity (ε_r)
1	1	-2	25	2.22	0.1052	1	1
2	2	0	25	2.22	0.1052	1	1
3	3	2	25	2.22	0.1052	1	1
4	0	-1	30	0.8	0.12	1	1
5	0	1	30	0.8	0.12	1	1

Figure 3 Line/Cable Data device input for modeling the three-phase line of Figure 2.

2.2.2 Bundled (B) conductors

For modeling overhead transmission lines with bundled conductors, the number of conductors in the bundle and the angle of reference are required. Figure 4 shows an example of a bundle of 4 conductors with the angle specification. In this case the angle is 0 degrees.

Note that when modeling a bundle of conductors, all individual conductors are given the same radius and the distances between consecutive conductors are the same. The Angle parameter can be specified individually for each Bundle. A case with two ground wires and three bundled conductors is shown in Figure 6.

The bundle radius for an equilateral triangle of 3 conductors is found by dividing the length of the side of the triangle by $\sqrt{3}$.

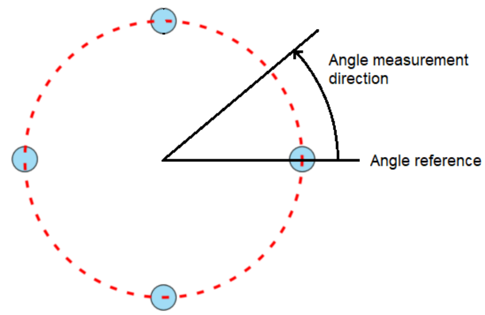


Figure 4 Bundle of 4 conductors, example at 0 degree.

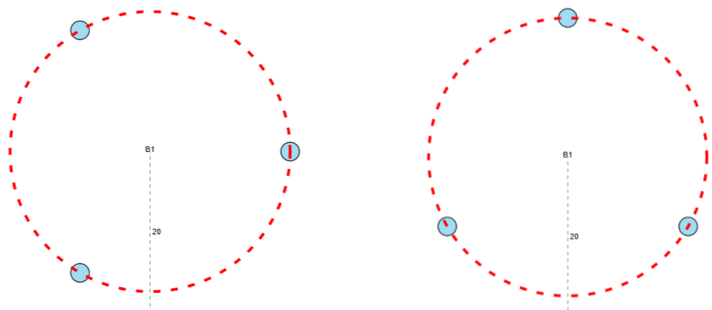


Figure 5 Bundle of 3 conductors at 0 degree (left) and 90 degrees (right).

Overhead line, Single-wire (W) conductors

Conductor	Phase	Horizontal position (m)	Height (m)	Radius (cm)	DC resistance (Ohm/km)	Conductor relative permeability (μ_r)	Conductor relative permittivity (ε_r)
1	0	-7	29	0.475	3.75	1	1
2	0	7	29	0.475	3.75	1	1

Overhead line, Bundled (B) conductors

Bundle	Phase	Horizontal position (m)	Height (m)	Number of conductors	Angle (deg)	Bundle radius (cm)	Conductor radius (cm)	DC resistance (Ohm/km)	Conductor relative permeability (μ_r)	Conductor relative permittivity (ε_r)
1	1	-10	20	3	90	23	1.529	0.0701	1	1
2	2	0	20	3	90	23	1.529	0.0701	1	1
3	3	10	20	3	90	23	1.529	0.0701	1	1

Figure 6 Data with Bundled conductors.

2.2.3 Overhead lines: database option

The Line/Cable Data device allows loading predefined transmission line configurations from a database. By clicking on the link **Use Overhead Line Database** (see Figure 3), a new window is opened, this window contains a list of predefined transmission line systems as shown in Figure 7.

The data of any transmission line from this database can be loaded into the Line/Cable Data device by selecting the corresponding row from the list, as illustrated in Figure 7 and closing with the OK button.

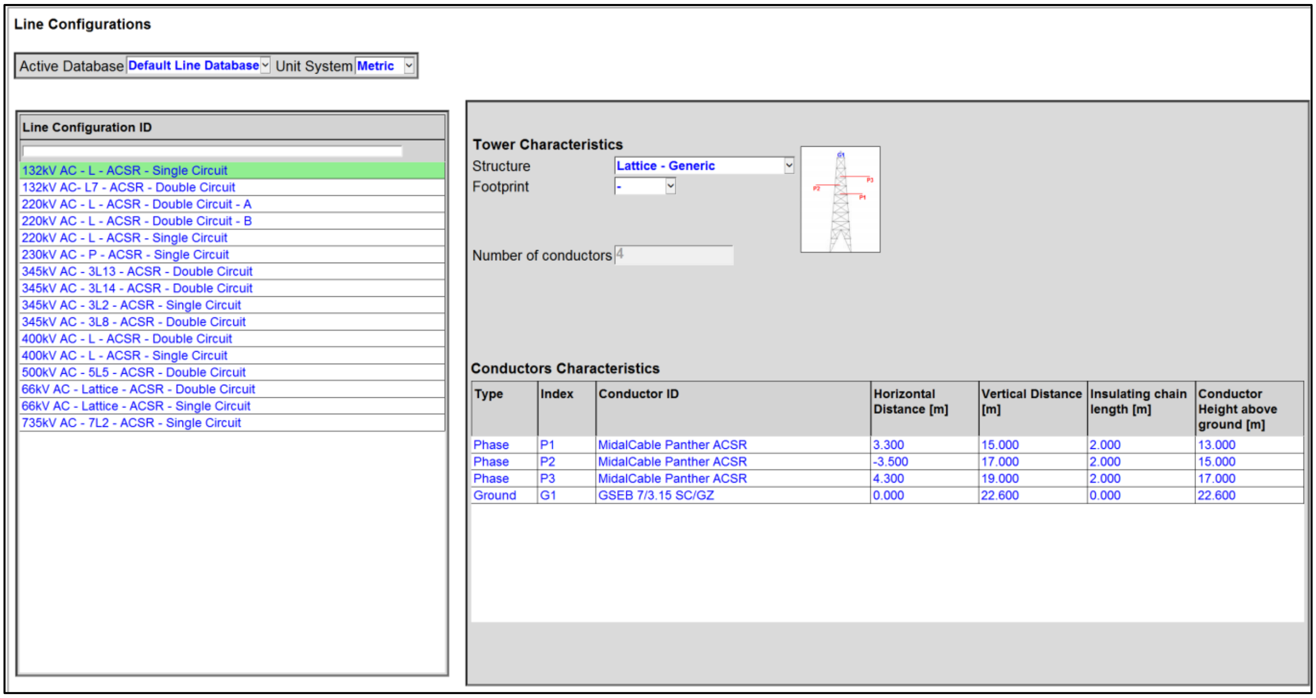


Figure 7 Overhead line database window.

2.3 Insulated cable

The Line/Cable Data device allows modeling insulated cables for both aerial and underground applications. Two types of insulated cables can be modeled, single-core coaxial cables and pipe-type cables. The latter permits modeling multiple cores with any number of coaxial conductor layers. The pipe-type cable representation also permits modeling tunnel installed cables.

2.3.1 Single-core (SC) cables

A set of three identical single-core cables buried 1.1 meters underground, is presented in Figure 8. This cable system can be modeled using the Line/Cable Data device as shown in Figure 9.
Note that the modeling of single-core cables requires entering data into two tables: **Single-core (SC) cables** and **SC-cables conductors/insulators**.
Note that negative values are required in the column **Vertical position** for representing underground cables. It is also possible to model cables above ground (positive values are required in such case).

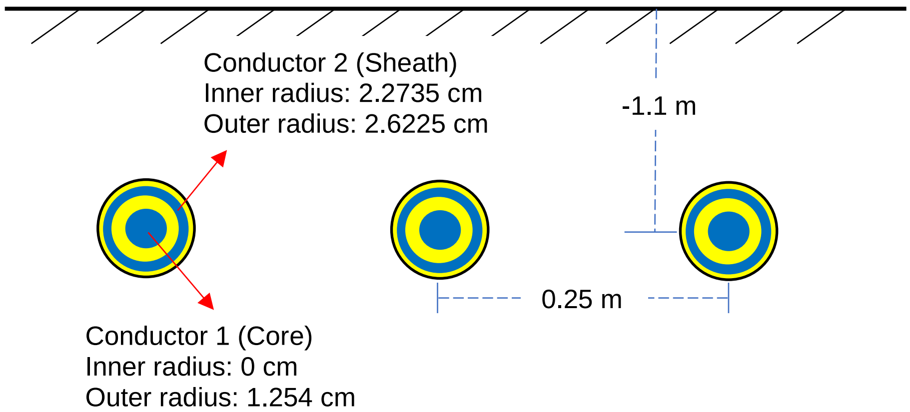


Figure 8 Example with three single-core cables.

Single-core (SC) cables

Cable	Number of conductors	Horizontal position (m)	Vertical position (m)	Radius (cm)
1	2	0	-1.1	2.9335
2	2	0.25	-1.1	2.9335
3	2	0.5	-1.1	2.9335

Load single-core cable from database for selected row

SC-cables conductors/insulators

Cable	Conductor	Phase	Inner radius (cm)	Outer radius (cm)	Conductor resistivity (Ohm m)	Conductor relative permeability (μ_r)	Conductor relative permittivity (ε_r)	Insulator relative permittivity (ε_r)	Insulator loss factor
1	1	1	0	1.254	0.17e-7	1	1	3.5	0.0004
1	2	2	2.2735	2.6225	0.21e-6	1	1	2	0.0004
2	1	3	0	1.254	0.17e-7	1	1	3.5	0.0004
2	2	4	2.2735	2.6225	0.21e-6	1	1	2	0.0004
3	1	5	0	1.254	0.17e-7	1	1	3.5	0.0004
3	2	6	2.2735	2.6225	0.21e-6	1	1	2	0.0004

Figure 9 Line/Cable data device for the three single-core cable system of Figure 8.

2.3.1.1 Insulator layers

For modeling single-core cables with the Line/Cable Data device, each conductor is assumed to be surrounded by an insulator layer. The thickness of the n^{th} insulator layer is defined by the difference between the outer radius of the n^{th} conductor and the inner radius of the $(n+1)^{th}$ conductor. Insulator layers are represented by relative permittivity, which is in general larger than 1 for insulator materials. Since insulator materials are not perfect, a loss factor, also referred as $\tan\delta$ by manufacturers in cable data sheets, is used to represent losses. This loss factor represents the current penetrating the insulators. The loss factor or $\tan\delta$ value is related to the material's relative permittivity as follows:

$$\tan\delta = \frac{\varepsilon_r'}{\varepsilon_r''}$$

where ε_r' and ε_r'' are the real and imaginary parts of the material's relative permittivity.
Then, the relative permittivity for the insulator material is given as

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

2.3.1.2 Semiconductor layers

Semiconductor layers usually appear between conductors and insulator layers and this affects the p.u.l. (per-unit-length) series impedance and shunt capacitance of the cable. A common practice to account for semiconductor layers is to consider them as part of the surrounding insulator applying a correction factor as

$$\varepsilon_{new} = \varepsilon_r \frac{\ln\left({}^{r_4}/_{r_1}\right)}{\ln\left({}^{r_3}/_{r_2}\right)}$$

where ε_{new} is the effective relative permittivity of the composed insulator layer (considering the semiconductor layer), ε_r is the relative permittivity of the insulator material, r_1 and r_2 are the inner and outer radiuses of the semiconductor layer (placed between the conductor and insulator), respectively, and r_3 and r_4 are the inner and outer radiuses of the insulator.
Following this approach, the Line/Cable Data device requires entering the new relative permittivity as shown above.
Alternatively, the semiconductor layer can be represented as another conductor, but with a resistivity value that corresponds to the semiconductor layer.

2.3.2 Single-core cable database

Predefined single-core cables can be loaded into the Line/Cable Data device from a database. This database is available from the button **Load single-core cable from database for selected row** (see Figure 9).

Note that a cable (row) must be selected in the table **Single-core (SC) cable main data** to assign the data from the database to the selected single-core cable.
The single-core cable database window is shown in Figure 10.

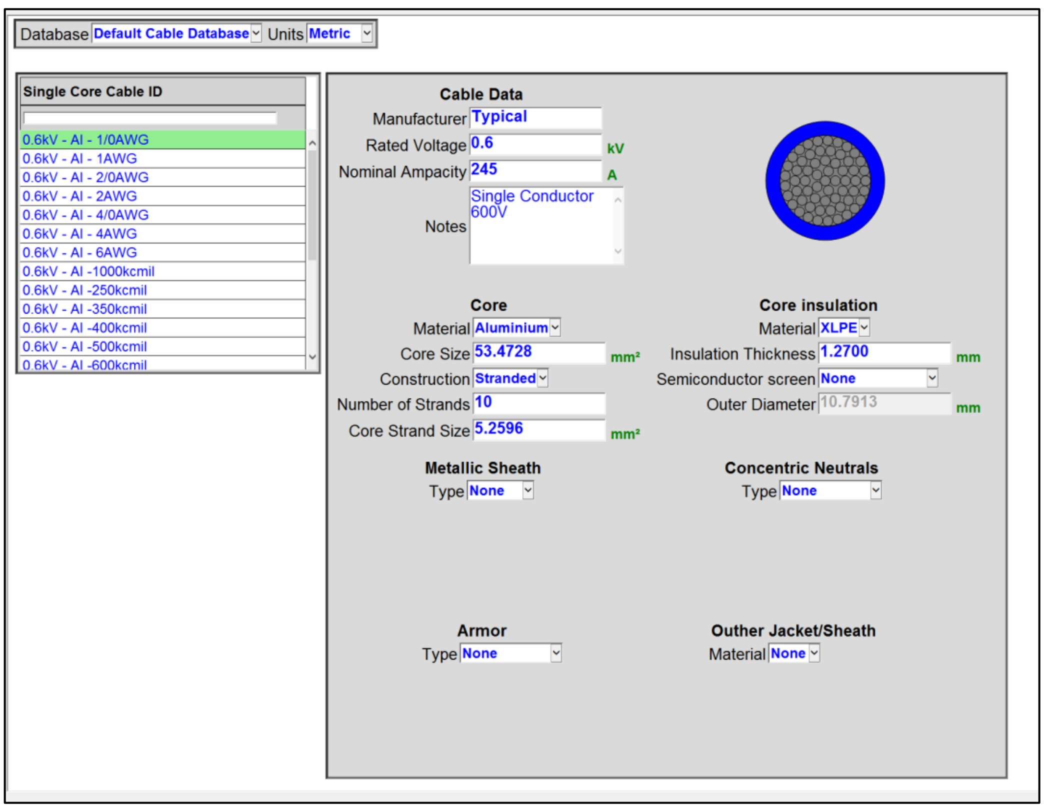


Figure 10 Single-core cable database.

2.3.3 *Pipe-type (PT) cables*

A 3-cores pipe-type cable example is shown in Figure 11. This cable can be modeled using the Line/Cable Data device by entering the data as shown in Figure 12. As for SC cables, positive numbers in the column of **Vertical position** can be entered for modeling pipe-type cables above ground. The numbering of conductors in the "Phase" column in Figure 12 is indicated in Figure 11.

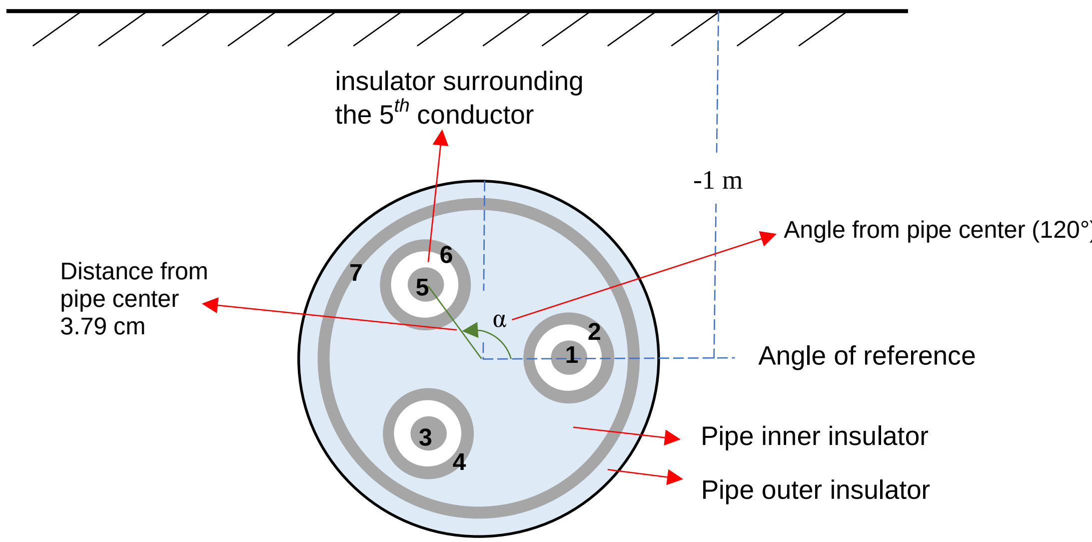
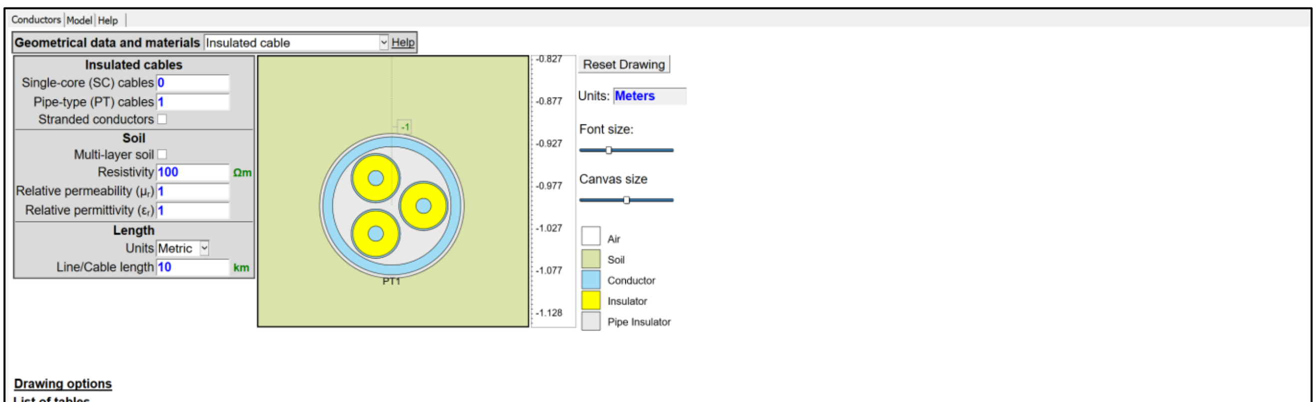


Figure 11 Pipe-type cable example.



Pipe-type (PT) cables

Pipe-type cable	Number of cores	Horizontal position (m)	Vertical position (m)	Pipe inner radius (cm)	Pipe outer radius (cm)	Pipe resistivity (Ohm m)	Pipe relative permeability (μ_r)	Pipe relative permittivity (ε_r)	Pipe phase	Inner insulator relative permittivity (ε_r)	Inner insulator loss factor	Outer insulator relative permittivity (ε_r)	Outer insulator loss factor	Total radius (cm)
1	3	0	-1	7	8.15	400	1	1	7	2.2	0.0001	2.5	0.001	8.55

PT-cables cores

Pipe-type cable	Core	Distance from center (cm)	Angle (deg)	Outer radius (cm)	Number of conductors
1	1	3.75	0	2.9	2
1	2	3.79	120	2.9	2
1	3	3.79	-120	2.9	2

PT-cables conductors/insulators

Pipe-type cable	Core	Conductor	Inner radius (cm)	Outer radius (cm)	Conductor resistivity (Ohm m)	Conductor relative permeability (μ_r)	Conductor relative permittivity (ε_r)	Insulator relative permittivity (ε_r)	Insulator loss factor	Phase
1	1	1	0	0.9	1.68e-8	0.99994	1	2.25	0.001	1
1	1	2	2.7	2.9	2.2e-7	0.9999983	1	2.25	0.001	2
1	2	1	0	0.9	1.68e-8	0.99994	1	2.25	0.001	3
1	2	2	2.7	2.9	2.2e-7	0.9999983	1	2.25	0.001	4
1	3	1	0	0.9	1.68e-8	0.99994	1	2.25	0.001	5
1	3	2	2.7	2.9	2.2e-7	0.9999983	1	2.25	0.001	6

Figure 12 Line/Cable Data device input for the pipe-type cable of Figure 11.

The Stranded conductors option allows to model a cylindrical conductor as a set of identical wires equally distributed along the cylindrical surface given by the inner and outer radius. The diameter of the individual wires is equal to the difference between outer and inner radius. When this option is selected the user must enter the number of stranded wires.

2.4 Load p.u.l. parameters from file

The Line/Cable Data device allows the user to load the per-unit-length series impedance and shunt admittance parameters from a file (calculated from an external source) as illustrated in Figure 13.

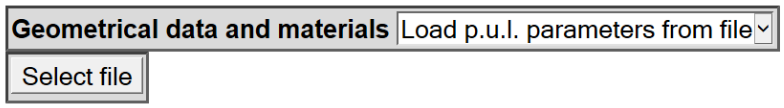


Figure 13 Loading p.u.l. parameters from file.

2.4.1 Format

The file containing the p.u.l. parameters must be a Matlab file (.mat extension) and it must contain the variables 'Z', 'Y', 'f', and 'line_length', corresponding to the p.u.l. impedance matrix, p.u.l. admittance matrix, frequency vector and line length, respectively. These variables must have consistent size as follows:

- The size of the frequency vector must be 1×Nsamples.
- The size of the impedance and admittance matrices must be Nconductors×Nconductors×Nsamples.
- The line length must be given in the units used for calculating the p.u.l. parameters. No conversion is performed.

In addition to the above, the following considerations must be taken into account:

- When using an input p.u.l. parameters file for CP model, a single frequency point is required.
- When using an input p.u.l. parameters file for FD or WB model, a minimum number of 40 logarithmically-spaced frequency samples is required.
- When using an input p.u.l. parameters file for FD model, it is required from the user to select the frequency of the transformation matrix (phase domain to modal domain) in the model tab.
- When using an input p.u.l. parameters file for Exact_PI model, the frequency samples must coincide with those of the frequency scan simulation to be performed.

2.5 Soil

The Line/cable Data device has two options for soil modelling, homogeneous soil and multilayer soil. By default, the homogeneous soil option is selected. To use the **Multilayer soil** capability the corresponding checkbox must be ticked (see Figure 3).

2.5.1 Homogeneous soil

The homogeneous soil model permits the representation of the earth return path for both impedance and admittance parts. The modelling of earth return is important for high frequency phenomena such as GIS modeling, lightning and surge analysis. In these type of simulations, the ground return effect is important to be represented since wave propagation mode transition takes place (TEM to quasi-TEM and quasi-TEM to FW) [1].

2.5.2 Multilayer soil

The multilayer soil option permits modelling different soil layers. This capability is important for special applications such as submarine cables or stratified earth. A maximum of 4 layers is allowed.

When using the multilayer soil option, underground cables should not be placed at the boundary between different soil layers. Also, note that the thickness of each soil layer is required from the user, but in the case of the last layer (deepest), the layer thickness is set to infinity internally in the code.

2.6 Computation methods

The computation methods used in the Line/Cable Data device can be found in references [2]-[4] and [5]-[9]. This work resulted from a direct collaboration with the authors of [2]-[4].

3 Model tab

The Model tab allows selecting the model for which data must be computed and loaded. The available models are listed and documented in the subsections below.

3.1 Introduction to transmission line equations

The lumped-element model of a transmission line (single-wire) for a section Δx is presented in Figure 14.

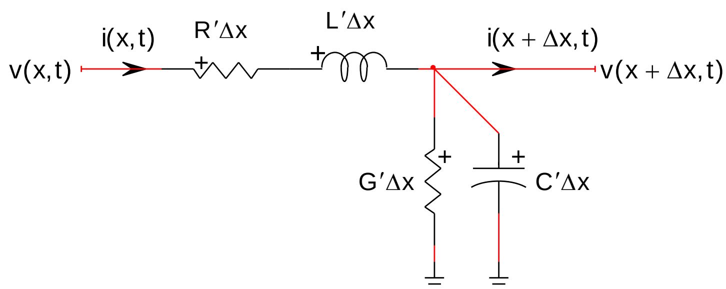


Figure 14 Lumped-element equivalent circuit transmission line model.

By making $\Delta x \to 0$ the following equations can be written:

$$\frac{\partial v(x,t)}{\partial x} = -R'\, i(x,t) - L' \frac{\partial i(x,t)}{\partial x} \tag{1}$$

$$\frac{\partial i(x,t)}{\partial x} = -G' v(x,t) - C' \frac{\partial v(x,t)}{\partial x} \tag{2}$$

where R' is per-unit length resistance, L' is the per-unit length inductance, G' is the per-unit length conductance and C' is the per-unit capacitance. When Laplace transformation ($s = j\omega$) is applied to the above equations:

$$\frac{\partial V(x,s)}{\partial x} = -Z'\, I(x,s) \tag{3}$$

$$\frac{\partial I(x,s)}{\partial x} = -Y'\, V(x,s) \tag{4}$$

with the longitudinal impedance

$$Z' = R' + sL' \tag{5}$$

and the shunt admittance

$$Y' = G' + sC' \tag{6}$$

The solution of equations (3) and (4) can be written as

$$V(x,s) = e^{-\Gamma x} V^{+} + e^{\Gamma x} V^{-} \tag{7}$$

$$I(x,s) = \frac{1}{Z_c}\left(e^{-\Gamma x} V^{+} - e^{\Gamma x} V^{-}\right) \tag{8}$$

where V^{+} and V^{-} denote the voltage incident and reflected waves, respectively; Γ is the propagation constant and Z_c is the characteristic impedance, defined as

$$\Gamma = \sqrt{Z'Y'} \tag{9}$$

$$Z_c = \sqrt{\frac{Z'}{Y'}} \tag{10}$$

The substitution of boundary conditions $x = 0$ and $x = \ell$ where ℓ denotes the line length, into (7) and (8), leads to the following line terminals equations:

$$V_k - Z_c I_k = e^{-\Gamma\ell}\left[V_m + Z_c I_m\right] \tag{11}$$

$$V_k + Z_c I_k = e^{\Gamma\ell}\left[V_m - Z_c I_m\right] \tag{12}$$

where k and m denote the terminals of the line corresponding to $x = 0$ and $x = \ell$, respectively. The currents I_k and I_m are entering the line at both ends. The above two equations are rewritten to give

$$I_k = Y_c V_k - H\left[Y_c V_m + I_m\right] \tag{13}$$

$$I_m = Y_c V_m - H\left[Y_c V_k + I_k\right] \tag{14}$$

where $Y_c = Z_c^{-1}$ denotes the characteristic admittance and $H = e^{-\Gamma\ell}$ denotes the propagation function. Equations (13) and (14) can be rewritten using vectors and matrices for a multi-conductor system:

$$\mathbf{I}_k = \mathbf{Y}_c \mathbf{V}_k - \mathbf{H}\left[\mathbf{Y}_c \mathbf{V}_m + \mathbf{I}_m\right] \tag{15}$$

$$\mathbf{I}_m = \mathbf{Y}_c \mathbf{V}_m - \mathbf{H}\left[\mathbf{Y}_c \mathbf{V}_k + \mathbf{I}_k\right] \tag{16}$$

The system of equations (15) and (16) can be solved using the Wideband line/cable model [10]-[15] of EMTP. This is the most accurate model for both lines and cables.

Modal analysis is used in CP and FD models. It is recalled here that modal decomposition can be applied considering the following transformations:

$$\mathbf{V}_{modal} = \mathbf{T}_v \mathbf{V} \tag{17}$$

$$\mathbf{I}_{modal} = \mathbf{T}_i\, \mathbf{I} \tag{18}$$

where the voltage $\mathbf{V}$ and current $\mathbf{I}$ vectors are in phase domain, whereas the corresponding $\mathbf{V}_{modal}$ and $\mathbf{I}_{modal}$ are in modal domain. The transformation matrices $\mathbf{T}_v$ and $\mathbf{T}_i$ (eigenvectors) can be found from eigenvalue analysis. The transformation matrices are normally complex and can be related by $\mathbf{T}_i = \left(\mathbf{T}_v^t\right)^{-1}$. When a transmission line is continuously transposed, it is possible to use the real Clarke transformation matrix.
The substitution of equations (17) and (18) into (3) and (4) results into:

$$\frac{\partial \mathbf{V}_{modal}(x,s)}{\partial x} = -\mathbf{T}_v \mathbf{Z}' \mathbf{T}_i^{-1} \mathbf{I}_{modal}(x,s) = -\mathbf{Z}'_{modal}\, \mathbf{I}_{modal}(x,s) \tag{19}$$

$$\frac{\partial \mathbf{I}_{modal}(x,s)}{\partial x} = -\mathbf{T}_i \mathbf{Y}' \mathbf{T}_v^{-1} \mathbf{V}_{modal}(x,s) = -\mathbf{Y}'_{modal}\, \mathbf{V}_{modal}(x,s) \tag{20}$$

The propagation constant and characteristic impedance can be defined in modal domain for each mode p:

$$\Gamma_p = \sqrt{Z'_p\ Y'_p} = \alpha_p + j\beta_p \tag{21}$$

$$Z_{c_p} = \sqrt{\frac{Z'_p}{Y'_p}} \tag{22}$$

where α_p is modal attenuation constant and β_p is modal phase constant.

3.2 Available models

3.2.1 CP-model

The constant parameter (CP) model is the basic line and cable model used in transient studies. Its main advantage is computational speed. It typically provides less optimal and accurate results and can become inaccurate for transients with wide dispersion of frequencies. The following simplifications are made in this model:

1. The frequency dependence of the pul parameters ($\mathbf{Z}'$ and $\mathbf{Y}'$) is ignored. Instead, the pul parameters are calculated at a single frequency which makes the model acceptable for simulations with reduced frequency content.
2. The resistive losses are ignored in the line equations, but included in a lumped form.
3. The line equations are solved in modal domain.
    a. For the balanced (continuously transposed) line case (only available for overhead transmission lines), the mutual elements in the series impedance and shunt admittance matrices are considered identical (the average value is used). The Clarke transformation matrix (purely real and constant) is applied. The line modal parameters are calculated at the given frequency.
    b. For the unbalanced case, the exact transformation matrix $\mathbf{T}_i$ (named also Q matrix) is used, but its imaginary part is minimized and cancelled. The CP-model accepts only a real transformation matrix.

Under the above assumptions it is possible to calculate the simplified modal propagation constant from (21):

$$\gamma_p = s\sqrt{L'_p\ C'_p} = j\beta_p \tag{23}$$

and the modal real characteristic impedance from (22):

$$Z_{c_p} = \sqrt{\frac{L'_p}{C'_p}} \tag{24}$$

The modal travelling wave velocity is given by

$$v_p = \frac{1}{\sqrt{L'_p C'_p}} \tag{25}$$

The modal propagation delay is found from

$$\tau_p = \ell\sqrt{L'_p C'_p} \tag{26}$$

When considering (13) and (14) for each mode, the following equations are obtained:

$$V_{k_p} - Z_{c_p} I_{k_p} = e^{-j\beta_p\ell}\left[V_{m_p} + Z_{c_p} I_{m_p}\right] \tag{27}$$

$$V_{k_p} + Z_{c_p} I_{k_p} = e^{j\beta_p\ell}\left[V_{m_p} - Z_{c_p} I_{m_p}\right] \tag{28}$$

Transforming the above equations into time-domain results into the delay equations:

$$v_{k_p}(t) - Z_{c_p} i_{k_p}(t) = v_{m_p}\left(t-\tau_p\right) + Z_{c_p} i_{m_p}\left(t-\tau_p\right) \tag{29}$$

$$v_{m_p}(t) + Z_{c_p} i_{m_p}(t) = v_{k_p}\left(t-\tau_p\right) + Z_{c_p} i_{k_p}\left(t-\tau_p\right) \tag{30}$$

The lossless transmission line model is given in Figure 15 by noting that

$$i^h_{k_p} = \frac{v_{m_p}\left(t-\tau_p\right)}{Z_{c_p}} + i_{m_p}\left(t-\tau_p\right) \tag{31}$$

$$i^h_{m_p} = \frac{v_{k_p}\left(t-\tau_p\right)}{Z_{c_p}} + i_{k_p}\left(t-\tau_p\right) \tag{32}$$

where the subscript h indicates history terms. The model of Figure 15 is applicable to any mode p of a transmission line. The modal transformation matrix is used to revert back to phase-domain equations of the simulated grid.

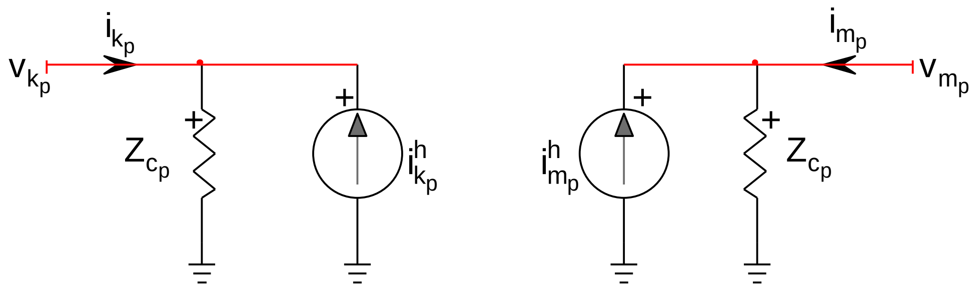


Figure 15 Lossless transmission line model.

The losses are included into the CP-model by distributing the resistance as shown in Figure 16 and using two lossless line sections. It is important to notice that this approach [16] is valid if $R'_p \ell \ll Z_{c_p}$.

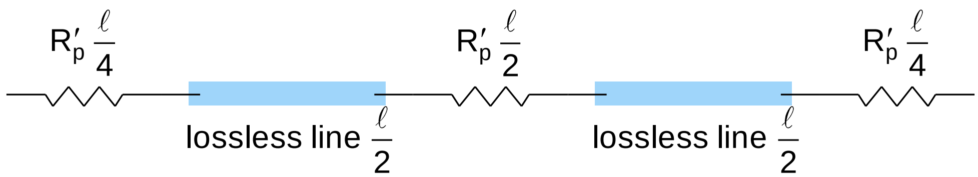


Figure 16 Complete CP-model with losses.

3.2.1.1 Model frequency

This option allows to select the desired frequency for the calculation of parameters and transformation matrix. In the balanced case, it is only applicable to the calculation of modal parameters.

3.2.1.2 Corresponding device input

This model can be used in the CP line/cable m-phase device (model) found in the EMTP lines library.
A "Load data from file" button is available in the CP line/cable m-phase device.
The model data file is named *name*_CP.mod, where *name* is an arbitrary device name from which this model is generated.

3.2.2 FD-model

The Frequency Dependent (FD) model [16] contrary to CP-model, is capable of accounting for the frequency dependency of line parameters. The FD model is based on modal decomposition as described in section 3.1.
As explained above, the transformation matrix $\mathbf{T}_i$ (named also Q matrix) is complex, but the FD-model is not able to use a complex transformation matrix and offers the following options:
For the balanced line model, the mutual elements in the series impedance and shunt admittance matrices are considered identical (the average value is used) and the Clarke transformation matrix, which is real and constant,56 is applied. In this case, the FD-model is very accurate.
When the line is not balanced (continuously transposed), then two options are available to obtain a real transformation matrix:

1. Q matrix type: Minimize Imaginary. This is the default option. The exact complex transformation matrix is rotated to make (minimization) the imaginary part of the transformation matrix equal to zero.
2. Q matrix type: G_{mode}=0. The exact transformation matrix is rotated to make (minimization) the modal conductance (real part of shunt admittance) equal to zero.

Both options are equivalent in most cases and maintained for compatibility with previous versions of EMTP. The default option can be used with confidence.
Modal decomposition is used and each mode adopts the formulation of (13)-(14). The modal functions $Y_c(s)$ and $H(s)$ are sampled for the selected frequency range and curve fitted using a Bode-based technique results into the equivalent rational functions:

$$Y_c(s) \approx r_0 + \sum_{i=1}^{N} \frac{r_i}{s - a_i} \tag{33}$$

$$H(s) \approx \left(\sum_{i=1}^{M} \frac{c_i}{s - p_i} \right) e^{-s\tau} \tag{34}$$

where coefficients (r_i, c_i) are denoted as residues and coefficients (a_i, p_i) are denoted as poles of the corresponding rational functions; N and M are the orders of the rational functions; r_0 gives the asymptotic value to the function $Y_c(s)$ for very high frequency values; and τ is the time delay extracted from the sampled function $H(s)$.

The modal solution of the transmission line equations (13)-(14) is obtained by discretizing the rational functions (33)-(34) for numerical integration. The equivalent model is similar to the one shown in Figure 15, except now, the equivalent admittance Y_{c_p} replaces Z_{c_p} and the history terms are found from the transformation of (13)-(14) into time-domain for each mode p:

$$i_{k_p}^{h} = h_p(t) * \left[y_{c_p}(t) * v_{m_p}(t) + i_{m_p}(t) \right] \tag{35}$$

$$i_{m_p}^{h} = h_p(t) * \left[y_{c_p}(t) * v_{k_p}(t) + i_{k_p}(t) \right] \tag{36}$$

where $*$ denotes convolution. The modal transformation matrix is used to revert back to phase-domain equations of the simulated grid. Other details on this model can be found in [16]-[18].

3.2.2.1 FD-model options

The FD-model options are :

1. Q matrix type: see explanations above.
2. Q matrix frequency: The frequency at which the transformation is calculated. See explanations above.
3. f_{min}: the minimum frequency for scanning the modal parameters.
4. Points/decade: number of points per decade for the logarithmic scale used for scanning parameters.
5. Decades: number of decades in the logarithmic scale.

3.2.2.2 Corresponding device input

This model can be used in the Frequency dependent line device (model) available in the EMTP Lines library. The Frequency dependent line needs the model file name. The model file is named *name*_FD.mod, where *name* is an arbitrary device name from which this model is generated. The model file name is referenced in the Frequency dependent line device.

3.2.3 WB-model

The Wideband model is the most accurate model for time domain simulations of lines and cables. It is recommended to use this model for accurate results for a large band of frequencies. This model works in phase-domain and accounts for full frequency dependency of transmission line or cable parameters. There are no approximations as in CP-model or FD-model.

The EMTP WB-model is based on research presented in [10]-[15]. Major improvements and new algorithms are presented in [11][12][14][15].

In the WB-model, the functions $\mathbf{Y}_c(s)$ and $\mathbf{H}(s)$ in (15)-(16) are sampled for the given frequency range and curve fitted using vector fitting resulting into

$$\mathbf{Y}_c(s) \approx \mathbf{G}_0 + \sum_{i=1}^{N_y} \frac{\mathbf{G}_i}{s - q_i} \tag{37}$$

$$\mathbf{H}(s) \approx \sum_{i=1}^{N} \left(\sum_{k=1}^{M_i} \frac{\mathbf{R}_{i,k}}{s - p_{i,k}} \right) e^{-s\tau_i} \tag{38}$$

where $\mathbf{G}_0$ is a constant matrix corresponding to $s \to \infty$, N_y represents the order of the fit, q_i represents the i^th fitting pole, $\mathbf{G}_i$ is the corresponding matrix of residues, N is the number of modes (conductors), M_i is the order of the fit for the i^th modal propagation function, $\mathbf{R}_{i,k}$ is the determined matrix of residues, $p_{i,k}$ represents the k^th fitting pole and τ_i is the time-delay associated with the i^th mode. The time-domain solution is performed once again using a delay based circuit with Norton equivalents, but in phase-domain.
Further details on the above can be found in [11].

3.2.3.1 Wideband fitting

The following fitting options are available for the wideband model.

1. Convergence tolerance: tolerance used for fitting error.
2. Cable model correction: In coaxial cables with several conductors, the conventional fitting approach [10] may cause unbalanced modal contributions in phase domain fitting with high ratio residue pole pairs having opposite signs from different modal groups. This amplifies the integration errors in time domain, resulting in numerical instability. In this case, it is recommended to choose the Cable model correction option [11], also called FDCM. In FDCM, modal contributions in phase domain are fitted individually and high ratio residue pole pairs with opposite signs are avoided. Since the fitting is performed directly in phase domain and per modal contribution, more poles are required compared to the conventional approach, to maintain similar precision. Modal contributions of repetitive eigenvalues are grouped in FDCM to obtain smooth functions to fit. The fitter switches to the FDCM option when selected and when the residue pole ratio (Residue/Pole threshold for correction) is above the specified threshold, which is by default 1000.
    a. Residue/Pole threshold: for Cable model correction.
3. DC correction: The line/cable model in HVDC simulations needs to be precise at DC frequencies (frequencies close to DC). However, extending the fitting band to cover frequencies very close to DC (e.g. below 0.01 Hz) stiffens the fitting. A simple yet very efficient DC correction feature is given in [12]. When the DC correction option is selected by the user, the fitter partitions the frequency band to relax fitting and finds a correction term for DC frequencies afterwards. The application of DC correction also helps maintaining passivity. When the DC Correction option is selected, it is recommended to set the lower frequency limit (f_{min}) to 0.001 Hz or below.
   If the DC solution in time-domain steady-state conditions is oscillating, then this option may allow obtaining more accurate results.
4. Apply grouping: When the ULM [10] methodology is used, the propagation function matrix is fitted in two stages. First stage is the identification of poles and delays through modal decomposition. By default, propagation modes having identical or almost identical delays are grouped. In some cases, disabling grouping may improve/correct the stability of the model. Second stage is the identification of residues directly in phase domain by using the poles and delays from all modal groups in every entry of the propagation function.

The Wideband fitting procedure uses a passivity test. Passivity violations may lead to numerical instabilities in time-domain simulations with the WB-model. In most cases the model is passive but if there exist passivity violations due to fitting errors, the user can vary fitting parameters to render the model passive. Perturbating the model by reducing the fitting error (Fitting convergence tolerance), adjusting the frequency band or number of frequency samples (Points/decade), enabling/disabling grouping (Apply grouping) and turning on/off DC correction, can help to establish passivity.
In addition to the above the WB-model requires the definition of scanning frequency range:

1. f_{min}: the minimum frequency for scanning the modal parameters.
2. Points/decade: number of points per decade for the logarithmic scale used for scanning parameters.
3. Decades: number of decades in the logarithmic scale.

3.2.3.2 Corresponding device input

This model can be used in the Wideband line/cable device (model) available in the EMTP Lines library. The Wideband line/cable needs the model file name. The model file is named *name*_WB.mod where *name* is an arbitrary device name from which this model is generated. The model file name is referenced in the Wideband line/cable device.

3.2.4 Exact-PI model

The Exact-PI multiphase model is only used for steady-state and frequency scan simulations. This model constitutes an exact steady-state PI model representation for the transmission line (or cable) from its terminal ends for the requested frequency range.

This model can be used only in the EMTP Steady-solution or Frequency scan solution. The model must be calculated at the Steady-state solution frequencies as imposed by available sources. The range of frequencies entered in the Frequency scan option (Simulation Options) must be exactly the same as the one selected for the model on the Model tab.

It is noted that the Wideband (WB-model) model can normally reproduce very accurately steady-state and frequency scan simulations, but this Exact-PI model is provided for testing and referencing.

The Exact-PI model is based on equations (11) and (14) that can be used also in the multiphase version. After some algebraic operations on these equations in frequency domain, it is possible to write:

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{series} + Y_{shunt} & -Y_{series} \\ -Y_{series} & Y_{series} + Y_{shunt} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \tag{39}$$

where the shunt and series admittances are found from:

$$Y_{series} = \frac{Y_c}{\sinh(\Gamma \ell)} \tag{40}$$

$$Y_{shunt} = Y_c \tanh\left(\frac{\Gamma \ell}{2}\right) \tag{41}$$

The resulting Exact-PI model is shown in Figure 17.

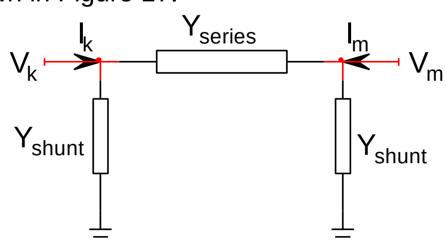


Figure 17 Exact-PI model, single-phase version.

The multiphase version is produced using vectors and matrices.

3.2.4.1 Corresponding device input

This model can be used only in the Frequency dependent line device (model) available in the EMTP Lines library. The Frequency dependent line needs the model file name. The model file is named *name*_Exact_PI.mod, where *name* is an arbitrary device name from which this model is generated. The model file name is referenced in the Frequency dependent line device. The model file format is as follows (line-by-line) for each frequency:

1. Frequency
2. Series real part of admittance
3. Series imaginary part of admittance
4. Shunt real part of admittance
5. Shunt imaginary part of admittance

Each admittance line, contains the following sequence in ℧ units using 6 entries per line:
Y(1,1) Y(2,1) Y(2,2) Y(3,1) Y(3,2) Y(3,3)
Y(4,1) Y(4,2)…

3.2.5 Nominal-PI

The Nominal-PI model is similar to Exact-PI, except now an approximate PI-section is derived from calculated per-unit-length parameters obtained at a single frequency and the given line/cable length. This results into series impedance $R + j\omega L$ and shunt part C in parallel with G.

The model file is named *name*_Nominal_PI.mod where *name* is an arbitrary device name from which this model is generated. The model file format is as follows (line-by-line):

1. Frequency
2. Series real (R in Ω)
3. Series imaginary (L in H)
4. Shunt real (G in a $\mho$)
5. Shunt imaginary (C in F)

The sequence of matrix output for each parameter is the same as for the Exact-PI case.

3.2.5.1 Corresponding device input

This model can be used in the PI multiphase device by loading the model file.

3.3 Options

The Line/Cable Data device provides additional options depending on the selected model. These options are listed below.

1. Proximity effect: This option allows considering the proximity effect in the model. Proximity effect is especially important for closely packed cables where the current distribution on the cross section of the conductor can become non uniform due to the currents in close conductors.
2. Earth return shunt admittance: This option accounts accurately for the real part of the model shunt admittance, which in should not be zero. This earth return path can be significant for high frequencies (10 kHz and above).
3. Enter G shunt: This option allows the user to enter an artificial conductance between the conductors and the ground. This conductance is helpful to model leakage currents through contaminated insulator chains.
4. Balanced line: Considers a transmission line continuously transposed. Under this assumption, all mutual impedances and admittances are considered equal (the average is used).
5. Segmented ground wires: The continuous ground wire model assumes that the ground wire is grounded at each tower and is continuous between adjacent towers. The segmented ground wires are grounded at one tower and insulated at adjacent towers at both ends of the segmentation interval.
   When this option is checked the mutual impedance between phase wire and ground wire is forced to zero.
6. Crossbonded. This option is only valid for three identical single-core cables with two conductors each (core and sheath). The impedances and admittances corresponding to sheath conductors are averaged out. No reduction is applied. The crossbonded conductors are identified by the Phase number 0 (zero).
7. Crossbonded and reduced. This option, also known as the homogeneous model in the literature, is only valid for three identical single-core cables with two conductors each (core and sheath). The impedances and admittances corresponding to sheath conductors are averaged out. Sheath-conductors are grouped into a common conductor (the last conductor).

4 References

[1] H. Xue, A. Ametani, J. Mahseredjian, Y. Baba, F. Rachidi and I. Kocar, "Transient Responses of Overhead Cables Due to Mode Transition in High Frequencies", IEEE Transactions on Electromagnetic Compatibility, Vol. 60, No. 3, , June 2018, pp. 785-794.

[2] U. R. Patel and P. Triverio, "MoM-SO: a complete method for computing the impedance of cable systems including skin, proximity, and ground return effects", IEEE Trans. Power Delivery, Vol. 30, No. 5, Oct. 2015, pp. 2110-2118.

[3] U. R. Patel and P. Triverio, "Accurate impedance calculation for underground and submarine power cables using MoM-SO and a multilayer ground model", IEEE Trans. Power Delivery, Vol. 31, No. 3, June 2016, pp. 1233-1241.

[4] U. R. Patel, “A Surface Admittance Approach for Fast Calculation of the Series Impedance of Cables Including Skin, Proximity, and Ground Return Effects”, M.Sc. Thesis, 2014, University of Toronto.

[5] H. Xue, J. Mahseredjian, A. Ametani, J. Morales, I. Kocar, “Generalized Formulation of Overhead Line Parameters for Multi-Layer Earth”, IEEE Trans. on Power Delivery, Jan. 2021, DOI: 10.1109/TPWRD.2021.3049595.

[6] H. Xue, A. Ametani, J. Mahseredjian, I. Kocar, “Computation of Line/Cable Parameters with Improved MoM-So Method”, 2018 Power Systems Computation Conference (PSCC), 10.23919/PSCC.2018.8442743, 11-15 June, Dublin.

[7] H. Xue, A. Ametani, J. Mahseredjian, I. Kocar, “Generalized Formulation of Earth-Return Impedance/Admittance and Surge Analysis on Underground Cables”, IEEE Trans. On Power Delivery, Vol 22, No. 6, Dec. 2018, pp. 2654-2663.

[8] H. Xue, A. Ametani, J. Mahseredjian, “Very Fast Transients in a 500 kV Gas-Insulated Substation”, IEEE Trans. on Power Delivery, Vol 34, No. 2, April 2019, pp. 627-637, 2019.

[9] J. Morales, J. Mahseredjian, I. Kocar, H. Xue, A. Daneshpooy, “Modeling of Overhead Transmission Lines for Trapped Charge Discharge Rate Studies”, Electric Power Systems Research, Volume 198, September 2021, 107343.

[10] A. Morched, B. Gustavsen, M. Tartibi, “A universal model for accurate calculation of electromagnetic transients on overhead lines and underground cables”. IEEE Trans. on Power Delivery, Vol. 14, No. 3, July 1999, pp. 1032 -1038.

[11] I. Kocar, J. Mahseredjian, “Accurate Frequency Dependent Cable Model for Electromagnetic Transients”, IEEE Trans. on Power Delivery, Vol. 31, No. 3, June 2016, pp. 1281-1288.

[12] M. Cervantes, I. Kocar, J. Mahseredjian, A. Ramirez, “Partitioned Fitting and DC Correction for the Simulation of Electromagnetic Transients in Transmission Lines”, IEEE Power Delivery Letters, Vol. 33, No. 6, Dec. 2018, pp. 3246 - 3248.

[13] B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by vector fitting", IEEE Trans. on Power Delivery, Vol. 14, no. 3, July 1999, pp. 1052-1061.

[14] I. Kocar, J. Mahseredjian, G. Olivier, “Weighting Method for Transient Analysis of Underground Cables”, IEEE Tran. on Power Delivery, Vol. 23, no. 3, July 2008, pp. 1629-1635.

[15] I. Kocar, J. Mahseredjian, “New procedure for computation of time delays in propagation function fitting for transient modeling of cables”, IEEE Trans. on Power Delivery, Vol. 31, no. 2, July 2008, pp. 613-621.

[16] H. W. Dommel, “EMTP Theory Book, Microtran Power System Analysis Corporation,” Vancouver, British Columbia, 1996.

[17] J. R. Marti, "Accurate Modelling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 1, pp. 147-157, Jan. 1982.

[18] W. Scott Meyer, H. Dommel, “Numerical modelling of frequency-dependent transmission-line parameters in an electromagnetic transients program”, ", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-93, No. 5, pp. 1401-1409, Sept. 1974.