POWERFACTORY

PowerFactory 2021

Technical Reference

External Grid

ElmXnet

PF2021

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

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Contents

1 General Description

The *PowerFactory* External Grid Element *ElmXnet* is used to represent external networks. The models used in the different calculation functions are described in the following chapters.

2 Load Flow Model

The model used for the Load Flow calculation depends upon the selected bus type:

- PQ Bus Type
  The external grid is modelled as a constant P (active power) and constant Q (reactive power) infeed. A positive value for P is considered to be a generated active power and a negative value is considered to be a consumed active power.
- PV Bus Type
  The external grid infeeds a constant active power (for $P > 0$) and by default controls the voltage of the busbar to which it is connected. Alternatively, the user may select a reference busbar for voltage control. The voltage setpoint is defined in p.u. of the busbar voltage. Only one external grid may control the voltage at any given busbar.
- SL Bus Type
  The external grid controls the voltage, the angle and the frequency of the busbar to which it is connected. If a reference busbar is selected, the voltage and the angle of this reference busbar are controlled. In such cases, the user must define the voltage set point (in p.u.) and the reference angle (in degrees).

Optionally, the active and reactive power input values may be entered as a combination of: P and cos(phi), S and cos(phi), Q and cos(phi), S and P or S and P.

If the active power is set to zero and the option *Out of service when active power is zero*, the machine does not take part in any voltage or frequency control.

2.1 Primary Frequency Control

A primary controlled state of a power system represents a state following an active power disturbance, in which the primary governors have settled and the system finds a “quasi steady-state” before the secondary controlled power plants take over the active power balancing task. During the primary frequency controlled state, the frequency deviates from nominal frequency. In order to represent this state, the Load Flow calculation to be executed using active power control according to primary control.

If the dispatched power of the participating elements is too low, in all isolated grids a common frequency deviation $dFin$ is calculated and the missing active power is distributed depending on the primary frequency bias Kpf of the participating elements (power balance is established):

$$P = P_{set} - K_{pf} \cdot dFin$$

where:

- P is actual active power in MW;
- P_{set} is active power setpoint in MW;
- Kpf is primary frequency bias in MW/Hz;
- $dFin = F - Fnom$ is frequency deviation in Hz.

Note: For SL Bus Type the frequency deviation is forced to 0. Hz ($dFin = 0.$).

An example of how the balancing active power is calculated and distributed to the participating elements is shows in Figure 2.1.

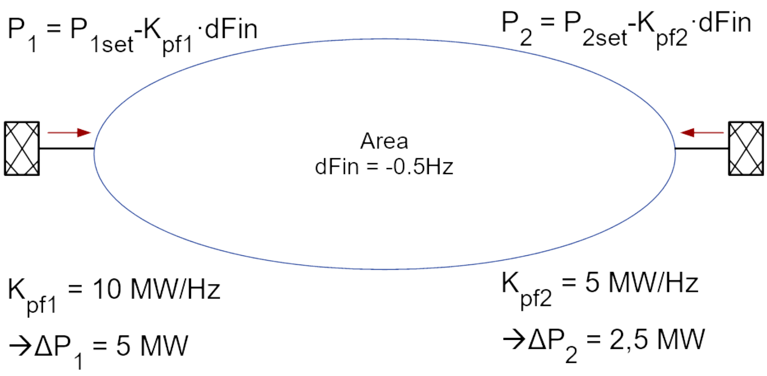

Figure 2.1: Example of a primary controlled Load Flow using Primary Frequency Bias factor

2.2 Secondary Frequency Control

For bringing frequency back to nominal frequency and/or for re-establishing area exchange flows of an interconnected power system, secondary controlled power plants take over the active power balancing task from the primary control after a few minutes (typically five minutes).

For simulating a secondary controlled state a power frequency controller needs to be specified and the participating element needs to be part of this controller. The Load Flow calculation needs to be executed using active power control according to secondary control. For more information related to the *Power Frequency Controller* object, refer to the corresponding Technical Reference Manual.

If a Load Flow with active power control according to secondary control is calculated, the External Grid participates to the secondary frequency control (as a part of a Power-Frequency controller) and the active power is modified as:

$$P = P_{set} + (Kp \cdot dPsco - K \cdot dFin)$$

where:

- P_{set} is the active power setpoint in MW,
- K is the secondary frequency bias,
- $dFin = F - Fnom$ is the frequency deviation,
- Kp is the external grid participation factor for secondary frequency control, as defined in the Power-Frequency controller,
- $dPsco$ is the power unbalance (deviation), as calculated by the Power-Frequency controller.

Normally the frequency deviation $dFin$ is always zero for the secondary frequency control. This is not the case when there is no frequency controller defined or if the participating elements in the frequency controller are already in the limit. The corresponding calculation quantities (signal) for the frequency deviation can be found in the variable selection dialogue ($s : dFin$ in Hz).

2.3 Operational Limits

The entered Reactive Power Operational Limits in the load flow page are considered in load flow analysis only if the option *Consider Reactive Power Limits* is selected in the Load Flow calculation dialogue. Alternatively, *PowerFactory* allows defining the Capability Curve, which can be manually entered. The P-Q characteristic of the capability curve is defined using either p.u. values or MW/Mvar values. *PowerFactory* allows defining the Capability Curve considering voltage dependent limits.

2.4 Unbalanced Load Flow

The calculation of the negative and zero sequence impedances used in the unbalanced Load Flow calculation is carried out using the positive sequence reactance. The positive sequence reactance is not used directly in the calculation for the load flow models. The maximum or the minimum entered values are used for the calculation depending if the minimum or maximum values option of the drop-down list *Use for calculation* is selected:

$$X1 = \frac{c_{factor}}{\sqrt{1+\left(\frac{R}{X}\right)^2}} \cdot \frac{U_{nom}^2}{S_k''} \quad [\Omega] \tag{1}$$

where :

- U_{nom} is the nominal voltage of the busbar to which the external grid is connected,
- c_{factor} is the c-factor coefficient (minimum or maximum value depending on the selected option *Use for calculation*),
- S_k'' is the short-circuit power (minimum value $snssmin$ or maximum value $snss$),
- $\frac{R}{X}$ is the positive sequence R to X short circuit-ratio (minimum value $rntxnmin$ or maximum value $rntxn$).

The zero sequence resistance and reactance are calculated as:

$$\begin{aligned} X0 &= \frac{X0}{X1} \cdot X1 \\ R0 &= \frac{R0}{X0} \cdot X0 \end{aligned} \tag{2}$$

where :

- $\frac{X0}{X1}$ is the short-circuit ratio between the zero and positive sequence reactance (minimum value $x0tx1min$ or maximum value $x0tx1$),
- $\frac{R0}{X0}$ is the zero sequence R to X short circuit-ratio (minimum value $r0tx0min$ or maximum value $r0tx0$).

The negative sequence resistance and reactance are calculated as:

$$\begin{aligned} Z2 &= \frac{Z2}{Z1} \cdot \frac{c_{factor}}{S_k''} \\ X2 &= \frac{Z2}{\sqrt{1+\left(\frac{R}{X}\right)^2}} \\ R2 &= \sqrt{Z2^2 - X2^2} \end{aligned} \tag{3}$$

where :

- $\frac{Z2}{Z1}$ is the negative to positive sequence short-circuit impedance ratio (minimum value $z2tz1min$ or maximum value $z2tz1$).

3 Short-Circuit Models

3.1 Short-Circuit Positive Sequence Model

The short-circuit positive sequence model is depicted in Figure 3.1.

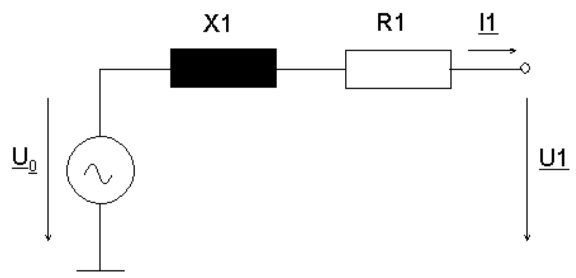

Figure 3.1: Short-Circuit Positive Sequence Model

$$X1 = \frac{c_{factor}}{\sqrt{1+(\frac{R}{X})^2}} \cdot \frac{U_{nom}^2}{S_k''} = \frac{c_{factor}}{\sqrt{1+(\frac{R}{X})^2}} \cdot \frac{U_{nom}^2}{\sqrt{3} \cdot I_k'' \cdot U_{nom}} \quad [\Omega] \tag{4}$$

and

$$R1 = \frac{R}{X} \cdot X1 \quad [\Omega] \tag{5}$$

where U_{nom} is the nominal voltage of the busbar to which the external grid is connected.

3.2 VDE/IEC Short-Circuit Model

The method used to calculate the internal resistance and reactance is dependent upon the short-circuit model used. For maximum short-circuits, the parameters S_{kmax}'' and $c_{factor} = c_{max}$ are used. For minimum short-circuits, the parameters S_{kmin}'' and $c_{factor} = c_{min}$ are used. The voltage factor, c_{factor}, depends on the voltage level of the busbar to which the external grid is connected. The internal voltage, U_0, is set according to one of the following equations:

$$\underline{U_0} = U_{nom} \cdot c_{max} \tag{6}$$

for maximum short-circuits, or:

$$\underline{U_0} = U_{nom} \cdot c_{min} \tag{7}$$

for minimum short-circuits.

For the internal voltage, the VDE/IEC calculation always uses the nominal voltage of the busbar multiplied by the corresponding voltage factor, c_{max} (or c_{min}). This voltage factor for the internal voltage depends on the voltage level at the short-circuit location.

3.3 ANSI Short-Circuit Model

The ANSI short-circuit method defines S_k'' and c_{factor} using the corresponding input parameters depending on whether the option “min. Values” or “max. Values” has been selected. The internal voltage is set to the nominal voltage of the busbar to which the external grid is connected.

$$\underline{U_0} = U_{nom} \tag{8}$$

The method does not use any voltage for the internal voltage.

3.4 Complete Short-Circuit Model

The Complete short-circuit method defines S_k'' and c_{factor} using the corresponding input parameters depending on whether the option “min. Values” or ”max. Values” has been selected. The pre-fault positive sequence model is depicted in Figure 3.2.

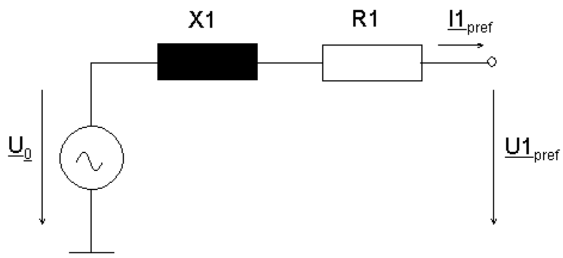

Figure 3.2: Short-Circuit Pre-Fault Positive Sequence Model

The internal voltage depends on the load flow result and the pre-fault voltage and current, and is calculated according to:

$$\begin{aligned} \underline{U_0} &= \underline{U_1}_{pref} + \underline{I_1}_{pref} \cdot (R1 + jX1) && (9) \\ \underline{U_1}_{pref} &= \underline{U1}_{ldf} && (10) \\ \underline{I_1}_{pref} &= \underline{I1}_{ldf} && (11) \end{aligned}$$

where $\underline{U1}_{ldf}$ is the positive sequence voltage and $\underline{I1}_{ldf}$ is the positive sequence current after a Load Flow calculation.

The entered S_k'' or I_k'' can be obtained from the element if the c_{factor} is set to 1 and in the Short-Circuit Calculation dialogue the load flow initialisation is disabled and the all positive sequence data is ignored.

3.5 Short-Circuit Zero Sequence Model

The short-circuit zero sequence model is depicted in Figure 3.3.

The zero sequence resistance and reactance are calculated according to following equations:

$$X0 = \frac{X0}{X1} \cdot X1 \tag{12}$$

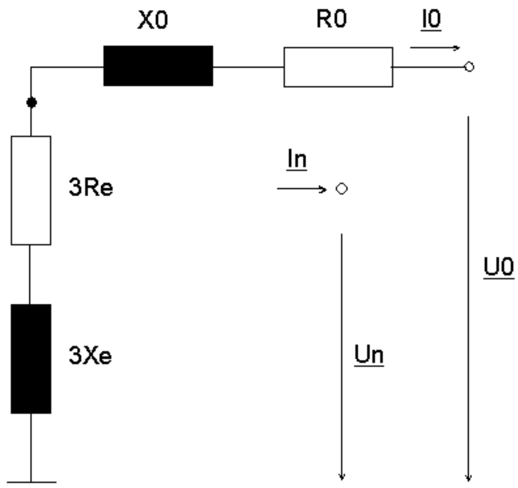

Figure 3.3: Short-Circuit Zero Sequence Model

$$R0 = \frac{R0}{X0} \cdot X0 \tag{13}$$

For ungrounded external grids, the grounding resistance (*Re*) and reactance (*Xe*) are neglected (infinitive). Additionally, it is possible to connect a neutral conductor to the star point (see option: *External Star Point*). Assuming that $Z1 = Z2$ where ($\frac{Z2}{Z1} = 1$), it is possible to calculate the $X0/X1$ ratio if the short-circuit current $I_k''(3p)$ for a three-phase fault and the short-circuit current $I_k''(1p)$ for a single-phase to ground fault are given. This ratio is calculated according to the following equation:

$$\frac{X0}{X1} = \frac{3 \cdot I''_{k3p}}{I''_{k1p}} - 2 \tag{14}$$

3.6 Short-Circuit Negative Sequence Model

The short-circuit negative sequence model is depicted in Figure 3.4.

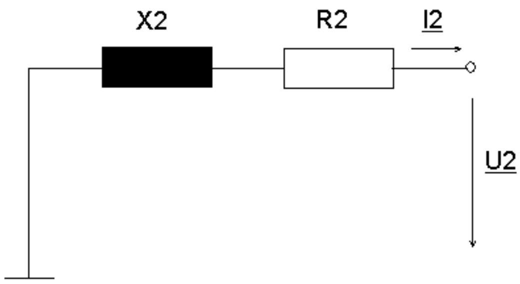

Figure 3.4: Short-Circuit Negative Sequence Model

The negative sequence resistance, $R2$, and reactance, $X2$, are calculated according to following equations:

$$R2 = \frac{Z2}{Z1} \cdot R1 \tag{15}$$

$$X2 = \frac{Z2}{Z1} \cdot X1 \tag{16}$$

4 Harmonics Model

4.1 Calculation of Network Impedance

The impedance of the external grid, which is taken into account for power quality assessment, is calculated internally based on one of: the short-circuit power, *Sk*, at normal operation; the maximum short-circuit power, *Sk”max* for faulted operation; or the minimum short-circuit power *Sk”min* for faulted operation, depending on the user’s selection.

If the user has selected the network impedance to be based on the short-circuit power, *Sk*, and impedance angle, *psik*, data for input fields *SkV*, *psikV*, *z2tz1kV*, *x0tx1kV*, and *r0tx0kV* can first be calculated from a detailed network model using the Harmonic Load Flow command option *Calculate Sk at Fundamental Frequency*, performed, for example, by the network operator. A third party, (i.e. a wind farm planner) could get this information for the point of common coupling (PCC for the planned wind farm) from the network operator. The planner can then enter the data into the external grid element, which is a simplified representation of the network as seen from the PCC.

4.1.1 Calculation of Positive Sequence Voltage

The positive sequence voltage, $\underline{u_{ini1}}$, is depicted in Figure 4.1.

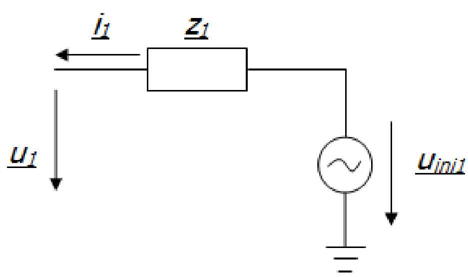

Figure 4.1: Harmonics Positive Sequence Model

The positive sequence voltage is calculated as follows:

$$\underline{u_{ini1}} = \underline{u_1} + \underline{i_1} \cdot \underline{z_1} \tag{17}$$

where $\underline{z_1} = R1 + jX1$ and is calculated using values which are dependent upon the setting of option ‘Used for calculation’ (*cusedhrm*):

1. If option ‘Max. Values’ has been selected:

$$X1 = c_{max}/snss/\sqrt{1 + rntxn^2} \tag{18}$$

$$R1 = rntxn \cdot X1 \tag{19}$$

2. If option ‘Min. Values’ has been selected:

$$X1 = c_{min}/snss_{min}/\sqrt{1 + rntxn_{min}^2} \tag{20}$$

$$R1 = rntxn_{min} \cdot X1 \tag{21}$$

3. If option 'Sk' has been selected:

$$X1 = \frac{1}{SkV} \cdot sin(psikV \cdot \frac{\pi}{180}) \tag{22}$$

$$R1 = \frac{1}{SkV} \cdot cos(psikV \cdot \frac{\pi}{180}) \tag{23}$$

Following the internal conversion of the calculated impedance values into units of Ohms, any user-defined characteristics for $R1$ and $L1$ are applied to $\underline{z_1}$ (see the 'Frequency Dependencies' tab on the 'Harmonics/Power Quality' page of the external grid element).

4.1.2 Calculation of Negative Sequence Voltage

The negative sequence voltage, $\underline{u_{ini2}}$, is depicted in Figure 4.2.

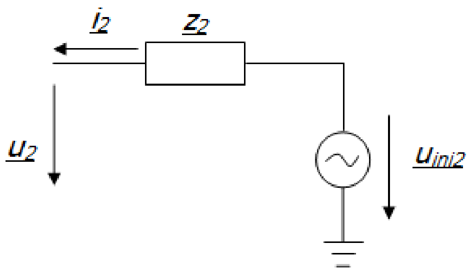

Figure 4.2: Harmonics Negative Sequence Model

The negative sequence voltage is calculated as follows:

$$\underline{u_{ini2}} = \underline{u_2} + \underline{i_2} \cdot \underline{z_2} \tag{24}$$

where $\underline{z_2} = R2 + jX2$ and is calculated using values which are dependent upon the setting of option 'Used for calculation' (*cusedhrm*):

1. If option 'Max. Values' has been selected:

$$X2 = z2tz1 \cdot X1 \tag{25}$$

$$R2 = z2tz1 \cdot R1 \tag{26}$$

2. If option 'Min. Values' has been selected:

$$X2 = z2tz1_{min} \cdot X1 \tag{27}$$

$$R2 = z2tz1_{min} \cdot R1 \tag{28}$$

3. If option 'Sk' has been selected:

$$X2 = z2tz1kV \cdot X1 \tag{29}$$

$$R2 = z2tz1kV \cdot R1 \tag{30}$$

where $X1$ and $R1$ are as defined in Section 4.1.1. Following the internal conversion of the calculated impedance values into units of Ohms, any user-defined characteristics for $R2$ and $L2$ are applied to $\underline{z_2}$ (see the 'Frequency Dependencies' tab on the 'Harmonics/Power Quality' page of the external grid element).

4.1.3 Calculation of Zero Sequence Voltage

The zero sequence voltage, $\underline{u_{ini0}}$, is depicted in Figure 4.3.

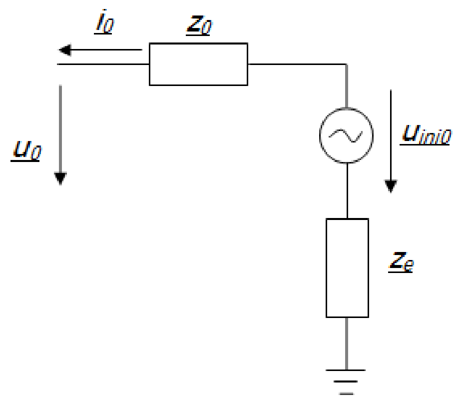

Figure 4.3: Harmonics Zero Sequence Model

The zero sequence voltage is calculated as follows:

$$\underline{u_{ini0}} = \underline{u_0} + \underline{i_0} \cdot (\underline{z_0} + 3z_e) \tag{31}$$

where $\underline{z_0} = R0 + jX0$ and is calculated using values which are dependent upon the setting of option ‘Used for calculation’ (*cusedhrm*):

1. If option ‘Max. Values’ has been selected:

$$X0 = x0tx1 \cdot X1 \tag{32}$$
$$R0 = r0tx0 \cdot X0 \tag{33}$$

2. If option ‘Min. Values’ has been selected:

$$X0 = x0tx1_{min} \cdot X1 \tag{34}$$
$$R0 = r0tx0_{min} \cdot X0 \tag{35}$$

3. If option ‘Sk’ has been selected:

$$X0 = x0tx1kV \cdot X1 \tag{36}$$
$$R0 = r0tx0kV \cdot X0 \tag{37}$$

where $X1$ is as defined in Section 4.1.1. Following the internal conversion of the calculated impedance values into units of Ohms, any user-defined characteristics for $R0$ and $L0$ are applied to $\underline{z_0}$ (see the ‘Frequency Dependencies’ tab on the ‘Harmonics/Power Quality’ page of the external grid element).

4.1.4 Calculation of Zero Sequence Voltage Considering Neutral

The zero sequence voltage, $\underline{u_{ini0}}$, for an external grid with neutral, is depicted in Figure 4.4.

The zero sequence voltage, for an external grid with neutral, is calculated as follows:

$$\underline{u_{ini0}} = \underline{u_n} - (\underline{i_0} \cdot \underline{z_0}) - \underline{u_0} \tag{38}$$

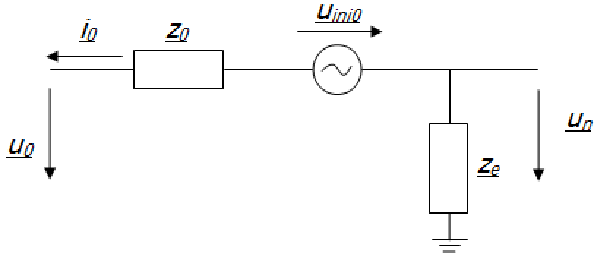

Figure 4.4: Harmonics Zero Sequence Model Considering Neutral

where $\underline{z_0}$ is as defined in Section 4.1.3. Following the internal conversion of the calculated impedance values into units of Ohms, any user-defined characteristics for $R0$ and $L0$ are applied to $\underline{z_0}$ (see the 'Frequency Dependencies' tab on the 'Harmonics/Power Quality' page of the external grid element).

4.2 Harmonic Voltages and Background Harmonics

Harmonic voltages may be entered according to one of the following two options:

- *Phase Correct* (where harmonic voltage magnitudes and angles may be entered for integer and non-integer harmonic orders)
- *IEC 61000* (where harmonic voltage magnitudes may be entered for integer and non-integer harmonic orders)

Background harmonics can be modelled using either the external grid element or the AC voltage source element, on their respective *Harmonics/Power Quality* pages. If only the harmonic voltage amplitude is known (and not the angle), the *IEC 61000* option can be selected.

The consideration of sequence component for the harmonic orders defined in the external grid is detailed in Table 4.1.

Table 4.1: Consideration of Sequence Components of Harmonic Injections for External Grid

Harmonic Load Flow	**ElmXnet Setting**	**Sequence Components of Harmonic Injections**
Balanced	*Phase Correct*	• Positive (i.e. 4, 7, 10, ...), negative (i.e. 2, 5, 8, ...) • Non-integer harmonic orders (i.e. 5.5, 6.2, 8.35, ...) are considered in the positive sequence • Zero sequence orders are ignored (with warning)
	IEC 61000	• Positive, negative • Zero sequence orders (i.e. 3, 6, 9, ...) and non-integer harmonics are in the positive sequence
Unbalanced	*Phase Correct*	• Positive, negative, zero • Non-integer harmonics are considered
	IEC 61000	• As for balanced harmonic load flow

4.3 Frequency Dependencies

Frequency dependent characteristics can be defined for the external grid. The definition of such characteristics is described in the User's Manual chapter *Harmonic Analysis*, section *Frequency Dependent Parameters*, and Chapter *Parameter Characteristics*.

5 RMS- and EMT-Simulation

For the simulation model of the external network a model of a synchronous generator is being used. The subtransient reactances of the model are predefined to $0.2p.u.$ and the saturation and leakage rectances are neglected in the model so that the model takes a simplified form.

5.1 Parameters

The nominal power of the *External Grid* is calculated depending if maximum or minimum short-circuit data is used:

$$s_{nom} = \begin{cases} 0.2 \cdot \sqrt{1 + rntxn^2} \cdot \dfrac{s_k''}{c_{max}} & [MVA] \quad \text{if maximum values are used} \\ \\ 0.2 \cdot \sqrt{1 + rntxn_{min}^2} \cdot \dfrac{s_{kmin}''}{c_{min}} & [MVA] \quad \text{if minimum values are used} \end{cases} \tag{39}$$

where:

- s_k'' is the short circuit ($snss$) power in $[MVA]$;
- $rntxn$ is the R to X ratio;
- c is the c-factor.

Similarly, the stator resistance is calculated depending if maximum or minimum short-circuit data is used:

$$r_s = \begin{cases} 0.2 \cdot rntxn & [p.u.] \quad \text{if maximum values are used} \\ \\ 0.2 \cdot rntxn_{min} & [p.u.] \quad \text{if minimum values are used} \end{cases} \tag{40}$$

where the minimum value is limited to $1e^{-4}$ $[p.u.]$

The internal grounding impedance and neutral connection information can be defined in the *Grounding/Neutral Conductor* tab of the *Basic Data* page of *ElmXnet*. The internal grounding impedance per unit values are calculated as:

$$\begin{aligned} r_{earth} &= R_e \cdot \frac{s_{nom}}{u_{nom}^2} \\ x_{earth} &= X_e \cdot \frac{s_{nom}}{u_{nom}^2} \end{aligned} \tag{41}$$

where u_{nom} is the nominal voltage of the connected busbar.

The zero sequence reactance and resistance are calculated as follows:

$$x_0 = \begin{cases} 0.2 \cdot x0tx1 & [p.u.] \quad \text{if maximum values are used} \\ \\ 0.2 \cdot x0tx1_{min} & [p.u.] \quad \text{if minimum values are used} \end{cases} \tag{42}$$

$$r_0 = \begin{cases} x_0 \cdot r0tx0 & [p.u.] \quad \text{if maximum values are used} \\ \\ x_0 \cdot r0tx0_{min} & [p.u.] \quad \text{if minimum values are used} \end{cases} \tag{43}$$

For the unbalanced RMS-simulation, the negative sequence resistance is set equal to the stator resistance $r_2 = r_s$ and using the pre-defined $\mathbf{X}$ and $\mathbf{Y}$ matrices, the negative sequence reactance is calculated as:

$$x_2 = \frac{1}{2} \cdot \left(\frac{\mathbf{X_{d11}}}{1 - \mathbf{X_{d12}} \cdot \mathbf{Y_{d21}} - \mathbf{X_{d13}} \cdot \mathbf{Y_{d31}}} + \frac{\mathbf{X_{q11}}}{1 - \mathbf{X_{q12}} \cdot \mathbf{Y_{q21}} - \mathbf{X_{q13}} \cdot \mathbf{Y_{q31}}} \right) \tag{44}$$

5.2 Flux equations and time constants

The rotor d-axis is modelled by two rotor loops representing the excitation (field) winding and the damper winding. The q-axis is modelled using two damper windings. The model is written using sub-transient variables.

The matrix of the d-axis and q-axis fluxes have the following forms:

$$\begin{bmatrix} \psi_d \\ \psi_e \\ \psi_D \end{bmatrix} = \begin{bmatrix} x_d & -1 & 1 \\ -(1-\sigma_e) \cdot x_d & 1 & -\mu_e \\ (1-\sigma_D) \cdot x_d & -\mu_D & 1 \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_e \\ i_D \end{bmatrix} = \mathbf{X_d} \cdot \begin{bmatrix} i_d \\ i_e \\ i_D \end{bmatrix} \tag{45}$$

$$\begin{bmatrix} \psi_q \\ \psi_x \\ \psi_Q \end{bmatrix} = \begin{bmatrix} x_q & -1 & 1 \\ -(1-\sigma_x) \cdot x_q & 1 & -\mu_x \\ (1-\sigma_Q) \cdot x_q & -\mu_Q & 1 \end{bmatrix} \cdot \begin{bmatrix} i_q \\ i_x \\ i_Q \end{bmatrix} = \mathbf{X_q} \cdot \begin{bmatrix} i_q \\ i_x \\ i_Q \end{bmatrix} \tag{46}$$

where μ is translation/screening factor and σ is decrement factor and saturation is neglected and leakage reactance xl is zero.

These factors are calculated as follows:

$$\begin{aligned} \sigma_e &= \frac{x'_d}{x_d} \\ \sigma_D &= \frac{x'_d \cdot x''_d}{x'_d \cdot x''_d + x_d \cdot (x'_d - x''_d)} \\ \mu_e &= \frac{x_d - x'_d}{x_d} \\ \mu_D &= \frac{x_d \cdot (x'_d - x''_d)}{x'_d \cdot x''_d + x_d \cdot (x'_d - x''_d)} \\ \\ \sigma_x &= \frac{x'_q}{x_q} \\ \sigma_Q &= \frac{x'_q \cdot x''_q}{x'_q \cdot x''_q + x_q \cdot (x'_q - x''_q)} \\ \mu_x &= \frac{x_q - x'_q}{x_q} \\ \mu_Q &= \frac{x_q \cdot (x'_q - x''_q)}{x'_q \cdot x''_q + x_q \cdot (x'_q - x''_q)} \end{aligned} \tag{47}$$

The time constants of the rotor winding are calculated as:

$$
\begin{aligned}
T_e &= \frac{t'_d \cdot x_d}{x'_d} \\
T_D &= \frac{t''_d \cdot x'_d}{x''_d} \cdot \frac{x'_d \cdot x''_d + x_d \cdot (x'_d - x''_d)}{x''^2_d} \\
\\
T_x &= \frac{t'_q \cdot x_q}{x'_q} \\
T_Q &= \frac{t''_q \cdot x'_q}{x''_q} \cdot \frac{x'_q \cdot x''_q + x_q \cdot (x'_q - x''_q)}{x''^2_q}
\end{aligned}
\tag{48}
$$

The stator and rotor currents can be expressed by using the inverse of the reactance matrices $\mathbf{Y_d} = \mathbf{X_d}^{-1}$ and $\mathbf{Y_q} = \mathbf{X_q}^{-1}$:

$$
\begin{bmatrix} i_d \\ i_e \\ i_D \end{bmatrix} = \mathbf{Y_d} \cdot \begin{bmatrix} \psi_d \\ \psi_e \\ \psi_D \end{bmatrix}
\tag{49}
$$

$$
\begin{bmatrix} i_q \\ i_x \\ i_Q \end{bmatrix} = \mathbf{Y_q} \cdot \begin{bmatrix} \psi_q \\ \psi_x \\ \psi_Q \end{bmatrix}
\tag{50}
$$

5.3 Rotor equations

The rotor equations presented in this sub-section are used in both RMS and EMT simulations.

The following expressions are valid for the rotor currents:

$$
\begin{aligned}
i_e &= \psi_d \cdot \mathbf{Y_{d21}} + \psi_e \cdot \mathbf{Y_{d22}} + \psi_D \cdot \mathbf{Y_{d23}} \\
i_D &= \psi_d \cdot \mathbf{Y_{d31}} + \psi_e \cdot \mathbf{Y_{d32}} + \psi_D \cdot \mathbf{Y_{d33}} \\
i_x &= \psi_q \cdot \mathbf{Y_{q21}} + \psi_x \cdot \mathbf{Y_{q22}} + \psi_Q \cdot \mathbf{Y_{q23}} \\
i_Q &= \psi_q \cdot \mathbf{Y_{q31}} + \psi_x \cdot \mathbf{Y_{q32}} + \psi_Q \cdot \mathbf{Y_{q33}}
\end{aligned}
\tag{51}
$$

The rotor voltage equations for the d-axis and q-axis have the following form:

$$
\begin{aligned}
\frac{d\psi_e}{dt} &= \frac{v_e - i_e}{T_e} \\
\frac{d\psi_D}{dt} &= -\frac{i_D}{T_D} \\
\frac{d\psi_x}{dt} &= -\frac{i_x}{T_x} \\
\frac{d\psi_Q}{dt} &= -\frac{i_Q}{T_Q}
\end{aligned}
\tag{52}
$$

5.4 Stator equations

5.4.1 Stator equations used in the RMS-simulation

The stator fluxes in the d- and q-axis are calculated using the following equations:

$$\begin{aligned}\psi_d &= x_d'' \cdot i_d - \psi_d'' \\ \psi_q &= x_q'' \cdot i_q - \psi_q''\end{aligned} \tag{53}$$

Using these definitions for the flux, the stator voltage equations can be written (with neglected stator flux derivatives) as:

$$\begin{aligned}u_d &= u_d'' - r_{str} \cdot i_d + n \cdot x_q'' \cdot i_q \\ u_q &= u_q'' - r_{str} \cdot i_q - n \cdot x_d'' \cdot i_d\end{aligned} \tag{54}$$

If the signal $fref$ is connected to the model then its value is used instead of the speed in Equation 54.

The subtransient stator voltages in Equation 54 are calculated as:

$$\begin{aligned}u_d'' &= -n \cdot \psi_q'' \\ u_q'' &= n \cdot \psi_d''\end{aligned} \tag{55}$$

where the subtransient stator fluxes ψ_d'' and ψ_q'' are calculated as:

$$\begin{aligned}\psi_d'' &= \frac{\psi_e \cdot \mathbf{Y_{d12}} + \psi_D \cdot \mathbf{Y_{d13}}}{\mathbf{Y_{d11}}} \\ \psi_q'' &= \frac{\psi_x \cdot \mathbf{Y_{q12}} + \psi_Q \cdot \mathbf{Y_{q13}}}{\mathbf{Y_{q11}}}\end{aligned} \tag{56}$$

The electrical torque t_e is calculated according to:

$$t_e = \frac{i_q \cdot \psi_d - i_d \cdot \psi_q}{cos_n} \qquad [p.u.] \tag{57}$$

In the case of unbalanced RMS simulation, additionally, the negative sequence, the zero sequence and neutral equations (if neutral is connected) have to be satisfied.

The negative sequence equations take into account the negative sequence impedance of the model:

$$\underline{u}_2 = -(r_2 + \jmath \cdot x_2) \cdot \underline{i}_2 \tag{58}$$

Three different cases can be distinguished depending on the neutral conductor and internal grounding impedance connection modes:

- No neutral connection and internal grounding impedance connected

  In this case there is need only for zero sequence equations:

  $$\underline{u}_0 = -(r_0 + \jmath \cdot x_0) \cdot \underline{i}_0 - 3 \cdot (r_{earth} + \jmath \cdot x_{earth}) \cdot \underline{i}_0 \tag{59}$$

- N-connection at terminal (ABC-N)

  When a neutral conductor is connected, zero sequence and equations for the neutral are required. Here two sub-cases are possible:

– Internal grounding impedance not connected

$$\underline{u}_0 = -(r_0 + \jmath \cdot x_0) \cdot \underline{i}_0 + \underline{u}_n \tag{60}$$
$$0 = 3 \cdot \underline{i}_0 + \underline{i}_n \tag{61}$$

– Internal grounding impedance connected

$$\underline{u}_0 = -(r_0 + \jmath \cdot x_0) \cdot \underline{i}_0 + \underline{u}_n \tag{62}$$
$$\underline{u}_n = -(r_{earth} + \jmath \cdot x_{earth}) \cdot (3 \cdot \underline{i}_0 + \underline{i}_n) \tag{63}$$

• N-connection at separate terminal (internal grounding impedance is never connected)

$$\underline{u}_0 = -(r_{0sy} + \jmath \cdot x_{0sy}) \cdot \underline{i}_0 + \underline{u}_n \tag{64}$$
$$0 = 3 \cdot \underline{i}_0 + \underline{i}_n \tag{65}$$

5.4.2 Stator equations used in the EMT-simulation

For the EMT model, the stator voltage equations are written using the stator $\alpha\beta 0$ stationary reference frame.

The following equations are obtained for the stator voltage $\underline{u}_{\alpha\beta} = u_\alpha + \jmath \cdot u_\beta$:

$$\underline{u}_{\alpha\beta} = \underline{u}''_{\alpha\beta} - r_{str} \cdot \underline{i}_{\alpha\beta} - \jmath \cdot 2 \cdot n \cdot x''_\Delta \cdot e^{\jmath \cdot 2 \cdot \varphi} \cdot \underline{i}^*_{\alpha\beta} - \frac{x''}{\omega_n} \cdot \frac{d\underline{i}_{\alpha\beta}}{dt} - \frac{x''_\Delta}{\omega_n} \cdot e^{\jmath \cdot 2 \cdot \varphi} \cdot \frac{d\underline{i}^*_{\alpha\beta}}{dt} \tag{66}$$

where the dq subtransient voltages are transformed to the $\alpha\beta$ stationary reference frame using the rotor position angle φ as $\underline{u}''_{\alpha\beta} = (u''_d + \jmath \cdot u''_q) \cdot e^{\jmath \cdot \varphi}$. The dq subtransient voltages are calculated as:

$$\begin{aligned} u''_d &= u'_d - n \cdot \psi_Q \cdot \frac{\mathbf{Y_{q13}}}{\mathbf{Y_{q11}}} + \frac{1}{\omega_n} \cdot \frac{d\psi_D}{dt} \cdot \frac{\mathbf{Y_{d13}}}{\mathbf{Y_{d11}}} \\ u''_q &= u'_q + n \cdot \psi_D \cdot \frac{\mathbf{Y_{d13}}}{\mathbf{Y_{d11}}} + \frac{1}{\omega_n} \cdot \frac{d\psi_Q}{dt} \cdot \frac{\mathbf{Y_{q13}}}{\mathbf{Y_{q11}}} \end{aligned} \tag{67}$$

where the transient voltages have the following form:

$$\begin{aligned} u'_d &= -n \cdot \psi_x \cdot \frac{\mathbf{Y_{q12}}}{\mathbf{Y_{q11}}} + \frac{1}{\omega_n} \cdot \frac{d\psi_e}{dt} \cdot \frac{\mathbf{Y_{d12}}}{\mathbf{Y_{d11}}} \\ u'_q &= n \cdot \psi_e \cdot \frac{\mathbf{Y_{d12}}}{\mathbf{Y_{d11}}} + \frac{1}{\omega_n} \cdot \frac{d\psi_x}{dt} \cdot \frac{\mathbf{Y_{q12}}}{\mathbf{Y_{q11}}} \end{aligned} \tag{68}$$

In the above equations, x''_Δ and x'' are calculated as: $x''_\Delta = \frac{x''_d - x''_q}{2}$ and $x'' = \frac{x''_d + x''_q}{2}$.

The electrical torque t_e is calculated the same as in the RMS simulation (according to Equation 57).

Three different cases can be distinguished depending on the neutral conductor and internal grounding impedance connection modes:

• No neutral connection and internal grounding impedance connected

In this case there is a need only for a zero sequence equation:

$$u_0 = -(r_0 + 3 \cdot r_{earth}) \cdot i_0 - (x_0 + 3 \cdot x_{earth}) \cdot \frac{1}{hpi} \cdot \frac{di_0}{dt} \tag{69}$$

- N-connection at terminal (ABC-N)

  When a neutral conductor is connected, a zero sequence and an equation for the neutral are required. Here two sub-cases are possible:

  – Internal grounding impedance not connected

$$u_0 = -r_0 \cdot i_0 - x_0 \cdot \frac{1}{hpi} \cdot \frac{di_0}{dt} + u_n \tag{70}$$

$$0 = 3 \cdot i_0 + i_n \tag{71}$$

  – Internal grounding impedance connected

$$u_0 = -r_0 \cdot i_0 - x_0 \cdot \frac{1}{hpi} \cdot \frac{di_0}{dt} + u_n \tag{72}$$

$$u_n = -r_e \cdot (3 \cdot i_0 + i_n) - \frac{x_e}{hpi} \cdot \left(3 \cdot \frac{di_0}{dt} + \frac{di_n}{dt}\right) \tag{73}$$

- N-connection at separate terminal (internal grounding impedance is never connected)

$$u_0 = -r_0 \cdot i_0 - x_0 \cdot \frac{1}{hpi} \cdot \frac{di_0}{dt} + u_n \tag{74}$$

$$0 = 3 \cdot i_0 + i_n \tag{75}$$

5.5 Mechanical Equations

The speed derivative dn/dt of the machine is calculated using the following equation:

$$\frac{dn}{dt} = \frac{t_m - t_e}{t_{ag}} \tag{76}$$

where:

- t_m is the mechanical torque in $[p.u.]$;
- t_e is the electrical torque in $[p.u.]$ calculated according to Equation 57;
- t_{ag} is the acceleration time constant in $[s]$ (also referred as the mechanical starting time and it is equal to $t_{ag} = 2 \cdot H$ where H is the inertia constant).

From Equation 76 can be seen that, if there is a difference between the torques, the rotor will be accelerated or decelerated. This equation represents the equation of motion.

The base torque is the ratio between the electrical active power and the nominal mechanical angular frequency in $[mech.rad/s]$:

$$t_{base} = \frac{sgn \cdot cosn}{\omega_{0m}} \qquad [p.u.] \tag{77}$$

The calculation of the mechanical torque t_m (parameter xmt) is calculated as:

$$t_m = \frac{pt}{n} + \frac{dp}{n} + xmdm + addmt \tag{78}$$

where:

- pt is the *Turbine Power* input signal in $[p.u.]$.

- dp is the output of internal speed controller;
- $xmdm$ is the *Torque Input* input signal in $[p.u.]$;
- $addmt$ is the *Additional Torque* parameter in $[p.u.]$. It can be used as an additional MDM torque for the motor or as an additional pt torque for the generator.

The parameter dp is calculated using the droop which in turn is calculated using the secondary frequency bias K:

$$\begin{aligned} dp &= droop \cdot (1 - n) \\ droop &= K \cdot \frac{f_{nom}}{s_{nom} \cdot cosn} \end{aligned} \tag{79}$$

5.5.1 Rotor angle definition

The angle φ (parameter phi) is the position of the rotor (d-axis) referenced to the reference voltage of the network. The angle φ is a state variable in the model and its time derivative $d\varphi/dt$ is calculated as follows:

$$\frac{d\varphi}{dt} = \begin{cases} \omega_n \cdot (n - f_{ref}) & [rad] \quad \text{in the RMS simulation} \\ \omega_n \cdot n & [rad] \quad \text{in the EMT simulation} \end{cases} \tag{80}$$

where f_{ref} is an input signal connected to the reference machine frequency automatically by *PowerFactory*.

In the RMS simulation, for the reference machine (slack), the reference frequency is equal to the speed ($f_{ref} = n$), so the derivative of the angle is set to zero ($\frac{d\varphi}{dt} = 0$). The state variable φ is initialised by first calculating the q-axis angle and then shifting this angle for $90°$:

$$\varphi = \arctan\left(\underline{u}_t + (r_s + \jmath \cdot x_q) \cdot \underline{i}_t\right) - \frac{\pi}{2} \qquad [rad] \tag{81}$$

where $\underline{u}_t$ is the terminal voltage of the machine, r_{str} is the stator resistance, x_q is the q-axis synchronous reactance of the machine and $\underline{i}_t$ is the current flowing through the machine.

5.5.2 Initialisation of the mechanical parameters

The mechanical torque is initialised with the value of the electrical torque. Since the initial speed is $1p.u.$, pt is initialised with the value of the electrical torque. $xmdm$ and $addmt$ are initialised to zero.

5.5.3 Excitation system interfacing

For interfacing with the excitation system, the excitation current output signal i_e and the excitation voltage input signal v_e are used which are based on a non-reciprocal p.u. system. This p.u. system can be also referred to as a no load, no saturation p.u.-system. Under no-load, steady-state and rated speed conditions, excitation current of $i_e = 1\ p.u.$ is required to produce $1\ p.u.$ stator voltage on the air-gap line. Excitation voltage of $v_e = 1\ p.u.$ is the corresponding excitation voltage. The excitation voltage input signal is being initialised as:

$$v_e = i_e \tag{82}$$

5.6 Using default machine input parameters

The default values of the synchronous, transient and sub-transient reactances, the transient and sub-transient time constants in the d- and q-axis and the power factor are presented in Table 5.1.

Table 5.1: Default machine parameters in the d- and q-axis

Parameter	Symbol	Value	Description
xd	x_d	$0.2p.u.$	Synchronous reactance d-axis
xq	x_q	$0.2p.u.$	Synchronous reactance q-axis
xds	x'_d	$0.2p.u.$	Transient reactance d-axis
xqs	x'_q	$0.2p.u.$	Transient reactance q-axis
$xdss$	x''_d	$0.2p.u.$	Subtransient reactance d-axis
$xqss$	x''_q	$0.2p.u.$	Subtransient reactance q-axis
tds	t'_d	$1s$	Short-circuit transient time constant d-axis
tqs	t'_q	$1s$	Short-circuit transient time constant q-axis
$tdss$	t''_d	$0.1s$	Short-circuit subtransient time constant d-axis
$tqss$	t''_q	$0.1s$	Short-circuit subtransient time constant q-axis

Using these default values, the model matrices get a simplified form, all the σ parameters obtain the value 1 $[p.u.]$ and all μ parameters obtain the value 0 $[p.u.]$. Similarly, the time constants in the d- and q-axis obtain the values $T_e = T_x = 1$ $[s]$ and $T_D = T_Q = 0.1$ $[s]$. The negative sequence reactance is obtained as $x_2 = 0.2$ $[p.u.]$. Using the default input parameters, the dynamic model of the external network is highly simplified.

5.7 Inputs/Outputs/State Variables of the Dynamic Model

5.7.1 Stability Model (RMS)

Table 5.2: Input Definition of the RMS-Model

Input Signal	Symbol	Description	Unit
ve	v_e	Excitation voltage	p.u.
pt		Turbine power	p.u.
xmdm		Torque input	p.u.
fref	f_{ref}	Reference frequency	p.u.

Table 5.3: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
psisr		Stator flux, real part	p.u.
psisi		Stator flux, imaginary part	p.u.
psie	ψ_e	Excitation flux	p.u.
psiD	ψ_D	Flux in D-damper winding, d-axis	p.u.
psix	ψ_x	Flux in x-damper winding, q-axis	p.u.
psiQ	ψ_Q	Flux in Q-damper winding, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 5.4: Output Definition of the RMS-Model

Parameter	**Symbol**	**Description**	**Unit**
uout		Terminal Voltage, magnitude	p.u.
xspeed		Speed ($xspeed = speed$)	p.u.

5.7.2 EMT-Model

Table 5.5: Input Definition of the EMT-Model

Input Signal	**Symbol**	**Description**	**Unit**
ve	v_e	Excitation Voltage	p.u.
pt		Turbine Power	p.u.
xmdm		Torque Input	p.u.

Table 5.6: State Variables Definition of the EMT-Model

Parameter	**Symbol**	**Description**	**Unit**
psie	ψ_e	Excitation flux	p.u.
psiD	ψ_D	Flux in D-damper winding, d-axis	p.u.
psix	ψ_x	Flux in x-damper winding, q-axis	p.u.
psiQ	ψ_Q	Flux in Q-damper winding, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 5.7: Output Definition of the EMT-Model

Parameter	**Symbol**	**Description**	**Unit**
usd	u'_d	Transient Voltage, d-axis	p.u.
usq	u'_q	Transient Voltage, q-axis	p.u.
uout		Terminal Voltage, magnitude	p.u.
xspeed		Speed ($xspeed = speed$)	p.u.

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