POWERFACTORY

PowerFactory 2021

Technical Reference

Overhead Line Models

ElmLne, TypLne, TypGeo, TypTow

PF2021

POWER SYSTEM SOLUTIONS
MADE IN GERMANY

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Contents

1 General Description

This document describes the models of transmission lines available in *PowerFactory*.

PowerFactory provides models which can represent dc and ac lines for all possible phase technologies (3-phase, 2-phase and 1-phase; with/without a neutral conductor and ground wires) for both single- and mutually-coupled parallel circuits. Table 1.1 provides an overview of the supported options and the corresponding element/type combinations.

Table 1.1: Overview of line models available in *PowerFactory*

System	Phase Technology	Element	Type
DC	Unipolar	*ElmLne*	*TypLne*
AC, single-circuit	1-ph	*ElmLne*	*TypLne*
	2-ph	*ElmLne*	*TypLne*
	3-ph	*ElmLne*	*TypLne*, *TypTow*, *TypGeo*
	1-ph with neutral	*ElmLne*	*TypLne*
	2-ph with neutral	*ElmLne*	*TypLne*
	3-ph with neutral	*ElmLne*	*TypLne*
AC, mutually-coupled circuits	Any combination of phase technologies	*ElmTow*	*TypTow*, *TypGeo*
DC, mutually-coupled circuits	Any combination of phase technologies	*ElmTow*	*TypTow*, *TypGeo*
AC/DC, mutually-coupled circuits	Any combination of phase technologies	*ElmTow*	*TypTow*

The line element *ElmLne* in *PowerFactory* is the constituent element of transmission lines. When referring to a type, the line element can be used to define single-circuit lines of any phase technology according to Table 1.1. In addition, the element parameter *Number of Parallel Lines* allows the representation of parallel lines without mutual coupling.

1.1 Mutual Coupling

If the mutual coupling between parallel lines is to be considered, then a line coupling element *ElmTow* has to be defined. In this case, the line element *ElmLne* points to a line coupling element *ElmTow* which in turns refers to the corresponding tower type (*TypTow*) or tower geometry type (*TypGeo*).

1.1.1 AC/DC Couplings

AC and DC circuits increasingly share rights-of-way, often with only small distances between the transmission lines, resulting in electromagnetic coupling effects. Voltage and current can be induced on either AC or DC lines under both steady-state and transient conditions. AC/DC tower couplings can be modelled by using the line coupling element (*ElmTow*) in conjunction with the tower type (*TypTow*). The tower type must have the *System Type* set to *AC/DC*. The impedances and admittances of the AC circuit/s will be solved using the user-defined *Nominal Frequency*, and of the DC circuit/s using the *Nominal Frequency (DC)*. AC/DC couplings are handled as follows in the various *PowerFactory* calculations:

- Load Flow: The transmission line equations are solved separately for the AC circuit/s and DC circuit/s. The DC circuit/s are always solved using the lumped parameter model, regardless of the selection of the *Line Model* in the line coupling element (*ElmTow*).

- Short-Circuit: AC circuit/s are considered and any DC circuit/s are ignored.
- RMS Simulation: The DC circuit/s are always solved using the lumped parameter model, regardless of the selection of the *Line Model* in the line coupling element (*ElmTow*).
- EMT Simulation: The frequency dependent phase-domain model is selected by default in the line coupling element (*ElmTow*). The user can choose between the Universal Line Model (ULM) or the Frequency Dependent Model (FDM).

1.2 Frequency Dependency

PowerFactory further distinguishes between constant and frequency dependent parameter models. Models based on tower geometry types (*TypTow* or *TypGeo*) use frequency dependent parameters. This means that the electrical parameters of the line per unit length are calculated from the mechanical characteristics of the tower and the conductors accounting for skin effect, the frequency dependent earth-return path of the line, etc. These types should be selected for use in simulations where a wide range of frequencies is involved or frequencies other than the nominal system frequency. For further information about the calculation of the per unit length parameters, please refer to [1].

Models based on line types (*TypLne*) are by default not frequency dependent. The user enters the electrical parameters per unit length of the line at system frequency. These parameters remain unchanged; if the frequency of the simulation changes, i.e. differs from the system frequency, then the program will adjust the reactance and susceptance of the line according to the new frequency but the inductances and capacitances will remain unchanged. For certain calculations (i.e. harmonic load flow, frequency sweep) the user still has the option of assigning a frequency characteristic to the parameters in the line type. Further details pertaining to input parameters for the different phase technologies (3-phase, 2-phase, 1-phase, w/o neutral) and frequency characteristics are discussed in the following sections.

1.3 Lumped and Distributed Parameters

For three-phase lines (either single or multiple parallel circuits), the user can choose between lumped or distributed parameters. For long transmission lines the distributed parameter model is preferred as it gives highly accurate results, while the lumped parameter model provides sufficient results for short lines. The details of the different models are discussed in the following sections.

Rating of the line/cable

The rated current is the base for per-unit current quantities. The rated current I_r of the three-phase line/cable is calculated as:

$$I_r = sline \cdot nlnum \qquad [kA] \tag{1}$$

or for a cable with the option Air for $Laying$ is selected:

$$I_r = InomAir \cdot nlnum \qquad [kA] \tag{2}$$

where:

- $sline$ is the rated current in kA from the type *TypLne*

- $nlnum$ is the number of parallel lines from
- $InomAir$ is the rated current in air in kA from the type *TypLne*

If line sections are defined in the line/cable, the smallest rated current of all sections is used as the rated current.

2 Equivalent Circuits

2.1 Lumped Parameters

Figure 2.1 shows the equivalent PI-circuit used by *PowerFactory* to represent AC transmission lines with lumped parameters. The subscripts *s* and *r* denote the *sending* and *receiving* ends of the line, respectively. The general formulation discussed in this section is valid for any phase technology by appropriate dimensioning of the impedance and admittance matrices, even though the formulation presented here is based on a 3-phase line with no neutral conductor.

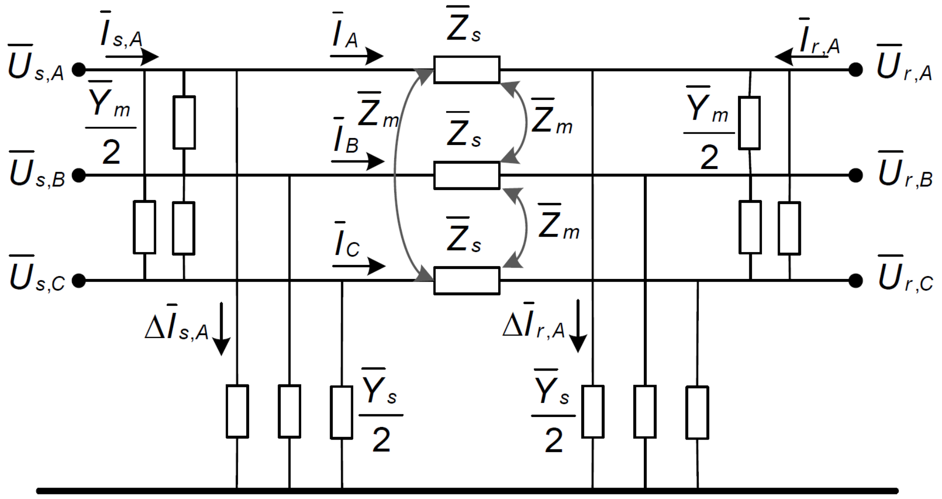

Figure 2.1: Equivalent PI-circuit of the line for lumped parameters

The equations of the voltages and currents at the sending and receiving ends of the line are formulated in terms of impedance and admittance matrices. The dimension of the matrices depends on the phase technology. The longitudinal voltage drop along the line is given by the impedance matrix in the following form:

$$\begin{bmatrix} \underline{U}_{s,A} \\ \underline{U}_{s,B} \\ \underline{U}_{s,C} \end{bmatrix} - \begin{bmatrix} \underline{U}_{r,A} \\ \underline{U}_{r,B} \\ \underline{U}_{r,C} \end{bmatrix} = \begin{bmatrix} \Delta\underline{U}_{A} \\ \Delta\underline{U}_{B} \\ \Delta\underline{U}_{C} \end{bmatrix} = \begin{bmatrix} \underline{Z}_s & \underline{Z}_m & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_s & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_m & \underline{Z}_s \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_{A} \\ \underline{I}_{B} \\ \underline{I}_{C} \end{bmatrix} \tag{3}$$

According to the sign convention assumed in Figure 2.1, the current at the sending end of the line is calculated in terms of the admittance matrix as follows:

$$\begin{bmatrix} \underline{I}_{s,A} \\ \underline{I}_{s,B} \\ \underline{I}_{s,C} \end{bmatrix} = \begin{bmatrix} \Delta\underline{I}_{s,A} \\ \Delta\underline{I}_{s,B} \\ \Delta\underline{I}_{s,C} \end{bmatrix} + \begin{bmatrix} \underline{I}_{A} \\ \underline{I}_{B} \\ \underline{I}_{C} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \underline{Y}_s & \underline{Y}_m & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_s & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_m & \underline{Y}_s \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{s,A} \\ \underline{U}_{s,B} \\ \underline{U}_{s,C} \end{bmatrix} + \begin{bmatrix} \underline{I}_{A} \\ \underline{I}_{B} \\ \underline{I}_{C} \end{bmatrix} \tag{4}$$

Similarly, the current at the receiving end of the line is given by:

$$\begin{bmatrix} \underline{I}_{r,A} \\ \underline{I}_{r,B} \\ \underline{I}_{r,C} \end{bmatrix} = \begin{bmatrix} \Delta\underline{I}_{r,A} \\ \Delta\underline{I}_{r,B} \\ \Delta\underline{I}_{r,C} \end{bmatrix} - \begin{bmatrix} \underline{I}_{A} \\ \underline{I}_{B} \\ \underline{I}_{C} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \underline{Y}_s & \underline{Y}_m & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_s & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_m & \underline{Y}_s \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{r,A} \\ \underline{U}_{r,B} \\ \underline{U}_{r,C} \end{bmatrix} - \begin{bmatrix} \underline{I}_{A} \\ \underline{I}_{B} \\ \underline{I}_{C} \end{bmatrix} \tag{5}$$

Equations (3), (4) and (5) completely define the PI-model of the line for lumped parameters. The impedance and admittance matrices:

$$[\underline{\boldsymbol{Z}}_{ABC}] = \begin{bmatrix} \underline{Z}_s & \underline{Z}_m & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_s & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_m & \underline{Z}_s \end{bmatrix} \qquad [\underline{\boldsymbol{Y}}_{ABC}] = \begin{bmatrix} \underline{Y}_s & \underline{Y}_m & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_s & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_m & \underline{Y}_s \end{bmatrix} \tag{6}$$

are the natural impedance and admittance matrices of the line after reduction of earth wires (if any).

Note that $\underline{Y}_s$ represents the sum of all admittances connected to the corresponding phase, while $\underline{Y}_m$ is the negative value of the admittance between two phases. Similarly, $\underline{Y}_p$ is the sum of all admittances connected to the neutral conductor and $\underline{Y}_{pn}$ is the negative value of the admittance between the neutral and the phase conductors.

The PI-circuit described here is the general formulation of the line model with lumped parameters in *PowerFactory*. The following sections discuss the application of the model to the different phase technologies (3-, 2-, 1-phase, w/o neutral conductors) and the required user-defined parameters in each case.

2.1.1 Single-Phase Line

The equivalent circuit in Figure 2.1 can be reduced to the PI-circuit in Figure 2.2 for the single-phase line.

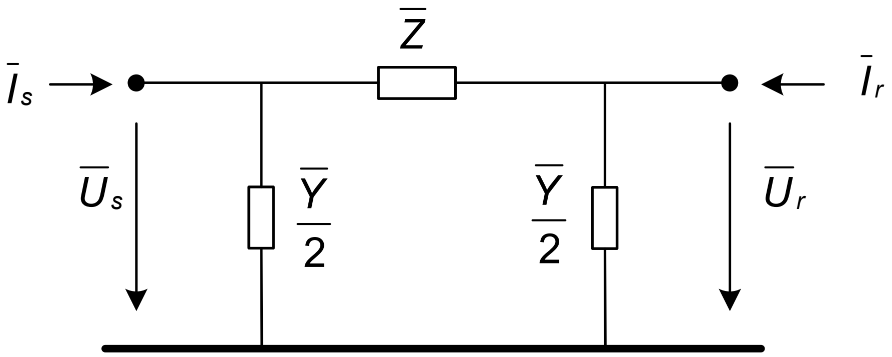

Figure 2.2: Lumped parameter model for a single-phase AC line

The impedance and admittance of the equivalent circuit are calculated from the input parameters defined in the line type (*TypLne*) according to the following equations:

$$\begin{aligned} Z &= Z_1^{'} \cdot l = \left(R_1^{'} + j\omega L_1^{'}\right) \cdot l \\ Y &= Y_1^{'} \cdot l = \left(G_1^{'} + j\omega C_1^{'}\right) \cdot l \\ G_1^{'} &= B_1^{'} \cdot tg\delta_1 \end{aligned} \tag{7}$$

where l is the length of the line in [km], and $R_1^{'}$,$L_1^{'}$, $G_1^{'}$ and $C_1^{'}$ are the line parameters per unit length. Note that the conductance $G_1^{'}$ can be defined in terms of the insulation factor, $tg\delta$. The reader is referred to Table A.1 for the complete list of input parameters.

The currents and voltages on both sides of the line in Figure 2.2 are related by the following equation:

$$\begin{bmatrix} U_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} U_r \\ -I_r \end{bmatrix} \quad (8)$$

where the *ABCD* parameters of the equivalent PI-circuit are:

$$\begin{aligned} A &= 1 + \tfrac{1}{2} Z^{'} \cdot Y^{'} \cdot l^2 \\ B &= Z^{'} \cdot l \\ C &= Y^{'} \cdot l \cdot \left(1 + \tfrac{Z^{'} \cdot Y^{'} \cdot l^2}{4}\right) \\ D &= A \end{aligned} \quad (9)$$

2.1.2 Two-Phase Line

From Figure 2.1, the equivalent circuit shown in Figure 2.3 can be now deduced for the 2-phase line model.

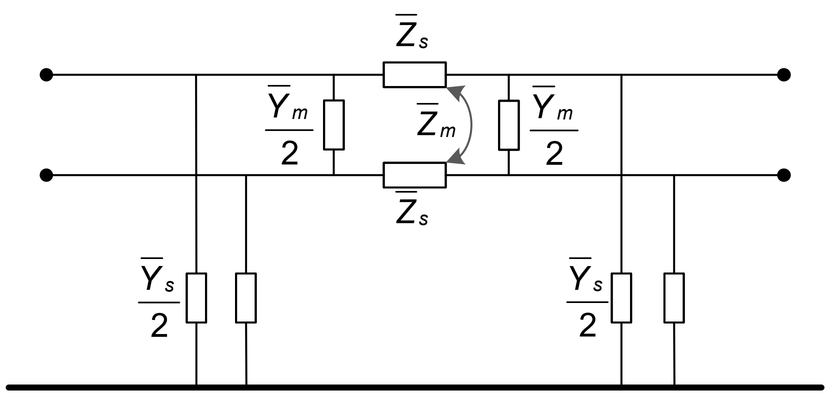

Figure 2.3: Equivalent circuit of the two-phase line model

The self- and mutual impedances and admittances of the equivalent circuit:

$$[\underline{\boldsymbol{Z}}_{ab}] = \begin{bmatrix} \underline{Z}_s & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_s \end{bmatrix} \qquad [\underline{\boldsymbol{Y}}_{ab}] = \begin{bmatrix} \underline{Y}_s & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_s \end{bmatrix} \quad (10)$$

are calculated from the input parameters defined in the line type (*TypLne*). The input parameters - positive and zero sequence components - are converted to the impedances and admittances in (10) via the following transformation:

$$[\underline{\boldsymbol{T}}_{S2ph}] = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad [\underline{\boldsymbol{T}}_{S2ph}]^{-1} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$[\underline{\boldsymbol{Z}}_{01}] = [\boldsymbol{T}_{S2ph}]^{-1} \times [\underline{\boldsymbol{Z}}_{ab}] \times [\boldsymbol{T}_{S2ph}]$$

Thus the self and mutual impedances and admittances in (10) are related to the input parameters $\underline{Z}_1, \underline{Z}_0, \underline{Y}_1$ and $\underline{Y}_0$ as follows:

$$[\underline{\boldsymbol{Z}}_{01}] = \begin{bmatrix} \underline{Z}_0 & 0 \\ 0 & \underline{Z}_1 \end{bmatrix} = \begin{bmatrix} \underline{Z}_s + \underline{Z}_g & 0 \\ 0 & \underline{Z}_s - \underline{Z}_g \end{bmatrix}$$

$$[\underline{\boldsymbol{Y}}_{01}] = \begin{bmatrix} \underline{Y}_0 & 0 \\ 0 & \underline{Y}_1 \end{bmatrix} = \begin{bmatrix} \underline{Y}_s + \underline{Y}_g & 0 \\ 0 & \underline{Y}_s - \underline{Y}_g \end{bmatrix}$$

2.1.3 Three-Phase Lines

The equivalent circuit of the three-phase line is shown in Figure 2.4. The self- and mutual impedances and admittances are given by:

$$[\underline{\boldsymbol{Z}}_{abc}] = \begin{bmatrix} \underline{Z}_s & \underline{Z}_m & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_s & \underline{Z}_m \\ \underline{Z}_m & \underline{Z}_m & \underline{Z}_s \end{bmatrix} \qquad [\underline{\boldsymbol{Y}}_{abc}] = \begin{bmatrix} \underline{Y}_s & \underline{Y}_m & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_s & \underline{Y}_m \\ \underline{Y}_m & \underline{Y}_m & \underline{Y}_s \end{bmatrix} \tag{11}$$

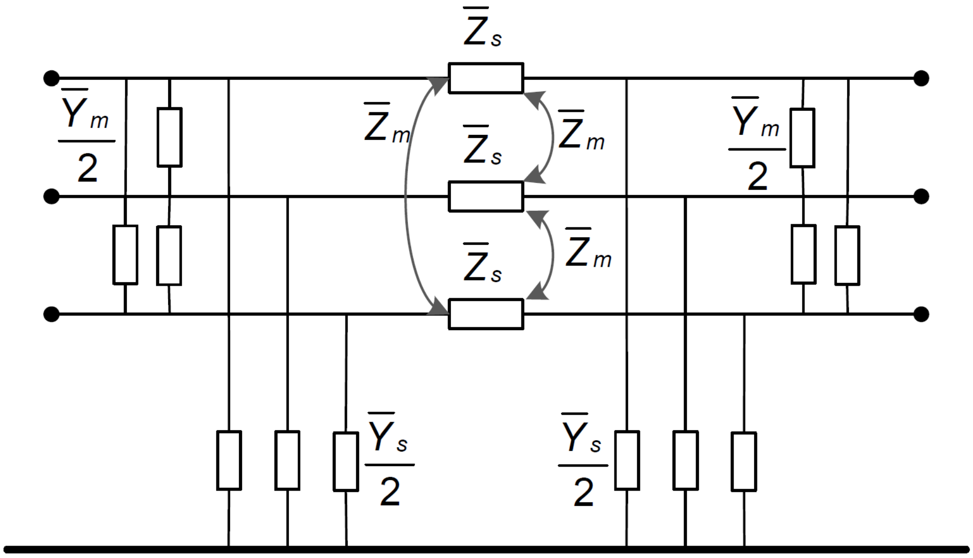

Figure 2.4: Equivalent circuit of the three-phase line

The input parameters in the line type (*TypLne*) are defined in terms of positive and zero sequence impedances and admittances $\underline{Z}_1, \underline{Y}_1, \underline{Z}_0$ and $\underline{Y}_0$. The negative sequence is assumed to be equal to the positive sequence.

The conversion from the sequence components into the natural components in (11) is done via the complex transformation matrix $[T_s]$ as follows:

$$[\underline{\boldsymbol{T}}_S] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad \rightarrow \quad [\underline{\boldsymbol{T}}_S]^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{12}$$

$$[\underline{\boldsymbol{Z}}_{012}] = [\boldsymbol{T}_S]^{-1} \times [\underline{\boldsymbol{Z}}_{abc}] \times [\boldsymbol{T}_S]$$

$$[\underline{\boldsymbol{Z}}_{012}] = \begin{bmatrix} \underline{Z}_0 & 0 & 0 \\ 0 & \underline{Z}_1 & 0 \\ 0 & 0 & \underline{Z}_2 \end{bmatrix} = \begin{bmatrix} \underline{Z}_s + 2\underline{Z}_m & 0 & 0 \\ 0 & \underline{Z}_s - \underline{Z}_m & 0 \\ 0 & 0 & \underline{Z}_s - \underline{Z}_m \end{bmatrix}$$

$$[\underline{\boldsymbol{Y}}_{012}] = \begin{bmatrix} \underline{Y}_0 & 0 & 0 \\ 0 & \underline{Y}_1 & 0 \\ 0 & 0 & \underline{Y}_2 \end{bmatrix} = \begin{bmatrix} \underline{Y}_s + 2\underline{Y}_m & 0 & 0 \\ 0 & \underline{Y}_s - \underline{Y}_m & 0 \\ 0 & 0 & \underline{Y}_s - \underline{Y}_m \end{bmatrix}$$

2.1.4 Three-Phase Line with Neutral Conductor

Figure 2.5 shows the equivalent circuit of the 3-phase line with neutral conductor. The voltages and the currents at both ends of the line are related by the impedance and admittance matrices:

$$[\underline{\boldsymbol{Z}}_{abcn}] = \begin{bmatrix} \underline{Z}_s & \underline{Z}_m & \underline{Z}_m & \underline{Z}_{pn} \\ \underline{Z}_m & \underline{Z}_s & \underline{Z}_m & \underline{Z}_{pn} \\ \underline{Z}_m & \underline{Z}_m & \underline{Z}_s & \underline{Z}_{pn} \\ \underline{Z}_{pn} & \underline{Z}_{pn} & \underline{Z}_{pn} & \underline{Z}_n \end{bmatrix} \qquad [\underline{\boldsymbol{Y}}_{abcn}] = \begin{bmatrix} \underline{Y}_s & \underline{Y}_m & \underline{Y}_m & \underline{Y}_{pn} \\ \underline{Y}_m & \underline{Y}_s & \underline{Y}_m & \underline{Y}_{pn} \\ \underline{Y}_m & \underline{Y}_m & \underline{Y}_s & \underline{Y}_{pn} \\ \underline{Y}_{pn} & \underline{Y}_{pn} & \underline{Y}_{pn} & \underline{Y}_n \end{bmatrix} \tag{13}$$

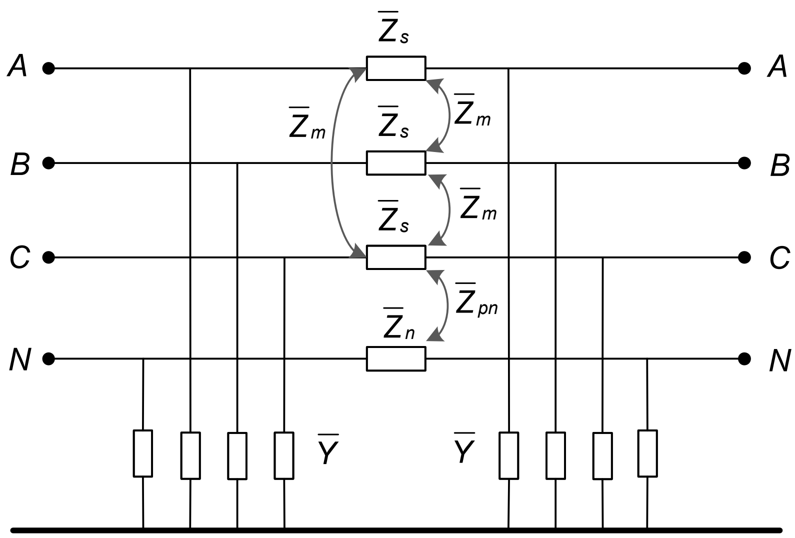

Figure 2.5: Equivalent circuit for the 3-phase line with neutral conductor

The input parameters of the model are the positive and zero sequence impedances $\underline{Z}_1$, $\underline{Z}_0$. The positive and zero sequence admittance, $\underline{Y}_1$ and $\underline{Y}_0$, the self- and mutual impedance $\underline{Z}_n$,

$\underline{Z}_{pn}$ and the admittance for the neutral conductor $\underline{Y}_p$, $\underline{Y}_{pn}$ are as listed in Table A.1 of §9 (input parameters of the line type *TypLne*).

The values $\underline{Z}_n$, $\underline{Z}_{pn}$, $\underline{Y}_p$ and $\underline{Y}_{pn}$ of the neutral conductor can be directly used in (13). The self- and mutual impedance of the phase conductors are calculated as follows:

$$\underline{Z}_s = \frac{1}{3} \cdot (\underline{Z}_0 + 2 \cdot \underline{Z}_1) \qquad \underline{Y}_s = \frac{1}{3} \cdot (\underline{Y}_0 + 2 \cdot \underline{Y}_1) \tag{14}$$

$$\underline{Z}_m = \frac{1}{3} \cdot (\underline{Z}_0 - \underline{Z}_1) \qquad \underline{Y}_m = \frac{1}{3} \cdot (\underline{Y}_0 - \underline{Y}_1) \tag{15}$$

or can be resolved in terms of the sequence magnitudes:

$$\underline{Z}_1 = (\underline{Z}_s - \underline{Z}_m) \qquad \underline{Y}_1 = (\underline{Y}_s - \underline{Y}_m) \tag{16}$$

$$\underline{Z}_0 = (\underline{Z}_s + 2 \cdot \underline{Z}_m) \qquad \underline{Y}_0 = (\underline{Y}_s + 2 \cdot \underline{Y}_m) \tag{17}$$

2.1.5 4-Wire model data conversion

The self- and mutual impedances and admittances are not always available in the format required by the line type (*TypLne*). The following subsections guide the reader on how to convert commonly available measurement data into the required input parameters.

2.1.5.1 Measurement between phase A and phase B wire

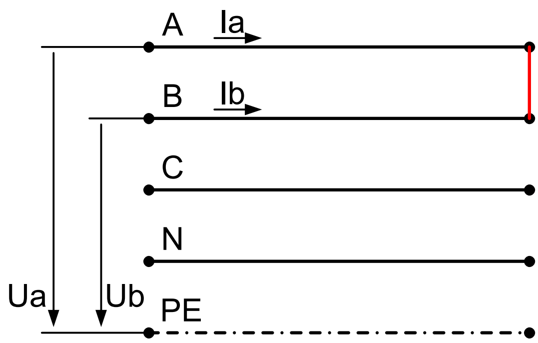

Figure 2.6: Phase to phase measurement loop

As per the impedance matrix in (13):

$$\begin{bmatrix} \underline{U}_a \\ \underline{U}_b \\ \underline{U}_c \\ \underline{U}_n \end{bmatrix} = \begin{bmatrix} \underline{Z}_s & \underline{Z}_m & \underline{Z}_m & \underline{Z}_{pn} \\ \underline{Z}_m & \underline{Z}_s & \underline{Z}_m & \underline{Z}_{pn} \\ \underline{Z}_m & \underline{Z}_m & \underline{Z}_s & \underline{Z}_{pn} \\ \underline{Z}_{pn} & \underline{Z}_{pn} & \underline{Z}_{pn} & \underline{Z}_n \end{bmatrix} \begin{bmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \\ \underline{I}_n \end{bmatrix} \tag{18}$$

thus:

$$\begin{array}{l} \underline{U}_a = \underline{Z}_s \cdot \underline{I}_a + \underline{Z}_m \cdot \underline{I}_b \\ \underline{U}_b = \underline{Z}_m \cdot \underline{I}_a + \underline{Z}_s \cdot \underline{I}_b \end{array}$$

According to the measurement in Figure 2.6:

$$\underline{I}_a = (-\underline{I}_b)$$
$$U_a - U_b = 2I_a \cdot (\underline{Z}_s - \underline{Z}_m)$$

the positive sequence impedance can be derived as follows:

$$\underline{Z}_1 = R_1 + jX_1 = \frac{1}{2}\frac{\underline{U}_a - \underline{U}_b}{\underline{I}_a} \tag{19}$$

2.1.5.2 Measurement between neutral and PE (earth) wire

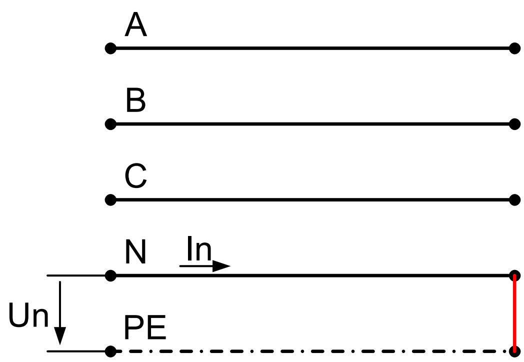

Figure 2.7: Neutral to ground measurement loop

Again from (18) now with Ia=Ib=Ic=0:

$$U_n = \underline{Z}_n \cdot \underline{I}_n$$

$$\underline{Z}_n = \frac{\underline{U}_n}{\underline{I}_n} \tag{20}$$

Note that $\underline{Z}_n$ represents the impedance of the neutral conductor, $\underline{Z}_{Neutral}$, plus the impedance of the earth-return path, $\underline{Z}_{earth}$.

2.1.5.3 Measurement between phase and PE (earth) wire

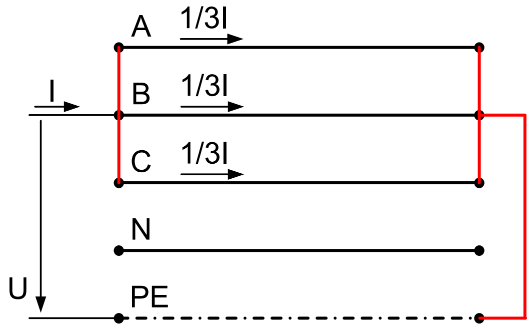

Figure 2.8: Phase – PE (earth wire) measurement

From 18 with In = 0

$$\underline{U} = \frac{1}{3}\left(\underline{Z}_s \cdot \underline{I} + \underline{Z}_m \cdot \underline{I} + \underline{Z}_m \cdot \underline{I}\right)$$

$$\underline{U} = \left(\frac{1}{3}\underline{I}\right) \cdot \underline{Z}_0$$

the zero-sequence impedance is:

$$\underline{Z}_0 = \frac{3 \cdot \underline{U}}{\underline{I}} \tag{21}$$

2.1.5.4 Measurement between phase and neutral wire

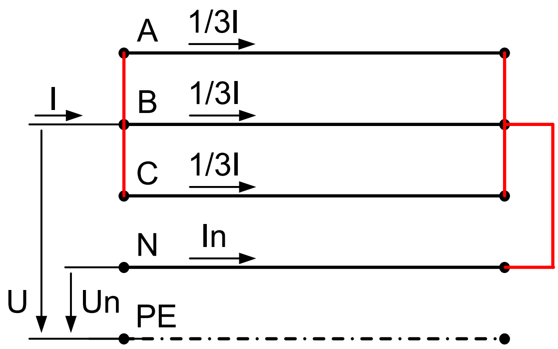

Figure 2.9: Phase – neutral measurement

From (18):

$$\underline{U} = \frac{1}{3}\left(\underline{Z}_s \cdot \underline{I} + \underline{Z}_m \cdot \underline{I} + \underline{Z}_m \cdot \underline{I}\right) + \underline{Z}_{pn} \cdot \underline{I}_n$$

$$\underline{U}_n = \frac{1}{3} \cdot \underline{I} \cdot \left(\underline{Z}_{pn} + \underline{Z}_{pn} + \underline{Z}_{pn}\right) + \underline{Z}_n \cdot \underline{I}_n$$

With $\underline{I}_n = -\underline{I}$:

$$\underline{U} = \frac{1}{3} \left(\underline{Z}_s \cdot \underline{I} + \underline{Z}_m \cdot \underline{I} + \underline{Z}_m \cdot \underline{I}\right) - \underline{Z}_{pn} \cdot \underline{I}$$

$$\underline{U}_n = \frac{1}{3} \cdot \underline{I} \cdot \left(\underline{Z}_{pn} + \underline{Z}_{pn} + \underline{Z}_{pn}\right) - \underline{Z}_n \cdot \underline{I}$$

And according to 14 and 15:

$$\underline{U} = \frac{1}{3}\underline{Z}_0 \cdot \underline{I} - \underline{Z}_{pn} \cdot \underline{I}$$

$$\underline{U}_n = \underline{I} \cdot \left(\underline{Z}_{pn} - \underline{Z}_n\right)$$

Subtracting these equations:

$$\underline{Z}_{0,PH-N} = \frac{3\left(\underline{U} - \underline{U}_n\right)}{\underline{I}} = \underline{Z}_0 - 6 \cdot \underline{Z}_{pn} + 3 \cdot \underline{Z}_n$$

$\underline{Z}_{0,PH-N}$ is commonly referred to as the zero-sequence impedance between with return over the neutral conductor. With $\underline{Z}_n$ given by (20) the mutual impedance between phase and neutral conductors is:

$$\underline{Z}_{pn} = \frac{\underline{Z}_0 + 3 \cdot \underline{Z}_n - \underline{Z}_{0,PH-N}}{6} \tag{22}$$

2.1.5.5 Data conversion without N-PE measurement

If the measurement between the neutral and the PE (earth) wire does not exist the following simplification can be made:

Phase-neutral loop:

$$\underline{Z}_{0,PH-N} = \underline{Z}_1 + 3 \cdot \underline{Z}_{Neutral} \tag{23}$$

Phase-ground loop:

$$\underline{Z}_0 = \underline{Z}_1 + 3 \cdot \underline{Z}_{Earth} \tag{24}$$

Thus the neutral-earth loop impedance:

$$\underline{Z}_{N-E} = \underline{Z}_{Neutral} + \underline{Z}_{Earth}$$

$$\underline{Z}_{N-E} = \underline{Z}_n = \frac{\underline{Z}_{0,PH-N} + \underline{Z}_0 - 2 \cdot \underline{Z}_1}{3} \tag{25}$$

And the phase-neutral mutual impedance:

$$\underline{Z}_{pn} = \frac{\underline{Z}_0 - \underline{Z}_1}{3} \tag{26}$$

2.2 Distributed Parameters Model

In addition to the lumped parameter models described in previous sections, *PowerFactory* also supports distributed parameters models for 3-phase line circuits. This kind of model accounts for the distributed nature of the line parameters and should therefore be the preferred option for the modelling of long lines. For short lines, the lumped parameter models discussed in the previous sections should provide sufficiently accurate solutions.

A line is considered to be long when its physical length is of the same order of magnitude as the length of wave of the voltage/current at the frequency under consideration (eg. system frequency for the Load Flow calculation). Note that for increasing frequencies, and hence for example for harmonic Load Flow calculations, the higher the frequency the lower the length of wave, so that even a physically short line may need to be treated as a long line, and therefore be represented using distributed parameters.

To select a distributed parameter model, the corresponding model option on the Basic Data page of the line element (*ElmLne*) or line coupling (*ElmTow*) should be selected.

2.2.1 General Formulation

Equations (27) and (28) describe the incremental transmission line model in the frequency domain of an elemental length Δx depicted in Figure 2.10.

$$\frac{\partial}{\partial x}V = I(x) \cdot Z' \tag{27}$$

$$\frac{\partial}{\partial x}I = V(x) \cdot Y' \tag{28}$$

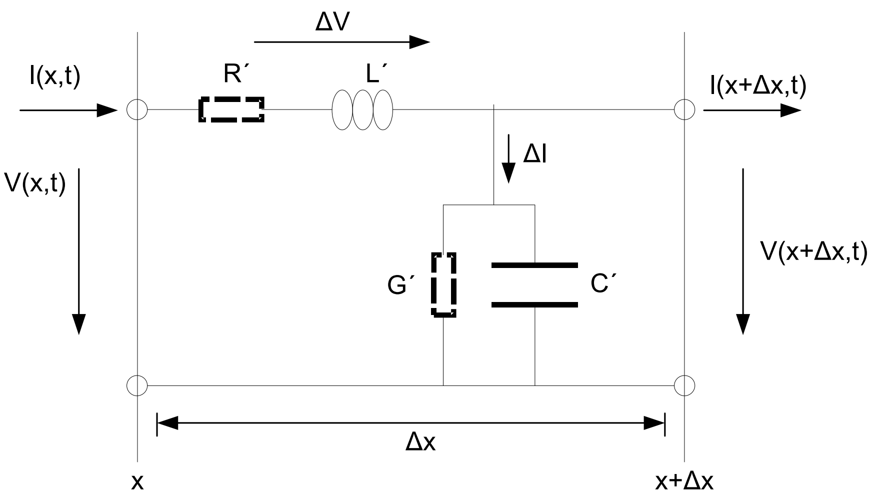

Figure 2.10: Incremental model for a line of elemental length

After taking the second derivatives of (27) and (28) with respect to x and rearranging the equations to separate the voltage from the current magnitudes, the system of differential equations can be rewritten as:

$$\frac{\partial^2}{\partial x^2}V = Z' \cdot Y' \cdot V(x)$$
$$\frac{\partial^2}{\partial x^2}I = Z' \cdot Y' \cdot I(x) \tag{29}$$

The general solution is of the form:

$$U(x) = K_1 \cdot e^{\gamma \cdot x} + K_2 \cdot e^{-\gamma \cdot x}$$
$$Z_C \cdot I(x) = -K_1 \cdot e^{\gamma \cdot x} + K_2 \cdot e^{-\gamma \cdot x} \tag{30}$$

with

$$Z_C = \sqrt{\frac{Z'}{Y'}} \tag{31}$$

$$\gamma = \sqrt{Z' \cdot Y'} = \alpha + j\beta \tag{32}$$

Both the surge (or characteristic) impedance Z_C and the propagation factor γ are frequency-dependent and uniquely characterise the behaviour of the transmission line. Further details regarding the derivation of these equations can be found in [1], [3].

The integration constants K_1 and K_2 in (30) are determined from the border conditions at either the receiving or the sending end of the line. According the sign convention in Figure 2.11, the particular solution of (30) results:

$$\begin{bmatrix} V_r \\ I_r \end{bmatrix} = \begin{bmatrix} \cosh\gamma \cdot l & -Z_C \cdot \sinh\gamma \cdot l \\ \frac{1}{Z_C} \cdot \sinh\gamma \cdot l & -\cosh\gamma \cdot l \end{bmatrix} \cdot \begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_s \\ I_s \end{bmatrix} \tag{33}$$

and therefore the impedance and admittance of the equivalent circuit are:

$$Z = Z_C \cdot \sinh\gamma \cdot l = Z' \cdot l \cdot \frac{\sinh\gamma \cdot l}{\gamma \cdot l}$$
$$Y = \frac{\cosh\gamma \cdot l - 1}{Z_C \cdot \sinh\gamma \cdot l} = \frac{1}{2} \cdot Y' \cdot l \cdot \frac{\tanh\left(\frac{\gamma \cdot l}{2}\right)}{\frac{\gamma \cdot l}{2}} \tag{34}$$

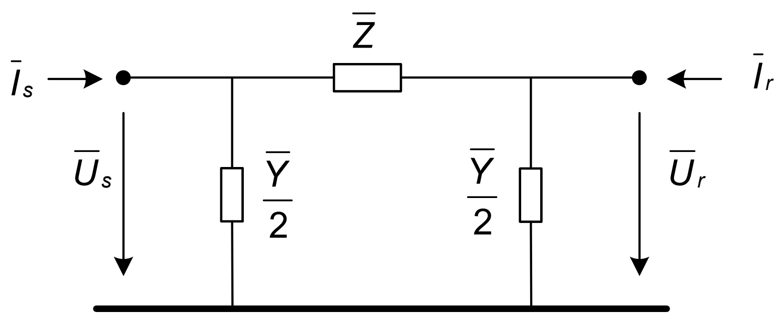

Figure 2.11: Equivalent pi-circuit for the line with distributed parameters in the frequency domain

It should be noted that Z and Y in Figure 2.11 are frequency-dependent parameters as both the surge impedance, Z_C, and the propagation factor, γ, are functions of the frequency.

Series expansion

The lumped parameter model described by (9) in Section 2.1.1 is a simplified model of the distributed parameters model. Taking a series expansion of the hyperbolic functions in (34) gives:

$$\cosh\vartheta = 1 + \frac{1}{2}\cdot\vartheta^2 + \frac{1}{24}\cdot\vartheta^4 + \frac{1}{720}\cdot\vartheta^6 + \dots$$

$$\frac{\sinh\vartheta}{\vartheta} = 1 + \frac{1}{6}\cdot\vartheta^2 + \frac{1}{120}\cdot\vartheta^4 + \frac{1}{5040}\cdot\vartheta^6 + \dots$$

Using $\vartheta = \gamma\cdot l = \sqrt{Z'\cdot Y'}\cdot l$ *A* and *B* in (33) can be expanded as follows:

$$A = \cosh\gamma\cdot l = 1 + \frac{1}{2}\cdot Z'\cdot Y'\cdot l^2 + \frac{1}{24}\cdot\left(Z'\cdot Y'\right)^2\cdot l^4 + \dots$$

$$B = Z'\cdot l\cdot\left(\frac{\sinh\gamma\cdot l}{\gamma\cdot l}\right) = Z'\cdot l\cdot\left[1 + \frac{1}{6}\cdot Z'\cdot Y'\cdot l^2 + \frac{1}{120}\cdot\left(Z'\cdot Y'\right)^2\cdot l^4 + \dots\right]$$

Considering up to the second order terms, equations (34) of the distributed parameter model go into equations (7) of the lumped parameter model:

$$Z = B = Z'\cdot l = R'\cdot l + j\omega\cdot L'\cdot l$$

$$Y = \frac{A-1}{B} = \frac{1+\frac{1}{2}\cdot Z'\cdot Y'\cdot l^2}{Z'\cdot l} = \frac{1}{2}\cdot Y'\cdot l = \frac{1}{2}\cdot\left(G'\cdot l + j\omega\cdot C'\cdot l\right)$$

The accuracy of the lumped model therefore depends on the weight of truncated terms in the series expansion, which in turns depends on the factor $f\cdot l$ (frequency multiplied by length). For overhead lines with a length less than 250km and at system frequency, this approximation is sufficient and the error is negligible. For longer lines or higher frequencies, a distributed parameter model will provide a more accurate solution.

Longer lines can be alternatively modelled by cascading line sections. In general, the longer the line or the higher the frequency, the more line sections are required in order to obtain the same accuracy. Increasing the number of line sections to infinity will turn the lumped parameter model into the distributed parameters model discussed previously.

3 Load Flow Analysis

3.1 Temperature dependency of line resistance

For a line type a temperature dependency can be defined either via the conductor material:

- Aluminium ($\alpha = 0.00403$ 1/K)
- Copper ($\alpha = 0.00393$ 1/K)
- Aldrey ($\alpha = 0.00360$ 1/K)
- Aluminium-Steel ($\alpha = 0.00403$ 1/K)
- Aldrey-Steel ($\alpha = 0.00360$ 1/K)

with a temperature coefficient α or with a resistance at max. operating temperature ($tmax$ in degC and $rline_{tmax}$ in Ohm/km)

Depending on the temperature setting e.g. in the load flow command, frequency sweep the positive sequence resistance is scaled as follow when using a line type (*TypLne*):

$$R_1^{'} = rline \cdot (1 + \alpha \cdot (temp - 20) \tag{35}$$

Note: The zero sequence resistance is not adapted.

At which temperature the resistance is modified depends on the setting e.g. of the load flow command or/and e.g. the entered operating temperature at the line.

- at 20 degC
- at max. operating temperature ($tmax$ in line type, conductor type, cable type)
- at operating temperature (Top entered in the line model)
- at temperature entered in load flow or frequency sweep command

Note: When using a tower model, and the temperature is configured as ”at operating temperature”, the earth conductor is still applied by the entered resistance at 20 degC. For lines using a cable type (*TypCabsys*), or a cable system (*TypCabsys*), the conductor, sheath and armour the corresponding temperature is applied.

3.2 AC model calculation parameters

Loading

The loading of the line/cable is calculated as follows:

$$loading = max\left(\frac{|I_{busi}|}{I_{nom(busi)}}, \frac{|I_{busj}|}{I_{nom(busj)}}\right) \cdot 100 \qquad [\%] \tag{36}$$

where:

- $I_{nom(busi)}$ is nominal current of the line/cable for terminal i in $[kA]$

- $I_{nom(busj)}$ is nominal current of the line/cable for terminal j in $[kA]$
- I_{busi} is magnitude of the current at terminal i
- I_{busj} is magnitude of the current at terminal j

If no thermal rating object is defined, the nominal current is:

$I_{nom(busi)} = I_{nom(busj)} = I_r \cdot fline$ (see equation 1 or 2).

where $fline$ is the derating factor of the line (if a thermal rating object is selected, $fline$ is not used in the calculation).

If a thermal rating object is used, the nominal currents are calculated using the parameter $ContRating$ and $U_{n(busi)}$,$U_{n(busj)}$ (nominal voltage in kV of the connected terminal i and j) as:

- if the continuous rating is entered in MVA:
  - 3-phase AC:

$$I_{nom(busi)} = ContRating/\left(\sqrt{3} \cdot U_{n(busi)}\right) \qquad [kA]$$
$$I_{nom(busj)} = ContRating/\left(\sqrt{3} \cdot U_{n(busj)}\right) \qquad [kA]$$

  - 2-phase AC:

$$I_{nom(busi)} = ContRating/U_{n(busi)} \qquad [kA]$$
$$I_{nom(busj)} = ContRating/U_{n(busj)} \qquad [kA]$$

  - 1-phase AC:

$$I_{nom(busi)} = ContRating \cdot \sqrt{3}/U_{n(busi)} \qquad [kA]$$
$$I_{nom(busj)} = ContRating \cdot \sqrt{3}/U_{n(busj)} \qquad [kA]$$

  - 1-phase connected on a AC/BI system:

$$I_{nom(busi)} = ContRating \cdot 2/U_{n(busi)} \qquad [kA]$$
$$I_{nom(busj)} = ContRating \cdot 2/U_{n(busj)} \qquad [kA]$$

- if the continuous rating is entered in kA:

$$I_{nom(busi)} = I_{nom(busi)} = ContRating \qquad [kA]$$

- if the continuous rating is entered in %:

$$I_{nom(busi)} = I_{nom(busi)} = ContRating/100 \cdot I_r \qquad [kA]$$

The nominal currents are generally the same ($I_{nom(busi)} = I_{nom(busj)}$), but not if the line/cable is connected between different voltage levels ($U_{n(busi)} \neq U_{n(busi)}$).

For an unbalanced load flow calculation the highest current of all phases is used.

Losses

The losses are calculated as:

$$Losses = (P_{busi} + P_{busj}) \cdot 1000 \qquad [kW] \tag{37}$$

where P_{busi} and P_{busj} are calculation parameters available for the branch element.

The total losses are obtained as:

$$\begin{aligned} Ploss &= P_{busi} + P_{busj} - P_{lineloads} \qquad [MW] \\ Qloss &= Q_{busi} + Q_{busj} - Q_{lineloads} \qquad [Mvar] \end{aligned} \tag{38}$$

where $P_{lineloads}$ and $Q_{lineloads}$ are the active and reactive power of the line loads.

The load losses are obtained using the no-load loss parameters:

$$\begin{aligned} Plossld &= Ploss - Plossnld \qquad [MW] \\ Qlossld &= Qloss - Qlossnld \qquad [Mvar] \end{aligned} \tag{39}$$

The no-load losses are calculated using the *Active no-load losses* $Gload$ and the *Capacitative loading* $Cload$ as follows:

$$\begin{aligned} \underline{S}_{lossnld} &= \underline{u}_{busi} \cdot (\underline{y}_{line} \cdot \underline{u}_{busi})^* + \underline{u}'_{busi} \cdot (\underline{y}_{line} \cdot \underline{u}'_{busj})^* \qquad [MVA] \\ Gload &= \Re(\underline{S}_{lossnld}) \cdot 1000 \qquad [kW] \\ Cload &= -\Im(\underline{S}_{lossnld}) \qquad [Mvar] \\ Plossnld &= Gload/1000 \qquad [MW] \\ Qlossnld &= -Cload \qquad [Mvar] \end{aligned} \tag{40}$$

where $\underline{u}_{busi}$ and $\underline{u}_{busj}$ are the terminal voltages where the line is connected in $p.u.$, $\underline{u}'_{busj} = \underline{u}_{busj} \cdot U_{n(busj)}/U_{n(busi)}$ (nominal voltages of the connected busbars) and $\underline{y}_{line}$ is the complex admittance of the line.

Voltage Drop

The voltage drop and voltage angle drops are calculated as:

$$\begin{aligned} du &= |u_{busi}| - |u_{busj}| \qquad [p.u.] \\ dupc &= du \cdot 100 \qquad [\%] \\ dphiu &= \phi_{u\_busi} - \phi_{u\_busj} \qquad [deg] \end{aligned} \tag{41}$$

and the positive-sequence voltage drop and positive-sequence voltage angle drop are calculated as:

$$\begin{aligned} d1u &= |u1_{busi}| - |u1_{busj}| \qquad [p.u.] \\ du1pc &= du1 \cdot 100 \qquad [\%] \\ dphiu1 &= \phi_{u1,busi} - \phi_{u1,busj} \qquad [deg] \end{aligned} \tag{42}$$

where u_{busi} and u_{busj} are the amplitudes of the corresponding terminal voltage in p.u. based on the rated voltage of the terminal, ϕ_{u_busi} and ϕ_{u_busj} are the terminal voltage angles in deg. For an unbalanced load flow du, $dupc$, and $dphiu$ are available per phase (e.g. $c:dupc:B$).

3.3 AC model calculation parameters for linear DC Load Flow

Loading

The loading of the line/cable is calculated as follows:

$$loading = max\left(\frac{|P_{busi}|}{P_{nom(busi)}}, \frac{|P_{busj}|}{P_{nom(busj)}}\right) \cdot 100 \qquad [\%]$$

where:

- P_{busi} : Active power at terminal i
- P_{busj} : Active power at terminal j
- $P_{nom(busi)}$: Nominal power at terminal i
- $P_{nom(busj)}$: Nominal power at terminal j

The nominal power is determined as follow when no thermal rating object is defined:

- $P_{nom(busi)} = \sqrt{3} \cdot U_{n(busi)} \cdot I_r$
- $P_{nom(busj)} = \sqrt{3} \cdot U_{n(busj)} \cdot I_r$

with the rated current of the line/cable I_r (see equation 1 or 2).
$U_{n(busi)}$, $U_{n(busj)}$ is the nominal voltage in kV of the connected terminals.

If a thermal rating object is used, the nominal power is calculated using the parameter $ContRating$ and $U_{n(busi)}$ and $U_{n(busj)}$ (nominal voltage in kV of the connected terminal i and j) as:

- if the continuous rating is entered in MVA:

$$P_{nom(busi)} = P_{nom(busj)} = ContRating \qquad [MW]$$

- if the continuous rating is entered in kA:

$$P_{nom(busi)} = \sqrt{3} \cdot U_{n(busi)} \cdot ContRating \qquad [MW]$$
$$P_{nom(busj)} = \sqrt{3} \cdot U_{n(busj)} \cdot ContRating \qquad [MW]$$

- if the continuous rating is entered in %:

$$P_{nom(busi)} = \sqrt{3} \cdot U_{n(busi)} \cdot ContRating/100 \cdot I_r \qquad [MW]$$
$$P_{nom(busj)} = \sqrt{3} \cdot U_{n(busj)} \cdot ContRating/100 \cdot I_r \qquad [MW]$$

The nominal powers are generally the same ($P_{nom(busi)} = P_{nom(busj)}$), but not if the line/cable is connected between different voltage levels ($U_{n(busi)} \neq U_{n(busi)}$).

Losses

Losses are not calculated in the linear DC Load Flow.

3.4 DC model calculation parameters

Loading

The loading of the line/cable is calculated as follows:

$$loading = max\left(\frac{|I_{busi}|}{I_{nom(busi)}}, \frac{|I_{busj}|}{I_{nom(busj)}}\right) \cdot 100 \qquad [\%]$$

- $I_{nom(busi)}$ is nominal current of the line/cable for terminal i in $[kA]$
- $I_{nom(busj)}$ is nominal current of the line/cable for terminal j in $[kA]$

- I_{busi} DC current at terminal i
- I_{busj} DC current at terminal j

If no thermal rating object is defined, the nominal current is:

$I_{nom(busi)} = I_{nom(busj)} = I_r \cdot fline$ (see equation 1 or 2).

where $fline$ is the derating factor of the line (if a thermal rating object is selected, $fline$ is not used in the calculation).

If a thermal rating object is used, the nominal currents are calculated using the parameter $ContRating$ and $U_{n(busi)}$,$U_{n(busj)}$ (nominal voltage in kV of the connected terminal i and j) as:

- if the continuous rating is entered in MVA:

$$I_{nom(busi)} = ContRating/U_{n(busi)} \qquad [kA]$$
$$I_{nom(busj)} = ContRating/U_{n(busj)} \qquad [kA]$$

- if the continuous rating is entered in kA:

$$I_{nom(busi)} = I_{nom(busj)} = ContRating \qquad [kA]$$

- if the continuous rating is entered in %:

$$I_{nom(busi)} = I_{nom(busj)} = ContRating/100 \cdot I_r \qquad [kA]$$

The nominal currents are generally the same ($I_{nom(busi)} = I_{nom(busj)}$), but not if the line/cable is connected between different voltage levels ($U_{n(busi)} \neq U_{n(busi)}$).

Losses

The losses are calculated as:

$$Losses = (P_{busi} + P_{busj}) \cdot 1000 \qquad [kW] \tag{43}$$

where P_{busi} and P_{busj} are calculation parameters available for the branch element.

The total losses are obtained as:

$$\begin{aligned} Ploss &= P_{busi} + P_{busj} \qquad [MW] \\ Qloss &= 0 \qquad [Mvar] \end{aligned} \tag{44}$$

The load losses are obtained using the no-load loss parameters:

$$\begin{aligned} Plossld &= Ploss - Plossnld \qquad [MW] \\ Qlossld &= 0 \qquad [Mvar] \end{aligned} \tag{45}$$

The no-load losses are calculated using the *Active no-load losses* $Gload$ as follows:

$$\begin{aligned} Gload &= (1/2 \cdot glne \cdot U_{busi}^2 + 1/2 \cdot glne \cdot U_{busj}^2) \cdot 1000 \qquad [kW] \\ Cload &= 0 \qquad [Mvar] \\ Plossnld &= Gload/1000 \qquad [MW] \\ Qlossnld &= 0 \qquad [Mvar] \end{aligned} \tag{46}$$

where $glne$ is the admittance (calculation parameter) of the line and U_{busi} and U_{busj} are the terminal DC voltages where the line is connected.

4 EMT Simulations

The models described in the previous sections are defined in the frequency domain and used in *PowerFactory* for all steady-state calculations such as load flow, short-circuit, harmonic load flow, frequency sweep, and the electromechanical (RMS) simulation.

This section introduces the models used in the electromagnetic transients (EMT) simulation. These models are obtained via the conversion of frequency-domain models into time-domain models.

4.1 Lumped Parameter Model

The lumped parameter model discussed in Section 2.1 can be directly used in EMT simulations by replacing the $j\omega$ operator by d/dt and thus the impedances and admittances by the corresponding inductances and susceptances.

For the pi-equivalent circuit in Figure 2.1, equations (3), (4) and (5) then become:

$$\begin{bmatrix} u_{s,A} \\ u_{s,B} \\ u_{s,C} \end{bmatrix} - \begin{bmatrix} u_{r,A} \\ u_{r,B} \\ u_{r,C} \end{bmatrix} = \begin{bmatrix} \Delta u_A \\ \Delta u_B \\ \Delta u_C \end{bmatrix} = \begin{bmatrix} R_s & R_m & R_m \\ R_m & R_s & R_m \\ R_m & R_m & R_s \end{bmatrix} \cdot \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L_s & L_m & L_m \\ L_m & L_s & L_m \\ L_m & L_m & L_s \end{bmatrix} \cdot \frac{d}{dx} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \tag{47}$$

$$\begin{bmatrix} \Delta i_{s,A} \\ \Delta i_{s,B} \\ \Delta i_{s,C} \end{bmatrix} = \frac{1}{2} \left(\begin{bmatrix} G_s & G_m & G_m \\ G_m & G_s & G_m \\ G_m & G_m & G_s \end{bmatrix} \cdot \begin{bmatrix} u_{s,A} \\ u_{s,B} \\ u_{s,C} \end{bmatrix} + \begin{bmatrix} C_s & C_m & C_m \\ C_m & C_s & C_m \\ C_m & C_m & C_s \end{bmatrix} \cdot \frac{d}{dx} \begin{bmatrix} u_{s,A} \\ u_{s,B} \\ u_{s,C} \end{bmatrix} \right) \tag{48}$$

$$\begin{bmatrix} \Delta i_{r,A} \\ \Delta i_{r,B} \\ \Delta i_{r,C} \end{bmatrix} = \frac{1}{2} \left(\begin{bmatrix} G_s & G_m & G_m \\ G_m & G_s & G_m \\ G_m & G_m & G_s \end{bmatrix} \cdot \begin{bmatrix} u_{r,A} \\ u_{r,B} \\ u_{r,C} \end{bmatrix} + \begin{bmatrix} C_s & C_m & C_m \\ C_m & C_s & C_m \\ C_m & C_m & C_s \end{bmatrix} \cdot \frac{d}{dx} \begin{bmatrix} u_{r,A} \\ u_{r,B} \\ u_{r,C} \end{bmatrix} \right) \tag{49}$$

4.2 Distributed Parameter Model

The distributed parameter model cannot be directly used for EMT simulations because the elements of the equivalent circuit are a function of the frequency, as shown in equations (34). To make the model usable for EMT simulations, further assumptions have to be made. The resulting distributed parameters models are described below.

The EMT models of distributed parameter lines are based on Bergeron's method for solution in the time domain. The following options are supported:

- Constant parameter model
- Frequency-dependent parameter model

- Frequency-dependent parameter model (Universal Line Model)

These options and their associated settings can be found on the *EMT-Simulation* page of the line element (*ElmLne*) and the line coupling (*ElmTow*) element.

4.2.1 Bergeron's Method for Solution in the Time Domain

Considering the border conditions depicted in Figure 2.11, (30) can be written as:

$$U_r = \left(\frac{U_s - I_s \cdot Z_C}{2}\right) \cdot e^{\gamma \cdot l} + \left(\frac{U_s - I_s \cdot Z_C}{2}\right) \cdot e^{-\gamma \cdot l} \tag{50}$$

$$Z_C \cdot I_r = \left(\frac{U_s - I_s \cdot Z_C}{2}\right) \cdot e^{\gamma \cdot l} - \left(\frac{U_s + I_s \cdot Z_C}{2}\right) \cdot e^{-\gamma \cdot l} \tag{51}$$

and subtracting 51 from 50:

$$U_r - Z_C \cdot I_r = (U_s + Z_C \cdot I_s) \cdot e^{-\gamma \cdot l} \tag{52}$$

or rewritten as

$$I_r = \frac{U_r}{Z_C} - \left(I_s + \frac{U_s}{Z_C}\right) \cdot e^{-\gamma \cdot l} \tag{53}$$

The expression $U + Zc \cdot I$ of the border condition at the sending end, *s*, is the same at the receiving end, *r*, after multiplication with the propagation factor $e^{-\gamma \cdot l}$.

By repeating this procedure and setting the initial conditions at node r, and then travelling with the wave from node r to node s, we obtain:

$$U_s - Z_C \cdot I_s = (U_r + Z_C \cdot I_r) \cdot e^{-\gamma \cdot l} \tag{54}$$

or rewritten as

$$I_s = \frac{U_s}{Z_C} - \left(I_r + \frac{U_r}{Z_C}\right) \cdot e^{-\gamma \cdot l} \tag{55}$$

Equations (52) and (54), or equations (53) and (55), define Bergeron's equations in the frequency domain. The method models the line using controlled current sources, *J*, with parallel admittances, Y_C, at both ends as shown in Figure 4.1 or alternatively, using a controlled voltage source, *V*, in series with the impedance, Z_C, as shown in Figure 4.2, where:

$$J_r = \left(I_r + \frac{U_r}{Z_C}\right) \cdot e^{-\gamma l} \tag{56}$$

$$V_r = (U_r + I_r \cdot Z_C) \cdot e^{-\gamma l} \tag{57}$$

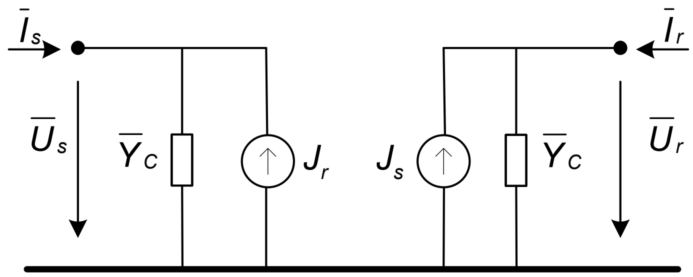

Figure 4.1: Bergeron's method: equivalent circuit with controlled current sources

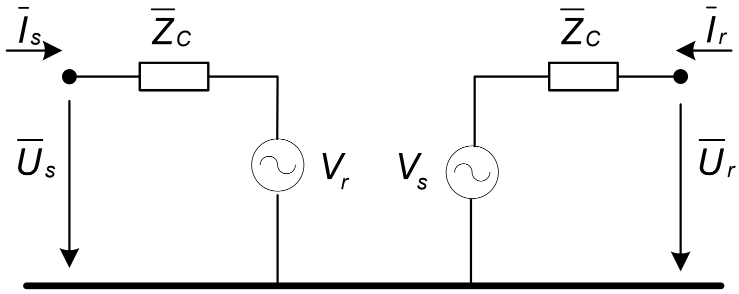

Figure 4.2: Bergeron's method: equivalent circuit with controlled voltage sources

The inverse Fourier transform is applied to transform the set of equations into the time domain:

$$u_s(t) = F^{-1}\left\{Z_C \cdot I_s + (U_r + Z_C \cdot I_r) \cdot e^{-\gamma \cdot l}\right\} \tag{58}$$

$$u_r(t) = F^{-1}\left\{Z_C \cdot I_r + (U_s + Z_C \cdot I_s) \cdot e^{-\gamma \cdot l}\right\} \tag{59}$$

or rewritten:

$$i_s(t) = F^{-1}\left\{\frac{U_s}{Zc} - \left(I_r + \frac{U_r}{Zc}\right) \cdot e^{-\gamma \cdot l}\right\} \tag{60}$$

$$i_r(t) = F^{-1}\left\{\frac{U_r}{Zc} - \left(I_s + \frac{U_s}{Zc}\right) \cdot e^{-\gamma \cdot l}\right\} \tag{61}$$

where both the characteristic impedance:

$$Z_C = Z_C(\omega) = \sqrt{\frac{R' + j\omega \cdot L'}{G' + j\omega \cdot C'}} \tag{62}$$

and the propagation constant:

$$\gamma = \gamma(\omega) = \alpha(\omega) + j\beta(\omega) = \sqrt{(R' + j\omega \cdot L') \cdot (G' + j\omega \cdot C')} \tag{63}$$

are frequency dependent, even for constant per unit length line parameters R', L', G' and C'.

4.2.2 Constant Parameter Model

The constant distributed parameter model in *PowerFactory* is based on Bergeron's method, which calculates the voltages and currents at one end of the line based on the voltage and current at the other end delayed in time (i.e. the history term). Specifically, *PowerFactory* uses the lossy constant distributed parameter model described in [3]. This model is valid for lossy lines with a series resistance, R', and a negligible shunt conductance. These kinds of lines can then be modelled as single or multiple sections of lossless lines with resistances lumped in three places: $R/4$ at both ends of the line, and $R/2$ in the middle [3]. This model provides sufficient accuracy only if $R/4 << Z$, and hence should not be used for lines with very high resistance. *PowerFactory* emits an error when $R/4 > Z$, and a warning when $R/4 > 0.05 \cdot Z$.

The surge impedance is no longer calculated according to (62), but instead as:

$$Z_C = \sqrt{\frac{L'}{C'}} \tag{64}$$

being real and constant. The damping coefficient $\alpha = 0$, and hence from (63):

$$\gamma = j\beta = j\omega\sqrt{L' \cdot C'} \tag{65}$$

The propagation velocity is the same regardless of frequency and is given by:

$$v = \frac{\omega}{\beta} = \frac{1}{\sqrt{L' \cdot C'}} \tag{66}$$

which allows the following definition of a travel time (frequency independent):

$$\tau = \frac{l}{v} = l \cdot \sqrt{L' \cdot C'} \tag{67}$$

In terms of travel time, the propagation constant can be rewritten as:

$$\gamma \cdot l = j\beta \cdot l = j\omega\sqrt{L' \cdot C'} \cdot l = j\omega \cdot \tau \tag{68}$$

and after simplifications we can rewrite (58) and (59) as:

$$\begin{aligned} U_s &= Z_C \cdot I_s + V_r \\ U_r &= Z_C \cdot I_r + V_s \end{aligned} \tag{69}$$

with:

$$\begin{aligned} V_r &= (U_r + Z_C \cdot I_r) \cdot e^{-j\omega \cdot \tau} \\ V_s &= (U_s + Z_C \cdot I_s) \cdot e^{-j\omega \cdot \tau} \end{aligned} \tag{70}$$

The inverse Fourier transform of the phase shift $e^{-j\omega \cdot \tau}$ in the frequency domain becomes a delay τ in the time domain, and the set of equations (69) and (70) transforms to:

$$\begin{aligned} u_s(t) &= Z_C \cdot i_s(t) + u_s(t - \tau) \\ u_r(t) &= Z_C \cdot i_r(t) + u_r(t - \tau) \end{aligned} \tag{71}$$

where the history terms are defined as:

$$\begin{aligned} u_s(t-\tau) &= u_r(t-\tau) + Z_C \cdot i_r(t-\tau) \\ u_r(t-\tau) &= u_s(t-\tau) + Z_C \cdot i_s(t-\tau) \end{aligned} \tag{72}$$

This can be reformulated in terms of current sources:

$$\begin{aligned} i_s(t) &= \tfrac{u_s(t)}{Z_C} + i_s(t-\tau) \\ i_r(t) &= \tfrac{u_r(t)}{Z_C} + i_r(t-\tau) \end{aligned} \tag{73}$$

where the history terms are defined as:

$$\begin{aligned} i_s(t-\tau) &= -\tfrac{u_r(t-\tau)}{Z_C} - i_r(t-\tau) \\ i_r(t-\tau) &= -\tfrac{u_s(t-\tau)}{Z_C} - i_s(t-\tau) \end{aligned} \tag{74}$$

The lumping of resistances according to the lossy model requires the modification of the impedance according to [3]:

$$Z_{mod} = Z + \frac{R}{4} \tag{75}$$

where Z is calculated according to (64). This results in the following modifications to the history terms in (74) [3]:

$$\begin{aligned} i_s(t-\tau) &= -\tfrac{Z}{Z_{mod}^2}[u_r(t-\tau) + (Z - \tfrac{R}{4}) \cdot i_r(t-\tau)] - \tfrac{R/4}{Z_{mod}^2}[u_s(t-\tau) + (Z - \tfrac{R}{4}) \cdot i_s(t-\tau)] \\ i_r(t-\tau) &= -\tfrac{Z}{Z_{mod}^2}[u_s(t-\tau) + (Z - \tfrac{R}{4}) \cdot i_s(t-\tau)] - \tfrac{R/4}{Z_{mod}^2}[u_r(t-\tau) + (Z - \tfrac{R}{4}) \cdot i_r(t-\tau)] \end{aligned} \tag{76}$$

In *PowerFactory* , the settings for this model can be adjusted on the *EMT-Simulation* page of the line element (*ElmLne*) or line coupling element (*ElmTow*) as follows:

- Line Model: Constant parameter
- Frequency for travel time estimation: enter a representative frequency for the transient under analysis. This frequency is used in (47) to calculate the propagation constant. In the case of a non-transposed line, the modal transformation matrix will also be calculated at this frequency.

Note*: press the* Calculate Line Parameters *button any time you modify these parameters.* PowerFactory *will then calculate the propagation factor and the surge impedance at the specified frequency and initialise the model.*

4.2.3 Frequency Dependent Parameter (Modal) Model

With the exception of lossless and distortion-less lines, the characteristic impedance, Z_C, and propagation constant, γ, are frequency dependent. The variation of Zc and γ with frequency is most pronounced in the zero sequence mode and hence frequency-dependent models should be used when zero sequence currents or voltages are involved (i.e. in a single phase-to-ground fault).

Approximation by Rational Functions

To handle frequency-dependent parameters, *PowerFactory* uses the approach proposed by J. Marti [3, 7]. The characteristic impedance and the propagation factor are developed in rational functions and then the poles and zeros of the rational expressions calculated using a Bode approximation.

For the propagation factor, $A(\omega) = e^{-\gamma(\omega)\cdot l}$:

$$A_{app}(s) = e^{-s\cdot\tau_{\min}} \cdot k \cdot \frac{(s+z_1)\cdot(s+z_2)\ldots(s+z_n)}{(s+p_1)\cdot(s+p_2)\ldots(s+p_m)} \tag{77}$$

with $s = j\omega$ and $n < m$.

Similarly for the characteristic impedance, Z_C:

$$Z_{c-app}(s) = k \cdot \frac{(s+z_1)\cdot(s+z_2)\ldots(s+z_n)}{(s+p_1)\cdot(s+p_2)\ldots(s+p_n)} \tag{78}$$

with $s = j\omega$. This expression can then be expanded into partial fractions:

$$Z_{c-app}(s) = k_0 + \frac{k_1}{(s+p_1)} + \frac{k_2}{(s+p_2)} \cdots \frac{k_n}{(s+p_n)} \tag{79}$$

The accuracy of the model depends on the quality of the rational function approximations for A and Zc. To verify the approximation *PowerFactory* provides plots the exact and approximated solutions of A and Z_c on the *EMT-Simulation* page (*Mode* tabs) of the line (*ElmLne*) and line coupling (*ElmTow*) elements as shown in Figure 4.3. Note that the plots for each mode are displayed on their own tabbed pages. Right click on the plot to zoom in and out.

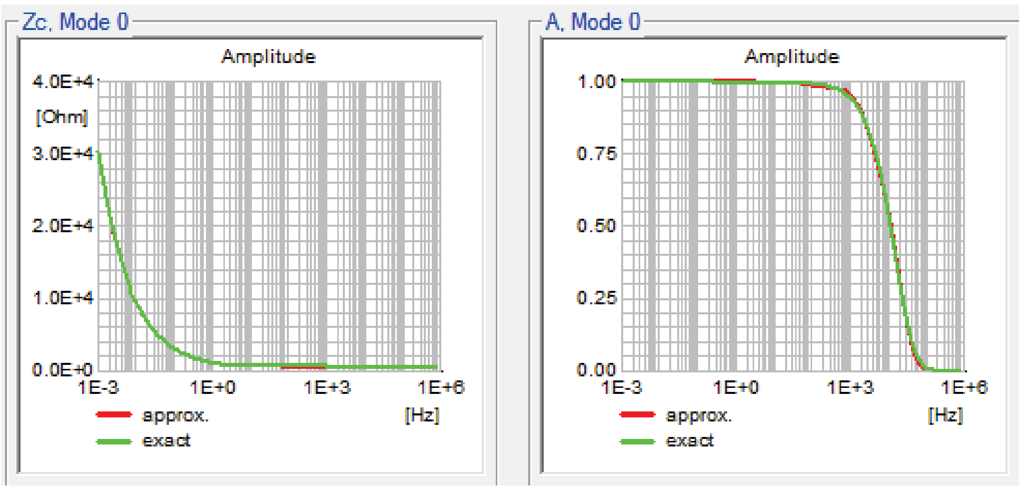

Figure 4.3: Bode approximations of A and Zc for the zero-sequence

Solution in the Time Domain

In this section, only equations for the equivalent circuit with current sources are described. Similar equations are used for the equivalent circuit with voltage sources.

Explicitly writing the frequency-dependent parameters, the input current at node *s* is:

$$I_s = \frac{U_s}{Z_C(\omega)} + J_r(\omega)$$

$$J_r(\omega) = -\left(I_r + \frac{U_r}{Z_C}\right) \cdot A(\omega)$$

The inverse Fourier transform of the controlled current source, J_r, can be evaluated by means of the convolution integral and hence:

$$j_r(t) = -\int_0^{\infty} \left[i_r(t-u) + \frac{i_r(t-u)}{Z_c}\right] \cdot a(u) \cdot du \tag{80}$$

with $a(t) = F^{-1}\{A(\omega)\}$, $\tau\min$ is the travel time of the fastest waves and $\tau\max$ is the travel time of the slowest waves. The convolution integral then only needs to be evaluated between $\tau\min$ and $\tau\max$ because $a(t)$ is zero up to $t = \tau\min$ and tends to zero for $t \to \tau\max$.

$a(t)$ is the inverse Fourier transform of $A(\omega)$. After $A(\omega)$ is expanded into partial fractions, the inverse Fourier transform then becomes a sum of exponentials:

$$a_{app}(t) = \begin{cases} 0 & \text{for } t < \tau_{\min} \\ k_1 e^{-p_1(t-\tau_{\min})} + k_2 e^{-p_2(t-\tau_{\min})} \ldots k_m e^{-p_m(t-\tau_{\min})} & \text{for } t \geq \tau_{\min} \end{cases} \tag{81}$$

Similarly, the inverse Fourier transform of (79) results in exponential terms of the form $e^{-t/RC}$ that corresponds to an RC network as shown in Figure 4.4 where:

$$R_0 = k_0 \;\; and \;\; R_i = \frac{k_i}{p_i}, \;\; C_i = \frac{1}{k_i} \;\; with \;\; i = 1 \ldots n \tag{82}$$

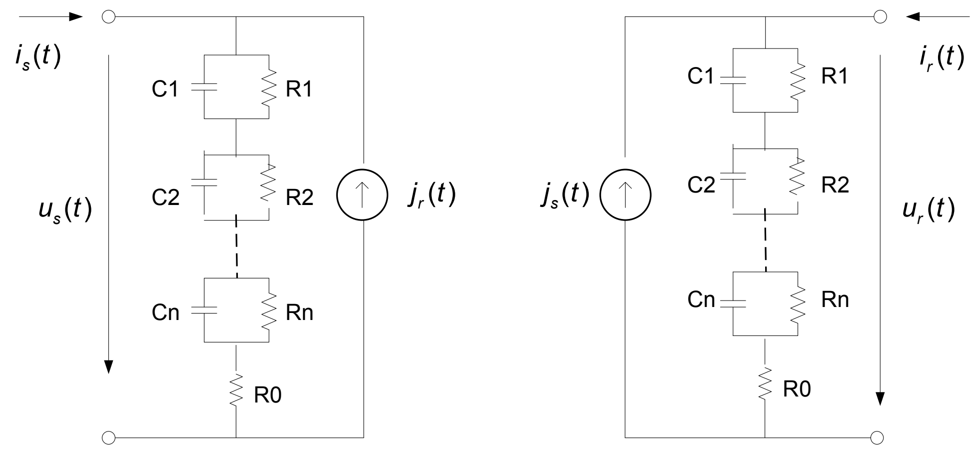

Figure 4.4: Equivalent circuit for the frequency-dependent parameter model

Then with $a(t)$ being a sum of exponential functions and Z_c developed as an RC-network, equation (80) can be solved using recursive convolution.

Data for the distributed frequency-dependent parameters model can be adjusted on the *EMT-Simulation* page of the line element (*ElmLne*) or line coupling element (*ElmTow*) as follows:

- Line Model: Frequency dependent parameter

- Frequency for travel time estimation: enter a representative frequency for the transient under analysis. The modal transformation matrix is calculated at this frequency, and afterwards remains real and constant.
- Min and Max. Frequency of parameter fitting: enter the minimum and maximum frequency for the approximation by rational functions of the propagation factor (70) and the characteristic impedance (73).
- Tolerance for Bode approximation: the maximum allowable error in % for the Bode approximation of the propagation factor (70) and the characteristic impedance (73). The lower the tolerance the higher the number poles and zeros of the approximated rational expressions.

Note*: press the* Calculate Line Parameters *button any time you modify these parameters or enter new ones.* PowerFactory *will then calculate the propagation factor and the characteristic impedance at the specified frequency and set up the model.*

4.2.4 Frequency Dependent Phase-Domain Models

In general, transmission lines can be characterised by two frequency-dependent matrix transfer functions:

- The propagation function, $\mathbf{A}(\omega)$
- The characteristic admittance, $\mathbf{Y}_c(\omega)$ (or characteristic impedance $\mathbf{Z}_c(\omega)$)

These are expressed mathematically as:

$$\mathbf{A} = e^{-\sqrt{\mathbf{YZ}}\cdot l} \tag{83}$$

and

$$\mathbf{Y}_c = \mathbf{Z}^{-1} \cdot \sqrt{\mathbf{ZY}} \tag{84}$$

where $\mathbf{Z}$ and $\mathbf{Y}$ are the impedance and admittance matrices, respectively, and l is the line length. The time-domain simulation could be formulated using the inverse Fourier transform of the above functions and then solving the associated equations in the time domain using numerical convolution. However, the preferred time-domain solution uses rational function approximations of low order to ensure a computationally-efficient solution. In *PowerFactory*, these rational function approximations are obtained using vector fitting [5].

4.2.4.1 Rational Function Approximation

The accuracy of the rational function approximations of $\mathbf{A}$ and $\mathbf{Y}_c$ (or $\mathbf{Z}_c$) strongly influences the quality of the time-domain solution. The fitting of $\mathbf{A}$ and $\mathbf{Y}_c$ (or $\mathbf{Z}_c$) in the phase domain means that the phase-domain transfer functions will be intrinsically stable [4].

4.2.4.2 Approximation of $\mathbf{Y}_c$ or $\mathbf{Z}_c$

The characteristic admittance, $\mathbf{Y}_c$, (or characteristic impedance, $\mathbf{Z}_c$), are smooth functions of frequency, hence the fitting is straightforward and can be carried out directly in the phase domain

[2]. The trace of $\mathbf{Y}_c$ is fitted in order to calculate the poles, and the residues are subsequently calculated per element (k,l) of $\mathbf{Y}_c$ using the following approximation:

$$(\mathbf{Y}_c(s))_{k,l} = d + \sum_{m=1}^{N} \frac{r_{i,m}}{s - p_{i,m}} \tag{85}$$

where constant d is real, N is the number of poles, $r_{i,m}$ are the residues, and $p_{i,m}$ are the poles. The residues and poles may be real or in complex conjugate pairs. Fitting is performed in the phase domain using vector fitting, and all elements of $\mathbf{Y}_c$ get identical poles. This procedure is used for the fitting of $\mathbf{Y}_c$ (or $\mathbf{Z}_c$) for both the ULM and FDM.

4.2.4.3 Universal Line Model

The Universal Line Model (ULM) proposed in [2] offers high accuracy and a phase-domain formulation.

Approximation of $\mathbf{A}$ The fitting of the propagation function, $\mathbf{A}$, is difficult because it contains modal components which have differing time delays [2]. In practicality, the differences in the time delays can be significant in the case of cables. This is due to the different permittivities in the insulation. Hence, the approximation of $\mathbf{A}$ is performed using a two-step approach; (i) fitting in the modal domain; followed by (ii) final fitting in the phase domain.

Modal-Domain Fitting of $\mathbf{A}$: The modes of $\mathbf{A}$ are calculated using a frequency-dependent transformation matrix, $\mathbf{T}$. The modal-domain fitting is comprised of three procedures:

Backwinding: Multiplication with a factor, $e^{(j\cdot\omega\cdot\tau)}$, in order to remove most of the oscillatory behaviour of the elements of $\mathbf{A}$. These elements are oscillating functions of frequency due to the time delay of the line [4]. The diagonal elements of the modal propagation matrix, $\mathbf{A}^m$, can be expressed as [8]:

$$a_i^m(\omega) = e^{-\alpha_i(\omega)+j\cdot\frac{\omega}{v_i(\omega)}\cdot l} \tag{86}$$

where α is the attenuation, v is the velocity, j is the imaginary unit and l is the line length. Each mode i is approximated by:

$$a_i^m(s) \approx \sum_{m=1}^{N} \frac{r_{i,m}}{s - p_{i,m}} \cdot e^{-s\cdot\tau_i} \tag{87}$$

where N is the number of poles for mode i, $r_{i,m}$ are the residues, and $p_{i,m}$ are the poles. The residues and poles may be real or in complex conjugate pairs.

Collapsing: The process of replacing modes having almost equal time delays with a single mode equal to the average of the modes. The criterion used for the formation of groups is provided in [2]. The concept of "groups" thereby replaces that of modes.

Fitting: Vector fitting is used to obtain the rational function approximation and all poles contribute to all elements of $\mathbf{A}$.

Phase-Domain Fitting of $\mathbf{A}$: The final fitting of $\mathbf{A}$ (i.e. the calculation of residues) is done in the phase domain using the poles and time delays found via fitting in the modal domain. Each element has the form:

$$\mathbf{A}(s) \approx \sum_{i=1}^{n}(\sum_{m=1}^{N} \frac{r_{i,m}}{s - p_{i,m}}) \cdot e^{-s\cdot\tau_i} \tag{88}$$

where n is now the number of groups, and the poles, $p_{i,m}$, and the time delays, τ_i are known.

4.2.4.4 Frequency Dependent Model (FDM)

The Frequency Dependent Model (FDM) introduced in [6] offers improved accuracy and stability via the simultaneous fitting of poles and residues in the phase domain. High residue-pole ratios are thereby avoided, making the FDM less prone to divergence due to such high ratios in EMT simulations.

Approximation of $\mathbf{A}$ The difficulties associated with the fitting of the propagation function, $\mathbf{A}$, were mentioned in Section 4.2.4.3. The approximation of $\mathbf{A}$ for the FDM is performed by fitting the modal contributions in the phase domain using a common set of poles for each modal contribution, i, below. The poles and residues of $\mathbf{A}$ are obtained simultaneously, as follows:

$$\mathbf{A}(s) \cong \sum_{i=1}^{n} \hat{\mathbf{A}}_i \cdot e^{-s \cdot \tau_i} \tag{89}$$

where n is the number of modal contribution groups. Fitting is then performed with the constant time delay, τ_i, removed:

$$\hat{\mathbf{A}}_i(s) \approx \sum_{j=1}^{M_i} \frac{\mathbf{R}_{i,j}}{s - p_{i,j}} \tag{90}$$

where M_i is the order of the approximation for the ith modal propagation function.

Fitting Procedure The following steps are repeated, increasing the number of poles until either: (i) the user-defined RMS error threshold has been met; or (ii) the user-defined maximum number of poles has been reached:

1. Vector fitting is applied iteratively to reduce the RMS error. Iteration stops if either the user-defined maximum RMS error or the user-defined maximum number of iterations is reached.
2. If using option *Increase and flip unstable poles*, unstable poles are flipped to the left-half plane and the RMS error is recalculated based on the resulting set of poles. This generally worsens the RMS error, as expected.
3. If using option *Increase until rms error is met*, the RMS error is calculated based on the unadjusted set of poles. This generally results in a lower RMS error than the previous option, however sometimes at the cost of unstable poles which can result in time-domain divergence in some cases.
4. For both of these options, if the RMS error does not meet the RMS error threshold, the number of poles is increased, and the algorithm continues from the first step.

Following the fitting process, *PowerFactory* reports the RMS error and the poles obtained by vector fitting (if option *Output poles* is selected).

The stability of the time-domain solution is dependent not only upon the accuracy of the rational function approximation (i.e. the resulting RMS error), but also upon the proximity of the poles to each other, and the ratio between residue and pole.

For $\mathbf{Y}_c$ and $\mathbf{Z}_c$, a worse RMS error is usually obtained when fitting starting at very low frequencies, and a better RMS error is usually obtained using a higher-order approximation (i.e. more poles).

For $\mathbf{A}$, a low number of poles is usually sufficient for accurate time-domain simulation, which assists in avoiding high residue-to-pole ratios that tend to occur with higher-order approximations (in particular for the ULM).

4.3 Diagonalisation

The modal-domain models presented in §4.2 implicitly assume a single-phase line. In reality however, distributed parameter models are required for three-phase long lines or for transmission systems with multiple 3-phase circuits. To handle this, equations (47) - (49) have to be diagonalised. After diagonalisation, the mutually-coupled equations of the 3-phase system transform to 3 independent, and hence decoupled, single-phase systems.

The diagonalisation in *PowerFactory* is carried out as follows:

- Balanced lines: the impedance and admittance matrices of these lines are diagonal-cyclic, i.e. Z/Y-matrices of the form (6). This is normally the case for transposed lines. To diagonalise the matrices, *PowerFactory* uses the transformation into symmetrical components according to (12). The transformation matrix is known a-priori and is constant (not frequency dependent).
- Unbalanced lines: this is typically the case for untransposed lines. The Z/Y-matrices are no longer diagonal-cyclic; hence to diagonalise them, a transformation into modal components is required. In this case, the transformation matrices are not known a-priori but are determined from an eigenvalue and eigenvector calculation. In this case, the transformation matrices are frequency dependent.

For unbalanced lines and steady-state calculations (i.e. harmonic load flow or frequency sweep), *PowerFactory* calculates the transformation matrices, and therefore the eigenvalues and eigenvectors, at each frequency of interest to account for the frequency dependency of the transformation matrices.

In the EMT-Simulation, the transformation matrix is calculated at a single frequency, i.e. at the one specified by the user on the *EMT-Simulation* page of the *ElmLne* or *ElmTow* element dialog. The transformation matrix then remains constant. Furthermore the approximation of the complex transformation matrix (eigenvectors) is made only using the real part.

A Parameter Definitions

Table A.1: Input parameter of the line type (*TypLne*)

Name	Description	Unit	Range	Default	Symbol
loc_name	Name				
uline	Rated Voltage	kV	x>=0	0	
sline	Rated Current	kA	x>0	1	
InomAir	Rated Current (in air)	kA	x>0	1	
frnom	Nominal Frequency	Hz	x>=0	50	
aohl_	Cable / OHL (overhead line)			cab	
systp	System Type		AC:DC	AC	
nlnph	No. of Phases		01:02:03	3	
nneutral	No. of Neutrals		00:01	0	
rline	Parameters per Length 1,2-Sequence: Resistance R' (20°C)	Ohm/km	x>=0	0	$R_1^{'}$
xline	Parameters per Length 1,2-Sequence: Reactance X'	Ohm/km		0	$X_1^{'}$
lline	Parameters per Length 1,2-Sequence: Inductance L'	mH/km	x>=0	0	$L_1^{'}$
rline0	Parameters per Length Zero Sequence: Resistance R0'	Ohm/km	x>=0	0	$R_0^{'}$
xline0	Parameters per Length Zero Sequence: Reactance X0'	Ohm/km	x>=0	0	$X_0^{'}$
lline0	Parameters per Length Zero Sequence: Inductance L0'	mH/km	x>=0	0	$L_0^{'}$
rnline	Parameters per Length, Neutral: Resistance Rn'	Ohm/km	x>=0	0	$R_n^{'}$
xnline	Parameters per Length, Neutral: Reactance Xn'	Ohm/km	x>=0	0	$X_n^{'}$
lnline	Parameters per Length, Neutral: Inductance Ln'	mH/km	x>=0	0	$L_n^{'}$
rpnline	Parameters per Length, Phase-Neutral Coupling: Resistance Rpn'	Ohm/km	x>=0	0	$R_{pn}^{'}$
xpnline	Parameters per Length, Phase-Neutral Coupling: Reactance Xpn'	Ohm/km	x>=0	0	$X_{pn}^{'}$
lpnline	Parameters per Length, Phase-Neutral Coupling: Inductance Lpn'	mH/km	x>=0	0	$L_{pn}^{'}$
tmax	Parameters per Length 1,2-Sequence: Max. Operational Temperature	°C	x>=20	80	
rline_tmax	Parameters per Length 1,2-Sequence: Resistance R' at max. operational temperature	Ohm/km	x>=0	0	

alpha	Parameters per Length 1,2-Sequence: Temperature Coefficient	1/K	x>=0	0.00403	α
mlei	Parameters per Length 1,2-Sequence: Conductor Material			Al	
bline	Parameters per Length 1,2-Sequence: Susceptance B'	uS/km		0	$B_1^{'}$
cline	Parameters per Length 1,2-Sequence: Capacitance C'	uF/km		0	$C_1^{'}$
tline	Parameters per Length 1,2-Sequence: Ins. Factor			0	$tg\delta_1$
gline	Parameters per Length 1,2-Sequence: Conductance G'	uS/km		0	$G_1^{'}$
bline0	Parameters per Length Zero Sequence: Susceptance B0'	uS/km		0	$B_0^{'}$
cline0	Parameters per Length Zero Sequence: Capacitance C0'	uF/km		0	$C_0^{'}$
Ices	Parameters per Length Zero Sequence: Earth-Fault Current	A/km		0	
tline0	Parameters per Length Zero Sequence: Ins. Factor			0	$tg\delta_0$
gline0	Parameters per Length Zero Sequence: Conductance G0'	uS/km		0	$G_0^{'}$
bnline	Parameters per Length, Neutral: Susceptance Bn'	uS/km	x>=0	0	$B_n^{'}$
cnline	Parameters per Length, Neutral: Capacitance Cn'	uF/km	x>=0	0	$C_n^{'}$
bpnline	Parameters per Length, Phase-Neutral Coupling: Susceptance Bpn'	uS/km	x>=0	0	$B_{pn}^{'}$
cpnline	Parameters per Length, Phase-Neutral Coupling: Capacitance Cpn'	uF/km	x>=0	0	$C_{pn}^{'}$
rtemp	Max. End Temperature	°C	x>0	80	
Ithr	Rated Short-Time (1s) Current (Conductor)	kA	x>=0	0	
picIn	Inrush Peak Current: Ratio Ip/In	p.u.		0	
pitIn	Inrush Peak Current: Maximum Time	s		0	
fcharC1	Frequency Dependency of Pos.-Sequence Capacitance: C1'(f) (ChaPol,ChaVec,ChaMat)				
fcharC0	Frequency Dependency of Zero-Sequence Capacitance: C0'(f) (ChaPol,ChaVec,ChaMat)				
fcharR1	Frequency Dependencies of Pos.-Sequence Impedance: R1'(f) (ChaPol,ChaVec,ChaMat)				

fcharL1	Frequency Dependencies of Pos.-Sequence Impedance: L1'(f) (ChaPol,ChaVec,ChaMat)				
fcharR0	Frequency Dependencies of Zero-Sequence Impedance: R0'(f) (ChaPol,ChaVec,ChaMat)				
fcharL0	Frequency Dependencies of Zero-Sequence Impedance: L0'(f) (ChaPol,ChaVec,ChaMat)				
pStoch	Stochastic model (StoTyplne)				
manuf	Manufacturer				
chr_name	Characteristic Name				
for_name	Foreign Key				
dat_src	Data source			MAN	
doc_id	Additional Data ()				
desc	Description				
miso	Insulation Material				
iopt_cnd	Cable is			mlt	
cmeth	Installation Method (IEC 364)			C	
iopt_ord	Conductors			tre	
qurs	Nominal Cross Section	mm*2		0	
cabdiam	Outer Diameter	mm		0	
iopt_dir	Arrangement			hor	
lcost	Line Cost	$/km	x>=0	0	

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