POWERFACTORY

PowerFactory 2021

Technical Reference

Synchronous Machine

ElmSym, TypSym

PF2021

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

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Contents

1 General Description

This document describes the *PowerFactory* synchronous machine models, as used for the various steady-state and dynamic power system analysis functions in *PowerFactory*.

2 Load Flow Analysis

Typically, in load flow calculations, the controlled operation of a synchronous generator is modelled. Figure 2.1 shows the basic concept of a controlled synchronous machine modelled for load flow analysis.

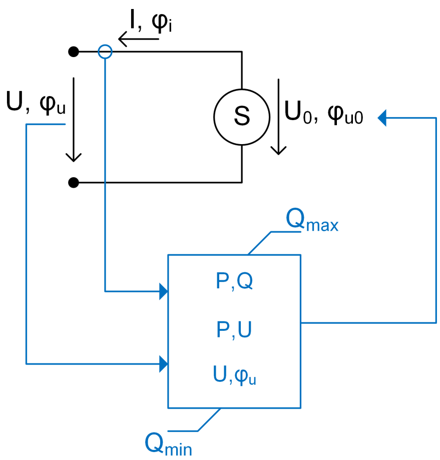

Figure 2.1: Basic concept of a controlled synchronous machine

2.1 Reactive Power/Voltage Control

The *PowerFactory* model of the synchronous machine, offers the following options for defining the Local Controller:

- Const. V
- Voltage Q-Droop
- Voltage Iq-Droop
- Const. Q
- Q(P)-Characteristic
- Const. cosphi

2.1.1 Const. V

The Local Controller defined as "Const. V" is typically used for large synchronous generators at large power stations which operate in voltage control mode ("PV" mode).

When enabling this option, the generator will control the voltage directly at its terminals. As basis for the controlled $[p.u.]$ value, the voltage of the connected terminal is used. For more complex control schemes, i.e. controlling the voltage at a remote bus bar or controlling the voltage at one bus bar using more than one generator, a *Station Controller* model needs to be defined.

In this case, the Station Controller adds an offset to the reactive power operating point specified in the synchronous generator element:

$$Q = Q_0 + K \cdot \Delta Q_{SCO} \quad (1)$$

For more details about the *Station Controller*, refer to the Technical Reference of the Station Controller.

2.1.2 Voltage Q-Droop control

Figure 2.2 describe the voltage control and droop function.

The droop control corresponds to a proportional control. This means the amount of reactive power is calculated in proportion to the deviation from the voltage set-point entered in the element. The droop control can be used if several voltage controlling machines are placed close together.

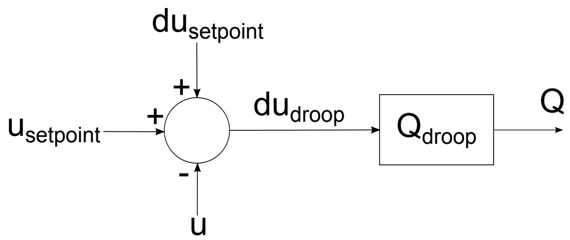

Figure 2.2: Voltage Q-Droop Control

When set to voltage q-droop control, a droop value can be entered. The voltage at the local busbar is then controlled according to the equations below. The equation is shown graphically in Figure 2.3. It can be inferred that a droop value of 1% and a voltage deviation of 0.01 p.u. result in an additional reactive power of 100% of the rated apparent power of the generator. Similarly, a droop value of 2% and the same voltage deviation of 0.01 p.u. result in an additional reactive power of 50% of the rated apparent power of the generator.

$$u = u_{setpoint} - \Delta u_{droop} \quad (2)$$

$$\Delta u_{droop} = \frac{Q - Q_{setpoint}}{Q_{droop}} \quad (3)$$

$$Q_{droop} = \frac{S_r \cdot 100}{ddroop} \quad (4)$$

where:

- u is the actual voltage value at the terminal
- $u_{setpoint}$ is the specified voltage setpoint
- Δu_{droop} is the voltage deviation
- $du_{setpoint}$ is the voltage signal coming from the station controller, when the station controller is set to *Voltage Setpoint Adaptation* method, otherwise is zero by default. Please consult the Technical Reference of the Station Controller
- Q is the actual reactive power output
- $Q_{setpoint}$ is the specified dispatch reactive power

- Q_{droop} is the additional reactive power for the specified voltage droop
- S_r is the rated apparent power
- $ddroop$ is the voltage droop value specified in percentage

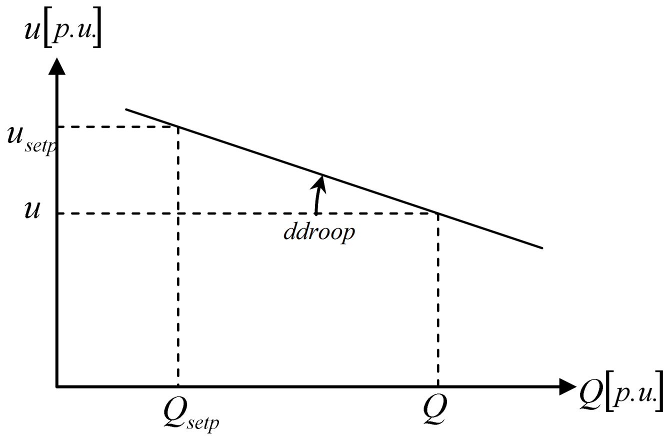

Figure 2.3: Voltage Q-Droop Control

2.1.3 Voltage Iq-Droop

The block diagram for this option is shown in Figure 2.4. The Voltage Iq-Droop control corresponds to a reactive current controller, in which the reactive current is calculated in proportion to the deviation from the voltage set point entered in the element.

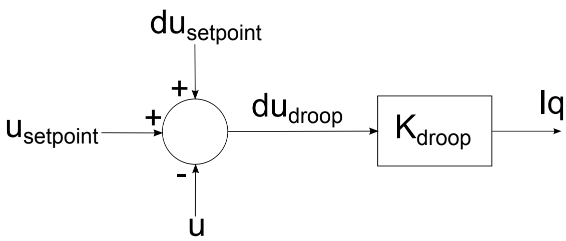

Figure 2.4: Voltage Iq-Droop Control

The voltage reactive current droop in p.u. is based on the rated active current of the machine and calculated as follows:

$$u = u_{setpoint} + du_{setpoint} - \Delta u_{droop} \tag{5}$$

$$\Delta u_{droop} = \frac{Iq - Iq_{setpoint}}{K_{droop} \cdot Ip_r} \tag{6}$$

$$K_{droop} = \frac{100}{ddroop} \tag{7}$$

with the reactive current setpoint:

$$Iq_{setpoint} = \frac{qgini \cdot ngnum}{\sqrt{3} \cdot U_{nom}} \tag{8}$$

and with the rated active current:

$$Ip_r = \frac{sgn \cdot ngnum \cdot cosn}{\sqrt{3} \cdot U_r} \tag{9}$$

Where:

- u is the actual voltage value at the terminal
- $u_{setpoint}$ is the specified voltage setpoint
- Δu_{droop} is the voltage deviation
- $du_{setpoint}$ is the voltage signal coming from the station controller, when the station controller is set to *Voltage Setpoint Adaptation* method, otherwise is zero by default. Please consult the Technical Reference of the Station Controller
- Iq is the reactive current output of the machine in kA
- $Iq_{setpoint}$ is the reactive current setpoint of the machine in kA
- K_{droop} is the gain
- $ddroop$ is the voltage droop value specified in percentage
- $qgini$ is the reactive power setpoint in MVA
- $ngnum$ is the number of parallel machines
- U_{nom} is the nominal voltage of the corresponding connected busbar in kV
- U_r is the rated voltage of the machine in kV
- Ip_r is the rated active current in kA
- sgn is the rated apparent power in MVA
- $cosn$ is the rated power factor

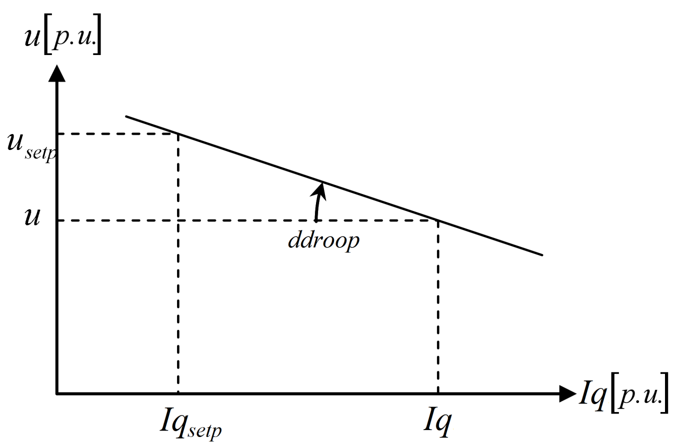

Figure 2.5: Voltage Iq-Droop Control

The dispatched reactive current is calculated by using the nominal voltage of the connected busbar instead of the rated voltage of the machine.

2.1.4 Const. Q

The Local Controller defined as “Const. Q” is typically used for smaller synchronous generators, like the ones embedded in distribution grids, where the power factor is keep constant (“PQ” mode). With this type of control, the user can specify the active and reactive power dispatch of the generator. These parameters can be specificated in different ways, depending on the selected *Input Mode*.

The Voltage and Angle boxes are disabled for the “Const. Q” control option. P_{sum} and Q_{sum} will be controlled in unbalanced load flow.

2.1.5 Q(P)-Characteristic

The Q(P) characteristic is a reactive power control and follows a user-specified characteristic as shown in the picture 2.6.

The local controller acts as a reactive power controller in which the reactive power setpoint is adapted according to the active power output of the machine.

The Q(P)-Curve is specified using the element *Q(P)-Curve* (*IntQpcurve*).

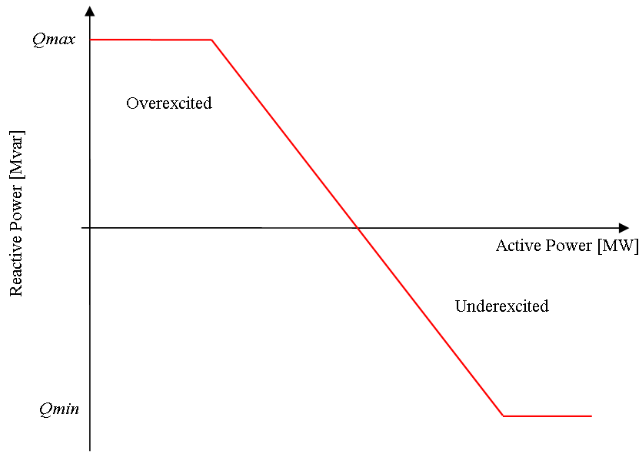

Figure 2.6: Q(P)-Characteristic

2.1.6 Const. cosphi

The local controller acts as a reactive power controller in which the reactive power setpoint is adapted according to the active power output of the machine, such that the specified power factor is kept constant.

For most cases, the active power setpoint does not vary during the solution, and therefore this mode acts as a constant reactive power control (see Section 2.1.4). However, for the cases where the generator is a slack, or a secondary controller is activated, or the load flow balancing is based on distributed slack by synchronous generators, then the active power output varies during the solution and this control mode is employed.

2.2 Reactive Power Limits

There are several ways for specifying reactive power limits:

- Fix reactive power limits in the element
- Fix reactive power limits in the type
- Capability Curve

Generally, reactive power limits are only considered, if the synchronous machine is set to voltage control (Const.V) and the load flow option *Consider reactive power limits* is enabled in the Load Flow Calculation command. If this option is disabled and the specified reactive power limits are exceeded, *PowerFactory* generates a warning message but doesn't apply any actual limit to the generator's reactive power output.

In the case that it is difficult to achieve a well balanced load flow state, an additional scaling factor can be applied to the reactive power limits. This scaling factor is more for "debugging reasons" and doesn't have any physical interpretation. The reactive scaling factor is only considered if the load flow option *Consider Reactive Power Limits Scaling Factor* is enabled.

2.2.1 Fix reactive power limits

Fix reactive power limits can either be specified at Element or Type level of the synchronous machine. Type limits are used when the option *Use Limits Specified in Type* is enabled, otherwise, the model takes the Element limits that can either be defined on a p.u.-basis or using actual units (Mvar).

2.2.2 Capability Curve

The capability curve allows specifying a complete, active power and voltage dependent capability diagram. User-defined capability diagrams are defined using the object *IntQlim*, which is stored in the Operational Library. Refer to the User Manual for more information.

For assigning a capability diagram to a Synchronous Machine Element, the corresponding reference (pQlim) must be set. If this pointer is assigned, all other attributes relating to reactive power limits are hidden and the local capability diagram of the Synchronous Machine Element displays the reactive power limits defined by the *Capability Curve* object (*IntQlim*) at nominal voltage.

2.3 Active Power Control and Balancing

2.3.1 Fix Active Power

Active power will be set to a fix value if:

- Option *Reference Machine* is disabled
- No *External Secondary Controller* object is selected
- No *Primary Frequency Bias* is defined

Besides these local settings, the corresponding options on the *Active Power Control* page of the Load Flow Calculation command either activate or deactivate the influence of Secondary Controller or Primary Frequency Bias.

2.3.2 Reference Machine

The option *Reference Machine* has two consequences:

- Voltage angle at the machine's terminal is fixed.
- Machine balances active power if the *Active Power Control* option *as Dispatched* is selected and the *Balancing* option *by Reference Machine* is enabled, or the *Active Power Control according to Secondary Control* is selected and no Secondary Controller is specified in the network.

2.3.3 Primary Frequency Bias

The primary frequency bias is considered if:

- Parameter Kpf (in MW/Hz) is $>$0 and
- *Active Power Control* option *According to Primary Control* is selected

In this case, *PowerFactory* considers in all isolated grids a common frequency deviation ΔF and establishes an active power balance through this variable and the primary frequency bias of the individual generators:

$$P = P_0 + K_{pf} \cdot \Delta F$$

where:

- P: Actual active power in MW
- P0: Active power setpoint in MW
- Kpf: Primary frequency bias in MW/Hz
- ΔF: Frequency deviation in Hz

The "Primary Controlled Load Flow" represents that state of a power system 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, there is a deviation from nominal frequency. The corresponding calculation quantities (signal) for the frequency deviation can be found in the variable selection dialogue ($s : dFin$ in Hz).

2.3.4 External Secondary Controller

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 the "Secondary Controlled" state, which is an (artificial) steady state following the settling of the secondary control system:

- A Power Frequency Controlled has to be specified and assigned to the machine
- *Active Power Control* option *according to Secondary Control* has to be activated.

The actual active power of each generator is the defined by:

$$P = P_0 + K \cdot \Delta P_{SCO} \tag{10}$$

where:

- P: Actual active power of the machine in MW
- P0: Active power setpoint in MW
- K: Participation factor (to be specified in the power-frequency control object)
- dPsco: Total active power deviation of all units controlled by the respective power frequency controller.

For more information related to the *Power Frequency Controller* object, refer to the corresponding Technical Reference Manual.

2.3.5 Inertial Power Flow

During the first seconds following an active power disturbance such as a loss of generation or load, before the primary control takes over, the active power balance of the system is established by releasing energy from the rotating masses of all electrical machines.

This situation can be modelled by enabling the *Active Power Control* option *According to Inertias*. In this case, the variable dF represents an equivalent frequency rate of change and active power will be balanced according to the inertia of all generators (defined by the Acceleration Time Constant, to be found on the *RMS*- and *EMT-simulation* pages of the generator type *TypSym*).

2.3.6 Active Power: Operational Limits, Ratings

The active power rating can be entered as a rating factor on basis of the rated active power, which is calculated by the rated apparent power times the rated power factor (type-level). Derating of generators can be considered by entering a rating factor < 1.

When considering active power limits in a load flow calculation, *PowerFactory* makes reference to the Operational Limits (Min. and Max.).

These limits are considered when:

- Generator participates in the active power balancing
- Load Flow option *Consider Active Power Limits* is selected.

2.4 Wind Speed Input for Wind Generators

When the synchronous generator is a wind generator (Category = Wind) an additional option on the load flow page is available to either enter the active power directly (Active power input) or alternatively via wind speed (Wind speed input) and a corresponding wind power curve.

The active power in MW is then calculated as follow:

$$P = f(windspeed) \tag{11}$$

In case of the wind power curve is defined in p.u., the base value is the rated active power $P_r = sgn \cdot cosn$ in MW.

where:

- $windspeed$ is the wind speed in m/s
- $f(windspeed)$ is the corresponding calculated active power value from the wind power curve
- sgn is the rated apparent power
- $cosn$ is the rated power factor

The max. active power ($Pmax$) is automatically limited by the max. possible active power for the entered wind speed:

$$Pmax = Min(\ f(windspeed)\ or\ Pmax_{uc}) \tag{12}$$

where $Pmax_{uc}$ is the max. active power operational limit.

2.5 Spinning if circuit breaker is open

This option decides whether a synchronous machine can be used for driving an island-network. Typical applications are:

- Load flow set-up for a dynamic simulation of a synchronisation event.
- Island around this generator shall form a supplied island-grid when disconnected from the main-grid (e.g. during Contingency Analysis).

In case of contingencies that split the system two of more isolated areas, *PowerFactory* requires at least one synchronous generator with this option being enabled for assuming that the corresponding island can continue operating after having been islanded. Otherwise, the load flow calculation will assume a complete black out in the corresponding island (all loads and generators unsupplied).

3 Short-Circuit Analysis

For short-circuit analysis, depending on the considered time phase following a grid fault, synchronous machines are represented by their:

- Subtransient equivalent
- Transient equivalent
- Synchronous equivalent

The distinction of the time dependence is due to the effect of increased stator currents on the induced currents in the damper windings, rotor mass and field winding. In the case of a fault near to a generator the stator current can increase so that the resulting magnetic field weakens the rotor field considerably. In steady state short circuit analysis, this field-weakening effect is represented by the corresponding equivalent source voltage and reactance. The associated positive sequence model of a synchronous machine is shown in Figure 3.1. The delayed effect of the stator field on the excitation and damping field is modelled by using different reactances depending on the time frame of the calculation.

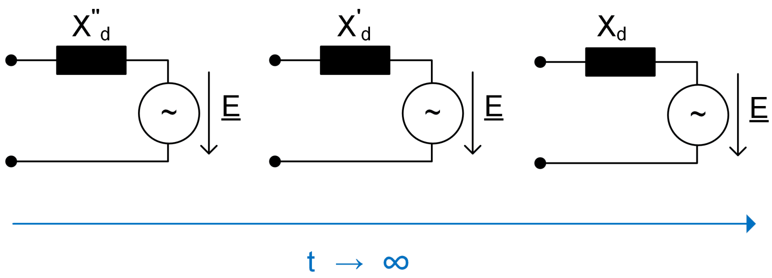

Figure 3.1: Single-phase equivalent circuit diagrams of a generator for short-circuit current calculations which include the modelling of the field attenuation

3.1 Calculation of transient and subtransient reactances

If only equivalent circuit data (please refer to section 6.1.1 for more information on dynamic data for the synchronous machine) is provided the short circuit impedances are calculated as follows [1]:

$$\begin{aligned} x'_d &= x_l + \frac{x_{ad} \cdot (x_{fd} + x_{rld})}{x_{ad} + x_{fd} + x_{rld}} \\ x''_d &= x_l + \frac{x_{1d} \cdot x_{fd} \cdot x_{ad} + x_{1d} \cdot x_{rld} \cdot x_{ad} + x_{rld} \cdot x_{fd} \cdot x_{ad}}{x_{ad} \cdot x_{fd} + x_{ad} \cdot x_{1d} + x_{1d} \cdot x_{fd} + x_{1d} \cdot x_{rld} + x_{rld} \cdot x_{fd}} \end{aligned} \tag{13}$$

If the parameter x_{rld} is not provided, the equation above becomes much simpler ($x_{rld} = 0$). The q-axis subtransient impedance is calculated as above, with using the q-axis instead of the d-axis parameters.

3.2 Short-Circuit According to IEC 60909 or VDE 102/103

The IEC 60909 (equivalent to VDE 102/103) series of standards only calculates the subtransient time phase. Short circuit currents of longer time phases are assessed based on empirical methods by multiplying the subtransient fault current with corresponding factors.

Figure 3.2 shows the basic IEC 60909 short circuit model of a synchronous machine.

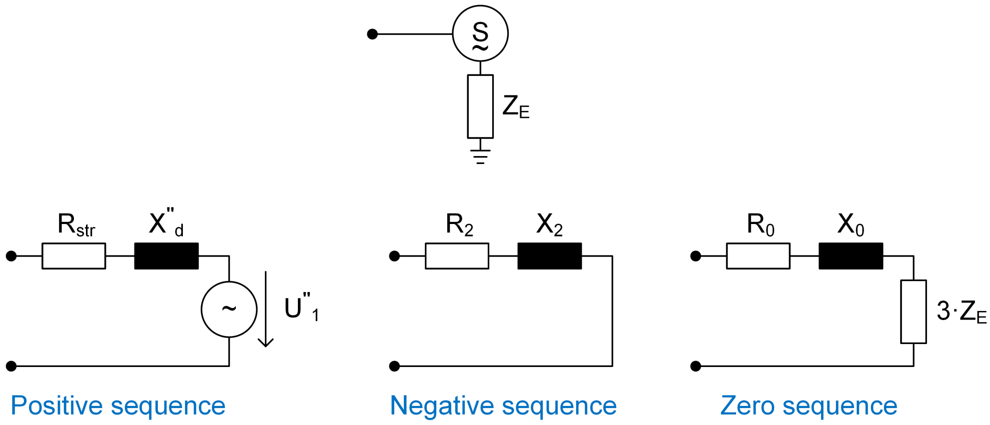

Figure 3.2: Short-circuit model for a synchronous machine

When calculating initial symmetrical (sub-transient) short-circuit currents in systems fed directly from generators without unit transformers, for example in industrial networks or in low-voltage networks, the following sequence-impedances have to be used:

- Positive sequence system:
$$\underline{z}_1'' = r_{str} + jx_d'' \tag{14}$$

- Negative sequence system:
$$\underline{z}_2 = r_2 + jx_2 \tag{15}$$
where normally it is assumed that $x_2 = x_d''$. If x_d'' and x_q'' differ significantly the following can be used:
$$x_2 = \frac{x_d'' + x_q''}{2} \tag{16}$$

- Zero sequence system:
$$\underline{z}_0 = r_0 + jx_0 \tag{17}$$

For the sub-transient reactance, the saturated value x_{dsat}'' has to be used leading to highest possible fault currents.

IEC 60909 (VDE 102/103) makes no provision of the pre-fault state. It always considers a voltage factor *cmax* of 1.1 (or 1.05 in LV-networks). Because this approach would lead to overestimated fault currents, the impedance is corrected by a correction factor. For power station units, the correction factor calculation takes into account the *Range of generator voltage Regulation* parameter pG which is located on the *Short-Circuit VDE/IEC* tab of *ElmSym*.

All short circuit indices are calculated precisely according to the IEC 60909 (VDE 102/103) standard.

3.3 Complete Short Circuit Method

In the complete short circuit method, the internal voltage source can be initialised by a preceding load flow calculation.

The complete short circuit method calculates subtransient and transient fault currents using subtransient and transient voltage sources and impedances. The subtransient impedances are calculated as in section 3.2. The positive sequence transient impedance is calculated as:

$$\underline{z}_1' = r_{str} + \jmath x_d' \tag{18}$$

Based on the calculated subtransient and transient (AC-) currents, *PowerFactory* derives other relevant short-circuit indices, such as peak short circuit current, peak-break current, AC-break current, equivalent thermal short circuit current by applying the relevant methods according to IEC60909.

3.3.1 Single phase machine model

The single phase machine is supported only by the complete short circuit method.

The transient and subtransient short circuit models for the single-phase machine are also modelled as a single impedance and a voltage source. The transient and sub-transient impedances used for the transient and sub-transient short circuit calculation are:

$$\begin{aligned} \underline{z}' &= r_{str} + \jmath \cdot \frac{\left(x_d' + \dfrac{x_d'' + x_q''}{2}\right)}{2} \\ \underline{z}'' &= r_{str} + \jmath \cdot \frac{\left(x_d'' + \dfrac{x_d'' + x_q''}{2}\right)}{2} \end{aligned} \tag{19}$$

3.4 ANSI-C37 Short-Circuit

Besides IEC 60909, *PowerFactory* supports short circuit calculation according to ANSI C-37. Similar to short circuit calculations according to IEC 60909, only subtransient fault currents are actually calculated.

For further details related to ANSI C-37, refer to the original ANSI C-37 standard and corresponding literature.

3.5 IEC 61363 Short-Circuit

The IEC 61363 standard describes procedures for calculating short-circuits currents in three-phase ac radial electrical installations on ships and on mobile and fixed offshore units.

The calculation of the short-circuit current for a synchronous machine is based on evaluating the envelope of the maximum values of the machine's actual time-dependent short-circuit current. The resulting envelope is a function of the basic machine parameters (power, impedance, etc.) and the active voltages behind the machine's subtransient, transient and steady-state impedance. The impedance is dependent upon the machine operating conditions immediately prior to the occurrence of the short-circuit condition.

When calculating the short-circuit current, only the highest values of the current are considered. The highest values vary as a function of time along the top envelope of the complex time-dependent function. The current defined by this top envelope is calculated from the equation:

$$i_K(t) = \sqrt{2} \cdot I_{ac}(t) + i_{dc}(t) \tag{20}$$

The a.c. component $I_{ac}(t)$ is calculated with:

$$I_{ac}(t) = (I''_{kd} - I'_{kd}) \cdot e^{-t/T''_d} + (I'_{kd} - I_{kd}) \cdot e^{-t/T'_d} + I_{kd} \tag{21}$$

The subtransient, transient and steady-state currents are evaluated using equations:

$$I''_{kd} = E''_{q0}/Z''_d \;\text{ with }\; \underline{Z}''_d = (R_{str} + \jmath X''_d) \tag{22}$$

and:

$$I'_{kd} = E'_{q0}/Z'_d \;\text{ with }\; \underline{Z}'_d = (R_{str} + \jmath X'_d) \tag{23}$$

Internal voltages considering terminal voltage and pre-load conditions are calculated using equations:

$$E''_{q0} = \underline{U}_0/\sqrt{3} + \underline{I}_0 \cdot \underline{Z}''_d \tag{24}$$

$$E'_{q0} = \underline{U}_0/\sqrt{3} + \underline{I}_0 \cdot \underline{Z}'_d \tag{25}$$

The d.c. component can be evaluated from equation:

$$I_{dc}(t) = \sqrt{2} \cdot (I''_{kd} - I_0 \cdot \sin\phi_0) \cdot e^{-t/T_{dc}} \tag{26}$$

4 Optimal Power Flow

The Optimal Power Flow (OPF) function in *PowerFactory* allows the user to calculate optimal operational conditions, e.g. the minimisation of losses or production costs by adjusting the active and reactive power dispatch of the generators.

To consider the synchronous machine in the OPF calculation the following options have to be assigned on the *Optimal Power Flow* page of the synchronous machine element.

4.1 OPF Controls

It is possible to enable and disable the active and reactive power optimisation of the machine. The active power flag allows the active power dispatch of the machine to be optimised in the *OPF* calculation. On the other hand, the reactive power flag allows the voltage reference of the machine to be adapted according to the *OPF* optimisation function.

When these options are disabled, the synchronous machine is treated as in a conventional load flow calculation during the execution of the *OPF*.

4.2 Constraints: Active / Reactive Power Limits

For every machine a minimum and maximum active and reactive power limit can be defined. For the reactive power limits there is also the possibility to use the limits which are specified in the synchronous machine type (enable the flag *Use limits specified in type*) or include a capability curve (see section 2.2.

The active and reactive power limits will be considered in the *OPF* if and only if the individual constraint flag is checked in the synchronous machine element and the corresponding global flag is enabled in the Optimal Power Flow command.

4.3 Operating Cost

The operating costs of the synchronous machine are defined on the *Operating Cost* The table Operating Costs specifies the costs ($/h) for the produced active power (MW) of the units. The representation of the data is shown automatically on the diagram below the table for checking purposes. The cost curve of a synchronous machine is calculated as the interpolation of the predefined cost points.

5 Harmonic Analysis

For frequency sweep calculation the synchronous machine is represented by an *Impedance* model. For harmonic load flow calculation, two additional models are available: *Thevenin Equivalent* and *Ideal Voltage Source*. The harmonic voltages given in the harmonic voltage source object are referred to the rated voltage of the synchronous machine.

The equivalent circuits of *Impedance* and the *Thevenin Equivalent* model for harmonics are shown in Figures 5.1 and 5.2 (using absolute values).

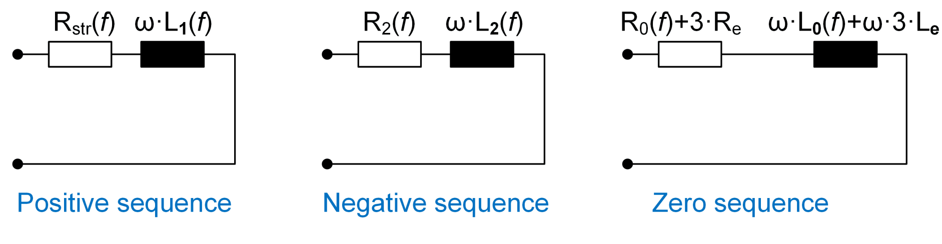

Figure 5.1: Harmonic load flow impedance model

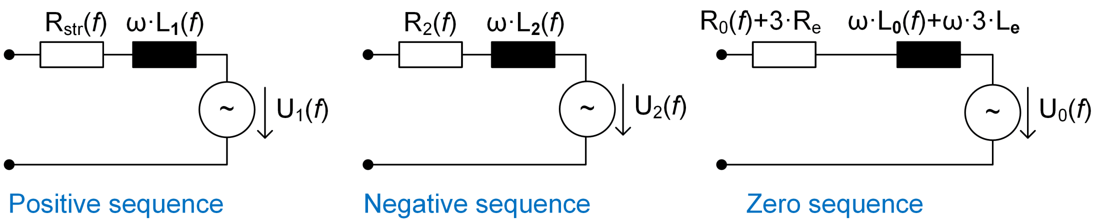

Figure 5.2: Harmonic load flow thevenin equivalent model

5.1 Frequency dependency

The input parameters for the reactances in the model are valid at the fundamental frequency. Therefore, the per-unit values of the inductances and reactances are equivalent for frequency f equal to the base frequency $f_{base} = f_{nom}$:

$$x = \frac{\omega}{\omega_{base}} \cdot \frac{L}{L_{base}} \quad \frac{[\Omega]}{[\Omega]} = \frac{2 \cdot \pi \cdot f}{2 \cdot \pi \cdot f_{nom}} \cdot \frac{L}{L_{base}} \quad \frac{[\Omega]}{[\Omega]} = \frac{f}{f_{nom}} \cdot l = l \quad [p.u.] \tag{27}$$

The impedances in the harmonic analysis functions have frequency-dependent reactances due to the change in frequency in the term $\omega_{nom} \cdot L$. In addition, it is possible to consider the frequency dependency of the inductances $l(f)$ and resistances $r(f)$:

$$z(f) = r(f) + \jmath \cdot x(f) = r(f) + \jmath \cdot \frac{f}{f_{nom}} \cdot l(f) = r(f) + \jmath \cdot h \cdot l(f) \tag{28}$$

where $h = f/f_{nom}$ is the harmonic order.

This frequency dependency of the inductances $l(f)$ and resistances $r(f)$ can be modelled using characteristics.
Several types of characteristics can be applied to the resistances and reactances, as shown on the *Harmonics/Power Quality* page of the synchronous machine type (*TypSym*) dialog:

- Frequency Polynomial Characteristic (*ChaPol*)

- Vector Characteristic (*ChaVec*)
- Matrix Characteristic (*ChaMat*)

For example, when using the vector characteristic, values for the resistance can be entered for predefined frequencies (defined through a frequency scale). When using the frequency polynomial characteristic, the stator resistance can be made frequency dependent using the parameters a and b according to the functions:

$$\begin{aligned} r_{str}(f) &= r_{str} \cdot k(f) = r_{str} \cdot \left((1-a) + a \cdot (f/f_{nom})^b\right) \\ r_{str}(f) &= r_{str} \cdot k(f) = r_{str} \cdot \left(1 + a \cdot ((f/f_{nom}) - 1)^b\right) \end{aligned} \tag{29}$$

5.2 Impedance calculation

There are two methods available to calculate the impedance:

- Using standard parameters
- Using frequency transfer functions

5.2.1 Calculation using standard parameters

In the presence of harmonic currents, the average inductance is approximated by:

$$l'' = \frac{l''_d + l''_q}{2} \tag{30}$$

If a characteristic is applied to l'', then the resulting value is $l''(f)$. The sequence and grounding impedance are then calculated as:

$$\begin{aligned} z_1(f) &= r_{str}(f) + \jmath \cdot h \cdot l''(f) \\ z_2(f) &= r_2(f) + \jmath \cdot h \cdot l_2(f) \\ z_0(f) &= r_0(f) + \jmath \cdot h \cdot l_0(f) \\ z_e(f) &= r_e + \jmath \cdot h \cdot l_e \end{aligned} \tag{31}$$

where the internal grounding impedance per-unit values are calculated as $(r_{esy} + \jmath \cdot x_{esy})/z_b = r_e + \jmath \cdot x_e$ using the base impedance $z_b = ugn^2/sgn$ (ugn is the rated voltage of the machine and sgn is the rated apparent power).

5.2.2 Calculation using frequency transfer functions (operational inductances)

If the option *Use frequency transfer functions* is enabled, the harmonic inductance is calculated using the input parameters provided on the RMS/EMT tabs of the *TypSym* dialog. Because of the accurate representation around nominal frequency, this model can increase the accuracy of sub-synchronous resonance studies based on frequency domain analysis. The effect of the transient and synchronous reactance is visible only in a very narrow band around nominal frequency (Figure 5.3).

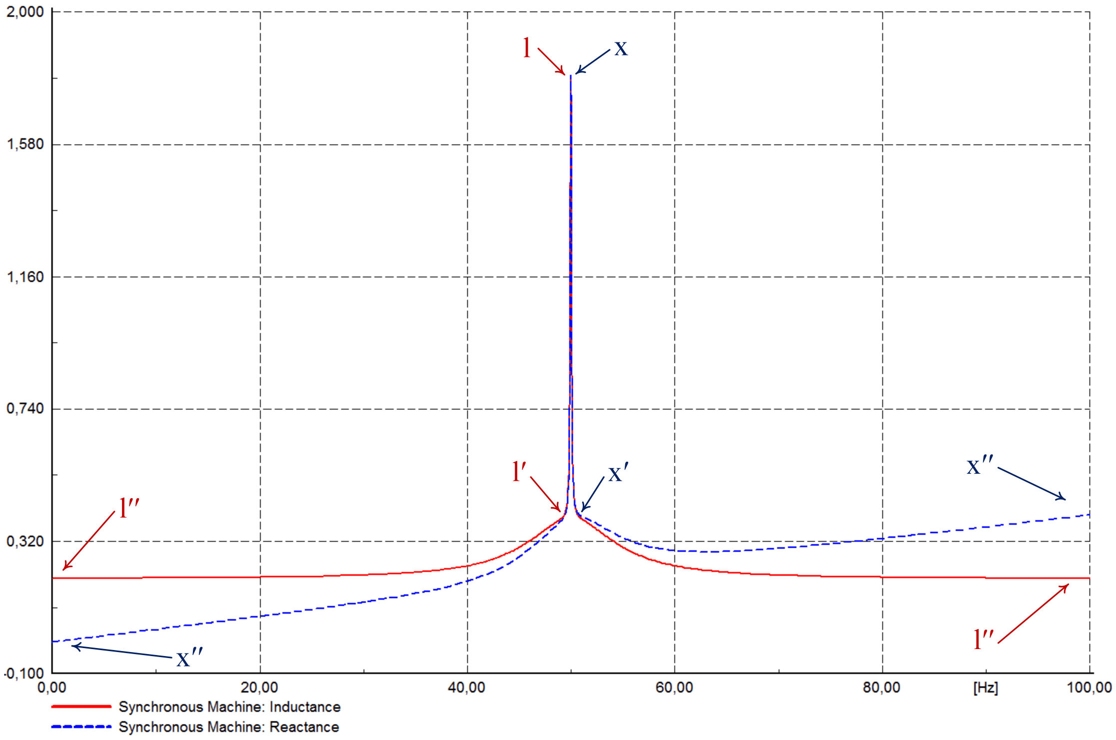

Figure 5.3: Frequency domain representation of synchronous machine using the option *Use frequency transfer functions*

The positive and negative sequence impedances are calculated using the operational inductances for the d and q axes as shown in Equation 32 (where s is the Laplace operator).

$$l_d(s) = l_d \cdot \frac{(1 + s \cdot t'_d) \cdot (1 + s \cdot t''_d)}{(1 + s \cdot t'_{d0}) \cdot (1 + s \cdot t''_{d0})}$$
$$l_q(s) = l_q \cdot \frac{(1 + s \cdot t'_q) \cdot (1 + s \cdot t''_q)}{(1 + s \cdot t'_{q0}) \cdot (1 + s \cdot t''_{q0})} \tag{32}$$

Equation 32 is valid for the standard round rotor synchronous machine model in *PowerFactory*. For the standard salient pole machine model, the parameters t'_q and t'_{q0} are zero and the terms $(1 + s \cdot t'_q)$ and $(1 + s \cdot t'_{q0})$ are neglected (this is valid for all following equations based on operational inductances).
Similarly, the operational inductances of the 3.3 model have an additional term in the numerator and denominator, utilising the sub-subtransient short-circuit and open-loop time constants t'''_d, t'''_{d0}, t'''_q and t'''_{q0}.

This option is not supported for the classical model and the model for asynchronous starting.

The frequency dependent inductances have the form:

$$\underline{l}_d(f) = l_d \cdot \frac{(1 + \jmath \cdot \omega \cdot t'_d) \cdot (1 + \jmath \cdot \omega \cdot t''_d)}{(1 + \jmath \cdot \omega \cdot t'_{d0}) \cdot (1 + \jmath \cdot \omega \cdot t''_{d0})}$$
$$\underline{l}_q(f) = l_q \cdot \frac{(1 + \jmath \cdot \omega \cdot t'_q) \cdot (1 + \jmath \cdot \omega \cdot t''_q)}{(1 + \jmath \cdot \omega \cdot t'_{q0}) \cdot (1 + \jmath \cdot \omega \cdot t''_{q0})} \tag{33}$$

where $\omega = \omega_{nom} \cdot (h - 1)$ for the positive sequence and $\omega = \omega_{nom} \cdot (-h - 1)$ for the negative sequence inductances.

The positive and negative sequence impedances are then calculated as:

$$
\begin{aligned}
z_1(f) &= r_{str}(f) + \jmath \cdot h \cdot \frac{\underline{l}_{d1}(f) + \underline{l}_{q1}(f)}{2} \\
z_2(f) &= r_{str}(f) + \jmath \cdot h \cdot \frac{\underline{l}_{d2}(f) + \underline{l}_{q2}(f)}{2}
\end{aligned} \tag{34}
$$

The zero sequence and grounding impedances are calculated as in Equation 31.

Depending on the input data available for the model, the time constants for the operational inductances are taken directly or calculated from the input parameters:

- Short-circuit input data - standard model

  The short-circuit time constants are taken directly from the input data and the open-loop time constants for the standard model are calculated as (using standard assumptions):

$$
\begin{aligned}
t'_{d0} &= t'_d \cdot \frac{l_d}{l'_d} \\
t''_{d0} &= t''_d \cdot \frac{l'_d}{l''_d} \\
t'_{q0} &= t'_q \cdot \frac{l_q}{l'_q} \\
t''_{q0} &= t''_q \cdot \frac{l'_q}{l''_q}
\end{aligned} \tag{35}
$$

  For the salient pole machine, the q-axis time constants are calculated as:

$$
\begin{aligned}
t'_{q0} &= 0 \\
t''_{q0} &= t''_q \cdot \frac{l_q}{l''_q}
\end{aligned} \tag{36}
$$

- Equivalent circuit parameters input data - standard and 3.3 models

  From the equivalent circuit parameters, the open-loop time constants and dynamic inductances are calculated according to [2] and [3]. The short-circuit time constants are then calculated according to Equation 35 and:

$$
\begin{aligned}
t'''_d &= t'''_{d0} \cdot \frac{l'''_d}{l''_d} \\
t'''_q &= t'''_{q0} \cdot \frac{l'''_q}{l''_q}
\end{aligned} \tag{37}
$$

- Operational inductances as input data - 3.3 model

  In this case no calculation is possible since the data used in the operational reactances is available. The time constants $t_{1d}, t_{2d}, t_{3d}, t_{1q}, t_{2q}, t_{3q}$ are the short-circuit time constants and $t_{4d}, t_{5d}, t_{6d}, t_{4q}, t_{5q}, t_{6q}$ are the open-loop time constants.

5.2.3 Impedance calculation for the single-phase model

The impedance for the single-phase machine is calculated similar as for the three phase machine model (equations 31 or equations 39). Depending on the calculation method we have the following:

- Using standard parameters

$$z(f) = r_{str}(f) + \jmath \cdot h \cdot l''(f) \tag{38}$$

- Using frequency transfer functions

$$z(f) = r_{str}(f) + \jmath \cdot h \cdot \frac{\frac{\underline{l}_{d1}(f) + \underline{l}_{q1}(f)}{2} + \frac{\underline{l}_{d2}(f) + \underline{l}_{q2}(f)}{2}}{2} \tag{39}$$

6 RMS/EMT Simulation

In the following subsections the available synchronous machine models together with the input and output signals and state variables used for the RMS and EMT simulation are presented. In the appendix B, the calculation of some additional parameters is presented.

6.1 Standard Model

Figures 6.1 to 6.3 show the equivalent circuit diagrams of the standard *PowerFactory* synchronous machine model, which are represented in a rotor reference system (Park coordinates, dq-reference frame).

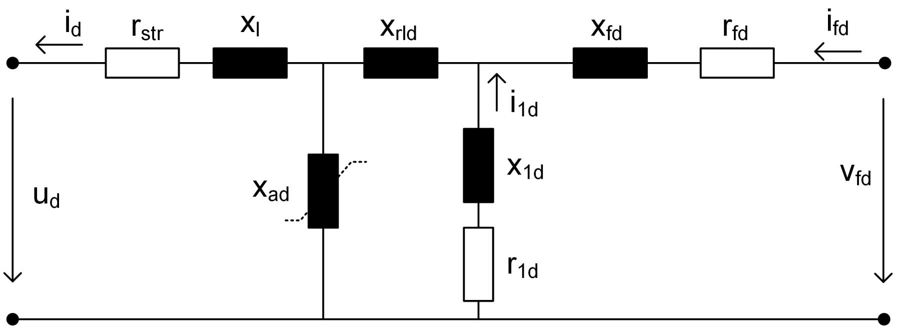

Figure 6.1: d-axis equivalent circuit

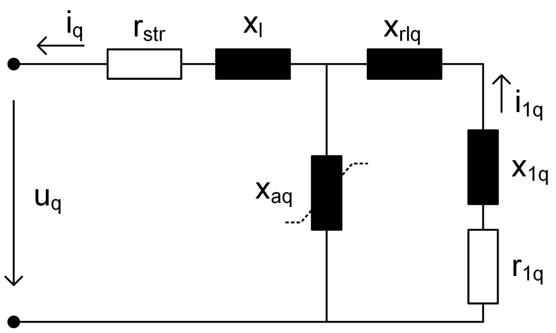

Figure 6.2: q-axis equivalent circuit - salient rotor

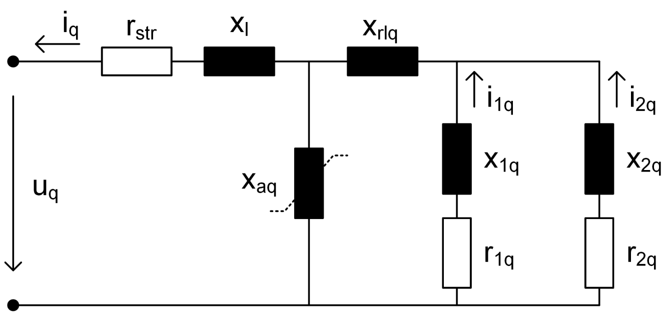

Figure 6.3: q-axis equivalent circuit - round rotor

The rotor d-axis is always modelled by two rotor loops representing the excitation (field) winding and the 1d-damper winding. For the q-axis, *PowerFactory* supports two models, a salient-pole rotor machine model having only the 1q-damper winding and a round-rotor machine model with the 1q- and 2q-damper windings. According to the designation in the IEEE guide [4], these two models can also be referred to as Model 2.1 and Model 2.2, respectively. The model is based on [5], [6].

The equations presented in this section are valid for the round-rotor machine. The equations for the salient-rotor machine can be obtained by ignoring the 2q-damper winding variables and equations.

The standard *PowerFactory* model is written using subtransient variables. An overview of the basic equations of the synchronous machine together with how the subtransient model is obtained is given in Section 6.1.2.

6.1.1 Input Parameters

The typical parameters available for a synchronous machine are the short-circuit parameters. They can be entered directly into the standard *PowerFactory* synchronous machine model (*TypSym*) and are listed in Table 6.1.

Table 6.1: Standard input parameters of the synchronous machine

Name in PF	Symbol	Unit	Description
$rstr$	r_{str}	$p.u.$	Stator resistance
xl	x_l	$p.u.$	Stator leakage reactance
xrl	x_{rld}	$p.u.$	Coupling reactance between field and damper winding
$xrlq$	x_{rlq}	$p.u.$	Coupling reactance between q-axis damper windings
xd	x_d	$p.u.$	Synchronous reactance d-axis
xq	x_q	$p.u.$	Synchronous reactance q-axis
xds	x'_d	$p.u.$	Transient reactance d-axis
xqs	x'_q	$p.u.$	Transient reactance q-axis
$xdss$	x''_d	$p.u.$	Subtransient reactance d-axis
$xqss$	x''_q	$p.u.$	Subtransient reactance q-axis
tds	t'_d	s	Short-circuit transient time constant d-axis
tqs	t'_q	s	Short-circuit transient time constant q-axis
$tdss$	t''_d	s	Short-circuit subtransient time constant d-axis
$tqss$	t''_q	s	Short-circuit subtransient time constant q-axis

As shown in Table 6.1, the short-circuit and not the open-loop time constants are used by the model. If open-loop time constants are selected as input ($tdss0$ (t''_{do}), $tqss0$ (t''_{qo}), $tds0$ (t'_{do}) and $tqs0$ (t'_{qo})), the short circuit time constants are automatically calculated during the entering of the open-loop constants in the synchronous machine type. The calculated values (values used by the model) can be seen if the input mode is switched to short-circuit time constants. There are two ways to calculate the short-circuit from the open-loop time constants:

- Standard procedure (using simplifications)

The conversion in this case is carried out as follows:

$$
\begin{aligned}
t''_d &= t''_{do} \cdot \frac{x''_d}{x'_d} \\
t''_q &= t''_{qo} \cdot \frac{x''_q}{x'_q} \\
t'_d &= t'_{do} \cdot \frac{x'_d}{x_d} \\
t'_q &= t'_{qo} \cdot \frac{x'_q}{x_q}
\end{aligned} \tag{40}
$$

In the case of a salient pole machine (the transient reactance x'_q and the transient time constant t'_q in the q-axis are not needed) the subtransient time constant t''_q is calculated using x_q instead of x'_q.

- Exact procedure

  The exact procedure is based on [7] and requires solution of a quadratic equation which is obtained from the following equations:

$$
\begin{aligned}
t'_{do} + t''_{do} &= \frac{x_d}{x'_d} \cdot t'_d + \left(1 - \frac{x_d}{x'_d} + \frac{x_d}{x''_d}\right) \cdot t''_d \\
t'_{do} \cdot t''_{do} &= \frac{x_d}{x''_d} \cdot t'_d \cdot t''_d
\end{aligned} \tag{41}
$$

  The option *Exact conversion of time constants* is available in the *Advanced* tab of the synchronous machine type.

Table 6.2: Model parameters of the synchronous machine

Name in PF	**Symbol**	**Unit**	**Description**
$rstr$	r_{str}	$p.u.$	Stator resistance
xl	x_l	$p.u.$	Stator leakage reactance
xrl	x_{rld}	$p.u.$	Coupling reactance between field and damper winding
$xrlq$	x_{rlq}	$p.u.$	Coupling reactance between q-axis damper windings
xad	x_{ad}	$p.u.$	Mutual (magnetising) reactance, d-axis
xaq	x_{aq}	$p.u.$	Mutual (magnetising) reactance, q-axis
xfd	x_{fd}	$p.u.$	Reactance of excitation (field) winding (d-axis)
$x1d$	x_{1d}	$p.u.$	Reactance of 1d-damper winding (d-axis)
$x1q$	x_{1q}	$p.u.$	Reactance of 1q-damper winding (q-axis)
$x2q$	x_{2q}	$p.u.$	Reactance of 2q-damper winding (q-axis)
rfd	r_{fd}	$p.u.$	Resistance of excitation winding (d-axis)
$r1d$	r_{1d}	$p.u.$	Resistance of 1d-damper winding (d-axis)
$r1q$	r_{1q}	$p.u.$	Resistance of 1q-damper winding (q-axis)
$r2q$	r_{2q}	$p.u.$	Resistance of 2q-damper winding (q-axis)

The parameters used by the model internally are the parameters shown in the equivalent circuits (Figure 6.1 to Figure 6.3) and are listed in Table 6.2. If available, the equivalent circuit parameters can be directly entered in the standard *PowerFactory* model.

The impedance base is calculated using the rated voltage and rated apparent power as $\frac{ugn^2}{sgn}$. The rotor variables are referred to the stator windings.

6.1.1.1 Conversion of Short-Circuit to Equivalent Circuit Parameters

From the short-circuit input parameters, the equivalent damper winding resistances and reactances can be calculated. *PowerFactory* applies an exact parameter conversion method as described in [8] and presented in [5] and [6]. Please note that the conversion is done when the RMS/EMT simulation is being initialised and the equivalent circuit type parameters are not being updated. The result parameters of the conversion process are available as calculation parameters.

The mutual reactances can be obtained from the synchronous and leakage reactances as follows:

$$\begin{aligned} x_{ad} &= x_d - x_l \\ x_{aq} &= x_q - x_l \end{aligned} \tag{42}$$

Using the help variables x_1, x_2, x_3, T_1, T_2, a and b, the equivalent model parameters for the d-axis are calculated as follows:

$$\begin{aligned} x_1 &= x_d - x_l + x_{rld} \\ x_2 &= x_1 - \frac{(x_d - x_l)^2}{x_d} \\ x_3 &= \frac{x_2 - x_1 \cdot \dfrac{x''_d}{x_d}}{1 - \dfrac{x''_d}{x_d}} \end{aligned} \tag{43}$$

$$\begin{aligned} T_1 &= \frac{x_d}{x'_d} \cdot t'_d + \left(1 - \frac{x_d}{x'_d} + \frac{xd}{x''_d}\right) \cdot t''_d \\ T_2 &= t'_d + t''_d \end{aligned} \tag{44}$$

$$\begin{aligned} a &= \frac{x_2 \cdot T_1 - x_1 \cdot T_2}{x_1 - x_2} \\ b &= \frac{x_3}{x_3 - x_2} \cdot t'_d \cdot t''_d \end{aligned} \tag{45}$$

$$\begin{aligned} T_{\sigma fd} &= \frac{-a}{2} + \sqrt{\frac{a^2}{4} - b} \\ T_{\sigma 1d} &= \frac{-a}{2} - \sqrt{\frac{a^2}{4} - b} \end{aligned} \tag{46}$$

$$\begin{aligned} x_{fd} &= \frac{T_{\sigma fd} - T_{\sigma 1d}}{\dfrac{T_1 - T_2}{x_1 - x_2} + \dfrac{T_{\sigma 1d}}{x_3}} \\ x_{1d} &= \frac{T_{\sigma 1d} - T_{\sigma fd}}{\dfrac{T_1 - T_2}{x_1 - x_2} + \dfrac{T_{\sigma fd}}{x_3}} \\ r_{fd} &= \frac{x_{fd}}{\omega_n \cdot T_{\sigma fd}} \\ r_{1d} &= \frac{x_{1d}}{\omega_n \cdot T_{\sigma 1d}} \end{aligned} \tag{47}$$

where $w_n = 2 \cdot \pi \cdot Fnom$ is the nominal angular frequency.

The q-axis model parameters can be calculated analogously to the d-axis parameters in case of a round-rotor machine (two rotor-loops). For a salient pole machine (one rotor loop), the model parameters can be calculated as follows:

$$\begin{aligned} x_{1q} &= \frac{(x_q - x_l) \cdot (x''_q - x_l)}{x_q - x''_q} \\ r1q &= \frac{x''_q}{x_q} \cdot \frac{x_q - x_l + x_{1q}}{\omega_n \cdot t''_q} \end{aligned} \tag{48}$$

6.1.2 Equations for the standard model in *PowerFactory*

The equations are written using the dq rotor reference frame in generator orientation.

The standard *PowerFactory* synchronous machine model for time domain simulations uses the rotor fluxes, the speed n and the angle φ as state variables. The equations for both the RMS and EMT model are written using subtransient variables.

In the case of balanced RMS simulation, the available simulated values are positive sequence complex values. In the case of unbalanced RMS simulation, the available complex phase values for currents and voltages are first transformed into symmetrical components. For transforming to the dq-reference frame, the variables are shifted by multiplying with the transformation $\cos\varphi - \jmath \cdot \sin\varphi$. The voltages and currents available from the EMT simulation are first transformed from instantaneous values in the $\alpha\beta\gamma$ system using the Clarke transformation. The same transformation as above is used for transforming to the dq rotating reference frame.

Based on the equivalent circuit diagrams according to Figure 6.1 to Figure 6.3, the differential equations for the model can be derived.

The stator voltage equations can be described as follows:

$$\begin{aligned} u_d &= -r_{str} \cdot i_d - n \cdot \psi_q + \frac{1}{\omega_n} \cdot \frac{d\psi_d}{dt} \\ u_q &= -r_{str} \cdot i_q + n \cdot \psi_d + \frac{1}{\omega_n} \cdot \frac{d\psi_q}{dt} \\ u_0 &= -r_{str} \cdot i_0 + \frac{1}{\omega_n} \cdot \frac{d\psi_0}{dt} \end{aligned} \tag{49}$$

where n is the speed of the rotor and $\omega_n = 2 \cdot \pi \cdot f_{nom}$ is the nominal angular frequency.

The stator flux linkage equations in the d- and q-axis have the following form:

$$\begin{aligned} \psi_d &= -(x_l + x_{ad}) \cdot i_d + x_{ad} \cdot i_{fd} + x_{ad} \cdot i_{1d} \\ \psi_q &= -(x_l + x_{aq}) \cdot i_q + x_{aq} \cdot i_{2q} + x_{aq} \cdot i_{1q} \end{aligned} \tag{50}$$

The stator flux equations can be also written in the following form:

$$\begin{aligned} \psi_d &= \psi_{ad} - x_l \cdot i_d \\ \psi_q &= \psi_{aq} - x_l \cdot i_q \end{aligned} \tag{51}$$

where ψ_{ad} and ψ_{aq} are the d- and q-axis components of the magnetising flux:

$$\begin{aligned} \psi_{ad} &= x_{ad} \cdot (-i_d + i_{1d} + i_{fd}) \\ \psi_{aq} &= x_{aq} \cdot (-i_q + i_{1q} + i_{2q}) \end{aligned} \tag{52}$$

The rotor flux linkage equations in the d- and q-axis have the following form:

$$\begin{aligned}
\psi_{fd} &= -x_{ad} \cdot i_d + (x_{ad} + x_{rld} + x_{fd}) \cdot i_{fd} + (x_{ad} + x_{rld}) \cdot i_{1d} \\
\psi_{1d} &= -x_{ad} \cdot i_d + (x_{ad} + x_{rld}) \cdot i_{fd} + (x_{ad} + x_{rld} + x_{1d}) \cdot i_{1d} \\
\psi_{1q} &= -x_{aq} \cdot i_q + (x_{aq} + x_{rlq}) \cdot i_{2q} + (x_{aq} + x_{rlq} + x_{1q}) \cdot i_{1q} \\
\psi_{2q} &= -x_{aq} \cdot i_q + (x_{aq} + x_{rlq} + x_{2q}) \cdot i_{2q} + (x_{aq} + x_{rlq}) \cdot i_{1q}
\end{aligned} \tag{53}$$

Introducing the subtransient fluxes:

$$\begin{aligned}
\psi_d'' &= k_{fd} \cdot \psi_{fd} + k_{1d} \cdot \psi_{1d} \\
\psi_q'' &= k_{1q} \cdot \psi_{1q} + k_{2q} \cdot \psi_{2q}
\end{aligned} \tag{54}$$

the stator fluxes can be expressed using subtransient values as:

$$\begin{aligned}
\psi_d &= -x_d'' \cdot i_d + \psi_d'' \\
\psi_q &= -x_q'' \cdot i_q + \psi_q''
\end{aligned} \tag{55}$$

Using these definitions for the flux, the stator voltage equations can be rewritten as ([5], [6]):

$$\begin{aligned}
u_d &= u_d'' - r_{str} \cdot i_d + n \cdot x_q'' \cdot i_q - \frac{x_d''}{\omega_n} \cdot \frac{di_d}{dt} \\
u_q &= u_q'' - r_{str} \cdot i_q - n \cdot x_d'' \cdot i_d - \frac{x_q''}{\omega_n} \cdot \frac{di_q}{dt} \\
u_0 &= -r_0 \cdot i_0 - \frac{x_0}{\omega_n} \cdot \frac{di_0}{dt}
\end{aligned} \tag{56}$$

where the subtransient voltages are calculated using coupling factors:

$$\begin{aligned}
u_d'' &= -n \cdot (k_{1q} \cdot \psi_{1q} + k_{2q} \cdot \psi_{2q}) + \left(\frac{k_{fd}}{\omega_n} \cdot \frac{d\psi_{fd}}{dt} + \frac{k_{1d}}{\omega_n} \cdot \frac{d\psi_{1d}}{dt} \right) \\
u_q'' &= n \cdot (k_{fd} \cdot \psi_{fd} + k_{1d} \cdot \psi_{1d}) + \left(\frac{k_{1q}}{\omega_n} \cdot \frac{d\psi_{1q}}{dt} + \frac{k_{2q}}{\omega_n} \cdot \frac{d\psi_{2q}}{dt} \right)
\end{aligned} \tag{57}$$

The coupling factors k_{fd} and k_{1d} and the subtransient reactance in the d-axis x_d'' are defined as:

$$\begin{aligned}
k_{fd} &= \frac{x_{ad} \cdot x_{1d}}{(x_{ad} + x_{rld}) \cdot (x_{1d} + x_{fd}) + x_{fd} \cdot x_{1d}} \\
k_{1d} &= \frac{x_{ad} \cdot x_{fd}}{(x_{ad} + x_{rld}) \cdot (x_{1d} + x_{fd}) + x_{fd} \cdot x_{1d}} \\
x_d'' &= x_{ad} + x_l - (k_{1d} + k_{fd}) \cdot x_{ad}
\end{aligned} \tag{58}$$

The coupling factors k_{1q} and k_{2q} and the subtransient reactance in the q-axis x_q'' are defined depending on whether the machine has a round-rotor or salient-pole rotor. For the salient-pole rotor machine:

$$\begin{aligned}
k_{1q} &= \frac{x_{aq}}{x_{aq} + x_{rlq} + x_{1q}} \\
k_{2q} &= 0 \\
x_q'' &= x_{aq} + x_l - k_{1q} \cdot x_{aq}
\end{aligned} \tag{59}$$

and for the round-rotor machine (similar as for the d-axis) we have the following:

$$\begin{aligned}
k_{1q} &= \frac{x_{aq} \cdot x_{2q}}{(x_{aq} + x_{rlq}) \cdot (x_{2q} + x_{1q}) + x_{2q} \cdot x_{1q}} \\
k_{2q} &= \frac{x_{aq} \cdot x_{1q}}{(x_{aq} + x_{rlq}) \cdot (x_{2q} + x_{1q}) + x_{2q} \cdot x_{1q}} \\
x_q'' &= x_{aq} + x_l - (k_{2q} + k_{1q}) \cdot x_{aq}
\end{aligned} \tag{60}$$

The electrical torque is calculated using the stator currents and stator fluxes and the rated power factor $cosn$:

$$t_e = \frac{i_q \cdot \psi_d - i_d \cdot \psi_q}{cosn} \qquad [p.u.] \tag{61}$$

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

$$\begin{aligned} v_{fd} &= r_{fd} \cdot i_{fd} + \frac{1}{\omega_n} \cdot \frac{d\psi_{fd}}{dt} \\ 0 &= r_{1d} \cdot i_{1d} + \frac{1}{\omega_n} \cdot \frac{d\psi_{1d}}{dt} \\ 0 &= r_{1q} \cdot i_{1q} + \frac{1}{\omega_n} \cdot \frac{d\psi_{1q}}{dt} \\ 0 &= r_{2q} \cdot i_{2q} + \frac{1}{\omega_n} \cdot \frac{d\psi_{2q}}{dt} \end{aligned} \tag{62}$$

The following expressions are valid for the rotor currents:

$$\begin{aligned} i_{fd} &= k_{fd} \cdot i_d + \frac{x_{1d\_loop} \cdot \psi_{fd} - (x_{ad} + x_{rl}) \cdot \psi_{1d}}{x_{det\_d}} \\ i_{1d} &= k_{1d} \cdot i_d + \frac{x_{fd\_loop} \cdot \psi_{1d} - (x_{ad} + x_{rl}) \cdot \psi_{fd}}{x_{det\_d}} \\ i_{1q} &= k_{1q} \cdot i_q + \frac{x_{2q\_loop} \cdot \psi_{1q} - (x_{aq} + x_{rlq}) \cdot \psi_{2q}}{x_{det\_q}} \\ i_{2q} &= k_{2q} \cdot i_q + \frac{x_{1q\_loop} \cdot \psi_{2q} - (x_{aq} + x_{rlq}) \cdot \psi_{1q}}{x_{det\_q}} \end{aligned} \tag{63}$$

where:

$$\begin{aligned} x_{det\_d} &= (x_{ad} + x_{rld}) \cdot (x_{1d} + x_{fd}) + x_{fd} \cdot x_{1d} \\ x_{det\_q} &= (x_{aq} + x_{rlq}) \cdot (x_{2q} + x_{1q}) + x_{2q} \cdot x_{1q} \end{aligned} \tag{64}$$

For a salient pole machine the current in the 2q-damper winding i_{2q} is zero and the current in the Q-damper winding has the following form:

$$i_{1q} = k_{1q} \cdot i_q + \frac{\psi_{1q}}{x_{1q}} \tag{65}$$

In the above equations the following reactances have been used (reactance sum per a winding loop):

$$\begin{aligned} x_{fd\_loop} &= x_{ad} + x_{rld} + x_{fd} \\ x_{1d\_loop} &= x_{ad} + x_{rld} + x_{1d} \\ x_{1q\_loop} &= x_{aq} + x_{rlq} + x_{1q} \\ x_{2q\_loop} &= x_{aq} + x_{rlq} + x_{2q} \end{aligned} \tag{66}$$

6.1.2.1 Equations for the RMS model

The RMS model uses the equations presented in Section 6.1.2 where some simplifications are being done. Normally, for large-scale stability studies the transformer voltage terms and the effect of speed variations are neglected in the stator voltage equations as discussed in [1]. These simplifications are also discussed in [4] where it is noted that the speed variation effect should not be neglected for frequency stability studies especially when studying islanding conditions.

The stator dynamics are relatively fast for stability studies. Therefore, for RMS-simulations, the derivatives of the stator quantities (transformer voltage terms) are not considered in the equations. This allows also using bigger time steps compared to the EMT model. Taking into account this simplification, the stator voltage Equations 56 and 57 can be written as:

$$\begin{aligned} u_d &= u''_d - r_{str} \cdot i_d + n \cdot x''_q \cdot i_q \\ u_q &= u''_q - r_{str} \cdot i_q - n \cdot x''_d \cdot i_d \end{aligned} \tag{67}$$

where the subtransient voltages are calculated as:

$$\begin{aligned} u''_d &= -n \cdot \psi''_q \\ u''_q &= n \cdot \psi''_d \end{aligned} \tag{68}$$

Additional simplification can be made to the model by modifying the effect of the speed variation on the stator voltages (option available on the *Advanced* tab of the *RMS-Simulation* page of the *TypSym* edit dialog). Depending on the option selected, Equation 67 and Equation 68 are modified as follows:

- Effect of speed variation considered

  The equations have the form as already presented and the speed is considered in the equations.

- Effect of speed variation neglected

  The speed is set equal to the initial speed in both equations. It is assumed that the speed changes are small and they don't have a big effect on the stator voltage [1]. The model is valid for speed deviations around initial speed.

- Effect of speed variation partially neglected

  The speed n is set to initial speed when multiplying with the sub-transient reactances and stator currents (only in Equation 67). The speed variation is considered when multiplying the sub-transient fluxes.

The option *Considered* should not be used for direct motor starting applications since during starting there is a big difference between the speed of the machine and the network frequency. The simulated results without this option are similar to the results of the EMT model. For motor starting applications including variable speed drives the speed effect variation option should be considered.

For studies where the torque is of true interest, the EMT model is more appropriate.

Another available option is to select an extended model [9] (*Advanced* tab of the *RMS-Simulation* page). This model provides an approximation of the rotor back-swing effect. It is using an iterative time scale separation and is based on the singular perturbation theory. The difference to the standard model is that in the extended model the electrical and mechanical state variables need to be corrected for every time step of the RMS simulation. The following corrections are applied to the rotor fluxes and rotor speed:

$$\begin{aligned}
\Delta\psi_{fd}^k &= -r_{fd}/x_d'' \cdot \Delta\psi_q^k \\
\Delta\psi_{1d}^k &= -r_{1d}/x_d'' \cdot \Delta\psi_q^k \\
\Delta\psi_{1q}^k &= r_{1q}/x_q'' \cdot \Delta\psi_d^k \\
\Delta\psi_{2q}^k &= r_{2q}/x_q'' \cdot \Delta\psi_d^k \\
\Delta n^k &= \frac{\Delta\psi_d^k/x_d'' \cdot (k_{fd} \cdot \psi_{fd} + k_{1d} \cdot \psi_{1d}) + \Delta\psi_q^k/x_q'' \cdot (\psi_{1q} \cdot k_{1q} + \psi_{2q} \cdot k_{2q})}{2 \cdot \pi \cdot f_{nom} \cdot t_{ag} \cdot cosn}
\end{aligned} \tag{69}$$

where the variation of the stator fluxes ψ_d and ψ_q over a time step is:

$$\begin{aligned}
\Delta\psi_d^k &= \psi_d^k - \psi_d^{k-1} \\
\Delta\psi_q^k &= \psi_q^k - \psi_q^{k-1}
\end{aligned} \tag{70}$$

The level of saturation depends on the magnetising fluxes ψ_{ad} and ψ_{aq}. The magnetisation fluxes are calculated differently dependent on the selected speed variation effect option:

- Magnetisation flux when the effect of speed variation is considered

  The magnetising fluxes ψ_{ad} and ψ_{aq} are calculated from Equation 51 and the magnitude of the magnetisation flux is calculated as:

$$\psi_m = \sqrt{(\psi_d + x_l \cdot i_d)^2 + (\psi_q + x_l \cdot i_q)^2} \tag{71}$$

- Magnetisation flux when the effect of speed variation is neglected or partially neglected

  It is assumed that the magnetising flux is equal to the magnetising voltage (speed has nominal value). This leads to the following simplification using the terminal voltage and current:

$$\psi_{ad} \approx u_q + r_{str} \cdot i_q + x_l \cdot i_d \tag{72}$$

$$\psi_{aq} \approx -(u_d + r_{str} \cdot i_d) + x_l \cdot i_q \tag{73}$$

$$\psi_m \approx u_m = \sqrt{\psi_{ad}^2 + \psi_{aq}^2} \tag{74}$$

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 as shown in Equation 75. Depending on the type of study, the studied phenomena of interest can be strongly influenced by the value of the negative sequence impedance. Therefore, it is worth noting that this value is not constant [1].

$$\underline{u}_2 = -(r_{2sy} + \jmath \cdot x_{2sy}) \cdot \underline{i}_2 \tag{75}$$

If the machine has *'YN'* connection (type parameter $nslty$), the zero sequence impedance $r_{0sy} + \jmath \cdot x_{0sy}$ can be entered in the model. The internal grounding impedance and neutral connection information can be also defined (*Grounding/Neutral Conductor* tab of the *Basic Data* page of *ElmSym*). The internal grounding impedance per unit values are calculated as $(r_{esy} + \jmath \cdot x_{esy})/z_b = r_e + \jmath \cdot x_e$ using the base impedance $z_b = ugn^2/sgn$ (ugn is the rated voltage of the machine and sgn is the rated apparent power).

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:

$$\underline{u}_0 = -(r_{0sy} + \jmath \cdot x_{0sy}) \cdot \underline{i}_0 - 3 \cdot (r_e + \jmath \cdot x_e) \cdot \underline{i}_0 \tag{76}$$

- 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

$$\underline{u}_0 = -(r_{0sy} + \jmath \cdot x_{0sy}) \cdot \underline{i}_0 + \underline{u}_n \tag{77}$$
$$0 = 3 \cdot \underline{i}_0 + \underline{i}_n \tag{78}$$

  – Internal grounding impedance connected

$$\underline{u}_0 = -(r_{0sy} + \jmath \cdot x_{0sy}) \cdot \underline{i}_0 + \underline{u}_n \tag{79}$$
$$\underline{u}_n = -(r_e + \jmath \cdot x_e) \cdot (3 \cdot \underline{i}_0 + \underline{i}_n) \tag{80}$$

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

$$\underline{u}_0 = -(r_{0sy} + \jmath \cdot x_{0sy}) \cdot \underline{i}_0 + \underline{u}_n \tag{81}$$
$$0 = 3 \cdot \underline{i}_0 + \underline{i}_n \tag{82}$$

For the unbalanced RMS simulation, a negative sequence torque is taken into the equation of motion (Equation 95) if the option *Consider negative sequence torque* is selected. The negative sequence torque is calculated as:

$$t_{e2} = \frac{(r_{2sy} - r_{str}) \cdot \underline{i}_2^2}{cosn} \tag{83}$$

The positive sequence torque t_{e1} is calculated according to Equation 61. The total electrical torque t_e is the sum of the positive and negative sequence torques

$$t_e = t_{e1} + t_{e2} \tag{84}$$

6.1.2.2 Equations for the EMT model

For the EMT model, the stator voltage equations are rewritten ([5], [6]) to be based on the stator $\alpha\beta 0$ stationary reference frame.

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

$$\begin{aligned} \underline{u}_{\alpha\beta} &= \underline{u}''_{\alpha\beta} - r_{str} \cdot \underline{i}_{\alpha\beta} - \jmath \cdot 2 \cdot n \cdot x''_\Delta \cdot e^{\jmath \cdot 2 \cdot \varphi} \cdot \underline{i}^*_{\alpha\beta} - \frac{x''}{\omega_n} \cdot \frac{d\underline{i}_{\alpha\beta}}{dt} - \frac{x''_\Delta}{\omega_n} \cdot e^{\jmath \cdot 2 \cdot \varphi} \cdot \frac{d\underline{i}^*_{\alpha\beta}}{dt} \\ u_0 &= -r_0 \cdot i_0 - \frac{x_0}{\omega_n} \cdot \frac{di_0}{dt} \end{aligned} \tag{85}$$

where the subtransient voltage is calculated by transforming the subtransient voltages in the dq axis (from Equation 57) to the $\alpha\beta 0$ stationary reference frame using the rotor position angle φ:

$$\underline{u}''_{\alpha\beta} = (u''_d + \jmath \cdot u''_q) \cdot e^{\jmath \cdot \varphi} \tag{86}$$

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

The level of saturation depends on the magnetising fluxes ψ_{ad} and ψ_{aq} which are calculated from Equation 51. The magnitude of the magnetisation flux is calculated as:

$$\psi_m = \sqrt{(\psi_d + x_l \cdot i_d)^2 + (\psi_q + x_l \cdot i_q)^2} \tag{87}$$

Same as for the RMS simulation, if the *Connection* is set to *'YN'* (type parameter $nslty$), the zero sequence parameters can be entered and the internal grounding impedance and neutral connection information can be defined.

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 a zero sequence equation:

$$u_0 = -(r_0 + 3 \cdot r_e) \cdot i_0 - (x_0 + 3 \cdot x_e) \cdot \frac{1}{hpi} \cdot \frac{di_0}{dt} \tag{88}$$

- 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

$$u_0 = -r_0 \cdot i_0 - x_0 \cdot \frac{1}{hpi} \cdot \frac{di_0}{dt} + u_n \tag{89}$$

$$0 = 3 \cdot i_0 + i_n \tag{90}$$

  – Internal grounding impedance connected

$$u_0 = -r_0 \cdot i_0 - x_0 \cdot \frac{1}{hpi} \cdot \frac{di_0}{dt} + u_n \tag{91}$$

$$u_n = -r_e \cdot (3 \cdot i_0 + i_n) - \frac{x_e}{hpi} \cdot \left(3 \cdot \frac{di_0}{dt} + \frac{di_n}{dt}\right) \tag{92}$$

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

$$u_0 = -r_0 \cdot i_0 - x_0 \cdot \frac{1}{hpi} \cdot \frac{di_0}{dt} + u_n \tag{93}$$

$$0 = 3 \cdot i_0 + i_n \tag{94}$$

6.1.2.3 Mechanical Equations

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

$$\frac{dn}{dt} = \begin{cases} \dfrac{t_m - t_e - t_{dkd} - t_{dpe}}{t_{ag}} & [p.u./s] \quad \text{for generators} \\[2ex] \dfrac{-t_m - t_e - t_{dkd} - t_{dpe}}{t_{ag}} & [p.u./s] \quad \text{for motors} \end{cases} \tag{95}$$

where:

- t_m is the mechanical torque in $[p.u.]$;

- t_e is the electrical torque in $[p.u.]$ calculated according to Equation 61;
- t_{dkd} is damping torque in $[p.u.]$
- t_{dpe} is damping torque based on power in $[p.u.]$
- t_{ag} is the acceleration time constant in $[s]$

From Equation 95 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.

In the case of a synchronous motor, if the speed falls under zero, the speed derivative $\frac{dn}{dt}$ is set to zero so that the motor can not get a negative speed.

The base torque is the ratio between the electrical active power and the nominal mechanical angular frequency in $\left[mech.\frac{rad}{s}\right]$:

$$t_{base} = \frac{sgn \cdot cosn \cdot 1e^6}{\omega_{mech\_n}} \qquad [Nm] \tag{96}$$

6.1.2.4 Mechanical Torque

The calculation of the mechanical torque t_m (parameter xmt) depends on if the machine is defined as a motor or as a generator:

$$t_m = \begin{cases} \frac{pt}{n} - xmdm - dpu \cdot n + addmt & [p.u.] \quad \text{for generators} \\ xmdm + dpu \cdot n + addmt & [p.u.] \quad \text{for motors} \end{cases} \tag{97}$$

where:

- $xmdm$ 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;
- $dpu \cdot n$ is turbine shaft friction torque in $[p.u.]$;
- pt is the *Turbine Power* input signal in $[p.u.]$;
- n is the *speed* in $[p.u.]$.

6.1.2.5 Damping Torque

In *PowerFactory*, the damping torque can be considered in the swing equation by using one (or more) of the three coefficients available in the synchronous machine type:

- *Turbine shaft friction torque coefficient* (dpu);
- *Damping torque coefficient* (dkd);
- *Damping torque coefficient based on power* (dpe).

The coefficients are used to calculate the damping torques as follows:

- dpu $[p.u.\ torque/p.u.\ speed]$ is multiplied by the speed to get the turbine shaft friction torque ($dpu \cdot n$) in $[p.u.]$. It is being considered in Equation 97;
- dkd $[p.u.\ torque/p.u.\ speed\ deviation]$ is used for calculating the *Damping torque* (parameter $c : xmdkd$) as follows:

$$t_{dkd} = dkd \cdot (n - n_{ref}) \tag{98}$$

  where n_{ref} can be selected to be the nominal speed ($1p.u.$) of the machine or the speed of the local reference machine. The damping torque is being considered in Equation 95;
- dpe $[p.u.\ power/p.u.\ speed\ deviation]$ is used for calculating the *Damping torque based on power* (parameter $c : xmdpe$) as follows:

$$t_{dpe} = \frac{dpe}{n} \cdot (n - n_{ref}) \tag{99}$$

  where n_{ref} can be selected to be the nominal speed ($1p.u.$) of the machine or the speed of the local reference machine. The damping torque based on power is being considered in Equation 95;

If the speed deviation for the damping torque t_{dkd} and t_{dpe} is calculated based on the nominal speed of the machine, it follows that:

- If the machine operates at nominal speed, the damping torque will be zero.
- If the speed of the machine deviates from the nominal speed, the damping torque will tend to return the machines speed towards nominal speed.

If the calculated speed deviation is based on the local reference machine speed, it follows that:

- If the machine is the reference machine, the damping torque will be zero.
- If the speed of the machine deviates from the speed of the reference machine, the damping torque will tend to return the machines speed towards the speed of the reference machine.

The damping torque based on power can be used to represents the change of electrical load dependent on frequency, as seen from the machine. This effect is usually included in the load model.

6.1.2.6 Acceleration Time Constant

The acceleration time constant t_{ag}, which is also referred as the mechanical starting time ([1]) is equal to $t_{ag} = 2 \cdot H$ in $[s]$ where H is the inertia constant. In *PowerFactory*, the inertia of teh machine can be entered using one of the following options:

- Acceleration time constant Tag rated to Pgn,
- Acceleration time constant Tag rated to Sgn,
- Inertia constant H rated to Pgn,
- Inertia constant H rated to Sgn,
- Moment of inertia J.

The following equation is used for calculating t_{ag} from the moment of inertia J:

$$t_{ag} = 2 \cdot H = \frac{J \cdot \omega_{mech\_n}^2}{sgn \cdot cosn \cdot 1e^6} \qquad [s] \qquad (100)$$

$$\omega_{mech\_n} = \frac{\omega_n}{\texttt{polepairs}} = \frac{2 \cdot \pi \cdot Fnom}{\texttt{polepairs}} \qquad \left[mech.\frac{rad}{s}\right] \qquad (101)$$

where:

- J is the moment of inertia in $[kg \cdot m^2]$;
- sgn is the *Rated Apparent Power* type parameter;
- $cosn$ is the *Rated Power Factor* type parameter;
- ω_{mech_n} is the rated mechanical angular frequency;
- ω_n is the rated electrical angular frequency;
- $Fnom$ is the nominal frequency $[Hz]$;
- `polepairs` is the number of pole-pairs.

The synchronous speed can be calculated as:

$$Ns = \frac{60 \cdot Fnom}{\texttt{polepairs}} \qquad [rev/min] \qquad (102)$$

Mechanical load definition for synchronous motors In the case of a synchronous motor, also a moment of inertia for a mechanical load can be entered (RMS- and EMT-Simulation pages of *ElmSym*). The calculation of t_{me} considers also the gear ratio (speed ratio) of a gear train. The total acceleration time t_{tot} for the motor is then:

$$\begin{aligned} t_{tot} &= t_{ag} + t_{me} \cdot \texttt{gear ratio}^2 \\ &= t_{ag} + \frac{J}{sgn \cdot cosn \cdot 1e^6} \cdot \left(\frac{\omega_n}{\texttt{polepairs}} \cdot \texttt{gear ratio}\right)^2 \\ &= t_{ag} + \frac{J}{sgn \cdot cosn \cdot 1e^6} \cdot (\omega_n \cdot gratio)^2 \qquad [s] \end{aligned} \qquad (103)$$

where $gratio = \texttt{gear ratio}/\texttt{polepairs}$ is a parameter which can be entered for the mechanical load (the number of pole-pairs has been introduced within $gratio$ in order that the acceleration time constants t_{ag} and t_{me} have the same base).

6.1.2.7 Initialisation of the mechanical parameters

The initialisation of the mechanical parameters depends on which input signals are connected to the model:

- Input signal pt is connected (if $xmdm$ is not connected, then $xmdm = 0$):

$$pt = (t_e + dpu \cdot n + xmdm) \cdot n \qquad [p.u.] \qquad (104)$$

- Input signal $xmdm$ is connected:

$$xmdm = -t_e - dpu \cdot n \qquad [p.u.] \qquad (105)$$

If both input signals pt and $xmdm$ are not connected, then for a generator case $xmdm = 0$ and pt is calculated according to Equation 104. For a motor case $pt = 0$ and $xmdm$ is calculated according to Equation 105.

The initialisation of the mechanical torque t_m (xmt) depends on whether if the machine is defined as a motor or as a generator:

$$t_m = \begin{cases} \frac{pt}{n} - (xmdm + dpu \cdot n) & [p.u.] \quad \text{for generators} \\ xmdm + dpu \cdot n & [p.u.] \quad \text{for motors} \end{cases} \tag{106}$$

Per default, the speed n of the machine is initialised to $n = 1$ $[p.u.]$. When the circuit-breaker of a synchronous motor is open and the motor is not spinning, the speed is initialised to zero. This is useful for motor starting applications in both RMS- and EMT-simulation.

6.1.3 Rotor angle definitions

PowerFactory defines several rotor angles based on different references. The values of the rotor angles are wrapped in the range between $-\pi$ and π degrees. An example of a graphical representation of the rotor angles is given in Figure 6.4.

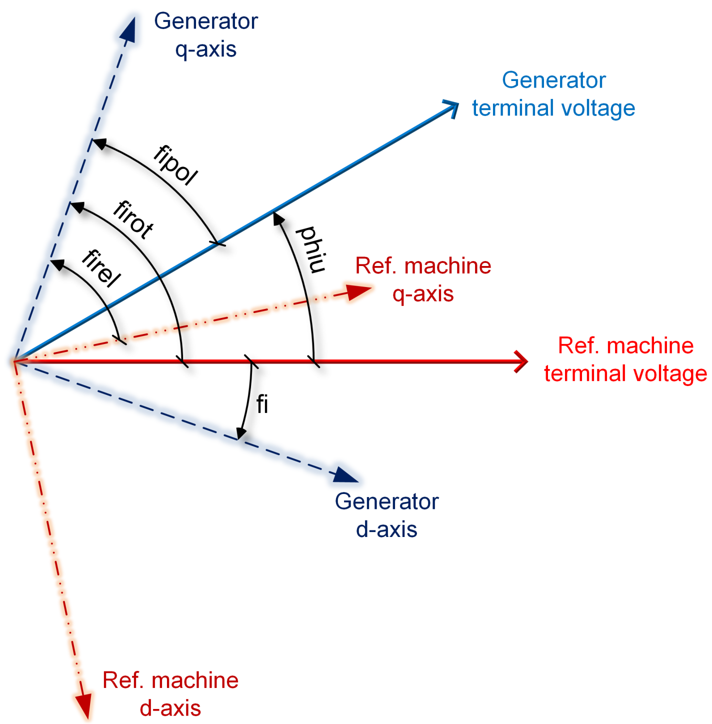

Figure 6.4: Rotor angle definitions example

The following variables are available:

- $fipol$ $[deg]$: Internal rotor angle of the machine (also called load angle). It is referred to the terminal voltage (local bus voltage) of the generator and is calculated as:

$$fipol = fi + 90° - phiu \qquad [deg] \tag{107}$$

where $phiu$ is the voltage angle of the machine terminal $m{:}phiu$ (for unbalanced calculation $m{:}phiu1$).

An info message is displayed in the output window of *PowerFactory* if $fipol \geq 85°$ and a warning message is printed if $fipol \geq 90°$;

- $firot$ $[deg]$: External rotor angle of the machine. It is referred to the reference voltage of the network (slack bus voltage) and is calculated as:

$$firot = fi + 90° - phiu_{ref} - (phiini - phiini_{ref}) \cdot 180°/\pi \qquad [deg] \tag{108}$$

where $phiu_{ref}$ is the voltage angle of the reference machine terminal $m{:}phiu$ (or for unbalanced calculation $m{:}phiu1$), $phiini$ and $phiini_{ref}$ represent the initial voltage angle of the generator and of the reference machine terminals.

The basic data parameter $b{:}phiini$ is available for terminals. It takes into account the initial dispatch angle of the reference machine and the vector group phase shift displacements of the transformers (e.g. if the initial dispatch angle of the reference machine is $0°$ and there is a Dyn5 transformer connected between the reference machine and the generator,the initial angle of the generator terminal will be $phiini = -210° \cdot \pi/180 = 150° \cdot \pi/180°$ $[rad]$);

- $firel$ $[deg]$: Rotor angle referred to that of the reference machine (slack machine). It is the angle between the q-axes (d-axes) of the reference machine and the generator. The angle $firel$ is being calculated according to the following equation:

$$firel = fi - fi_{ref} - (phiini - phiini_{ref}) \cdot 180°/\pi \qquad [deg] \tag{109}$$

where fi_{ref} is the fi angle of the reference machine;

- phi $[rad]$: The angle phi, also referenced to as φ, is the position of the rotor (d-axis) referred 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:

$$\frac{d\varphi}{dt} = \begin{cases} \omega_n \cdot (n - f_{ref}) & [rad] \quad \text{in the RMS simulation} \\ \omega_n \cdot n & [rad] \quad \text{in the EMT simulation} \end{cases} \tag{110}$$

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

The state variable φ is initialised by the q-axis angle, and then it is shifted to the d-axis ($-90°$):

$$\varphi = \arctan\left(\underline{u}_t + (r_{str} + \jmath \cdot x_q) \cdot \underline{i}_t\right) - \frac{\pi}{2} \qquad [rad] \tag{111}$$

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.

For the reference machine (slack), the reference frequency is equal to the speed ($f_{ref} = n$) and the derivative of the angle is zero ($\frac{d\varphi}{dt} = 0$). When the reference systems of two separated areas are merged using the pre-synchronising event (*EvtPresync*), the input signal f_{ref} of one reference machine is connected to the main reference machine automatically.

- fi $[deg]$: The angle fi is equal to phi expressed in degrees.

6.1.3.1 Out of step detection

The out of step detection (pole slip) is based on the angle $firel$ (rotor angle of the synchronous machine in respect to the rotor angle of the local reference).

The parameter ***outofstepdet*** in deg is used for the out of step detection. This parameter can be changed by the user (located in the calculation of the initial conditions 'Basic Options' page) and its default value is 360 degrees. There are two different options available depending on the $iopt\_outofstep$ parameter:

- Out of step is detected when the rotor angle $firel$ reaches the angle $outofstepdet$ defined by the user.
- Out of step is detected when the rotor angle $firel$ changes by $outofstepdet$ degrees from its initial operating point.

When this happens, an out of step message is printed in the output window and the output signal $outofstep$ is set to one. To reset the out of step signal, the value of the parameter $slipreset$ needs to be changed using a parameter event to $slipreset = 1$. Please note that the loss of synchronism tool uses the $outofstep$ output signal.

If the machine is the local reference machine, then $firel$ remains zero and no out of step can be detected.

The out of step detection is carried out only for RMS simulation.

6.1.4 Saturation

The model described so far is a purely linear model not considering any saturation effects. Generally, there exists saturation for all reactances of the synchronous machine model. However, for the purpose of system analysis, main flux saturation can be considered in the model by considering saturation of the mutual (magnetising) reactances x_{ad} and x_{aq}.

Figure 6.5 shows a main-flux saturation curve (full line). The linear line represents the air-gap line indicating the excitation current required to overcome the reluctance of the air-gap. The degree of saturation is the deviation of the open-circuit characteristic from the air-gap line. The y-axis is the terminal voltage in $[p.u.]$ and the x-axis is the excitation current in $[p.u.]$.

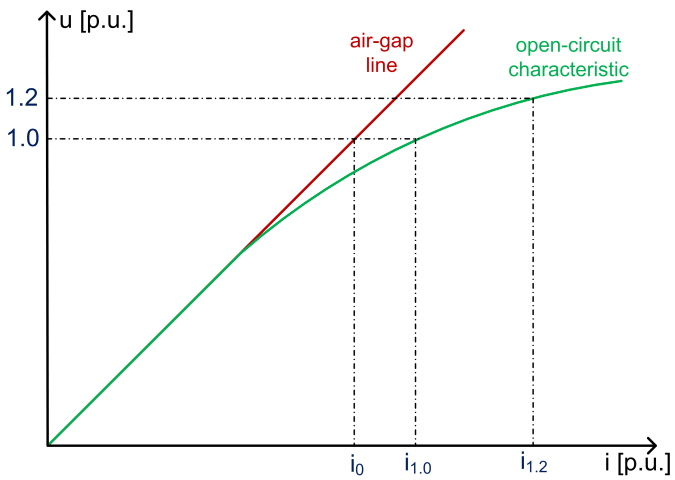

Figure 6.5: Open-circuit saturation characteristic

The extent of main flux saturation is different in the d- and q-axis. The saturation data usually provided is the open circuit saturation characteristic (Figure 6.5) which represents the saturation in the d-axis. In power system studies this data is being used to calculate the main flux saturation in the d-axis for salient-pole machines and the main flux saturation in the d- and q-axis in the case of round-rotor machines [1].

Measurements of the saturation in the q-axis of a round-rotor machines [2], have shown that the q-axis saturates in a greater extent compared to the d-axis (Figure 6.6). The model in *PowerFactory* supports data for separate saturation in the d- and q-axis.

The saturation curve of the main-flux can be defined in *PowerFactory* by a:

- *Quadratic* function using parameters SG_{10} and SG_{12};
- *Exponential* function using parameters SG_{10} and SG_{12};
- Smoothed curve with point-pairs of terminal voltage and the corresponding field current or $SG(u)$ entered in a table (*Tabular Input*).

In all cases, a saturation coefficient c_{sat} is calculated which is used for the calculation of the saturation factors in the d- and q-axis sat_d and sat_q. The saturated values of the mutual reactances are then calculated as:

$$\begin{aligned} x_{ad} &= sat_d \cdot x_{adu} \\ x_{aq} &= sat_q \cdot x_{aqu} \end{aligned} \tag{112}$$

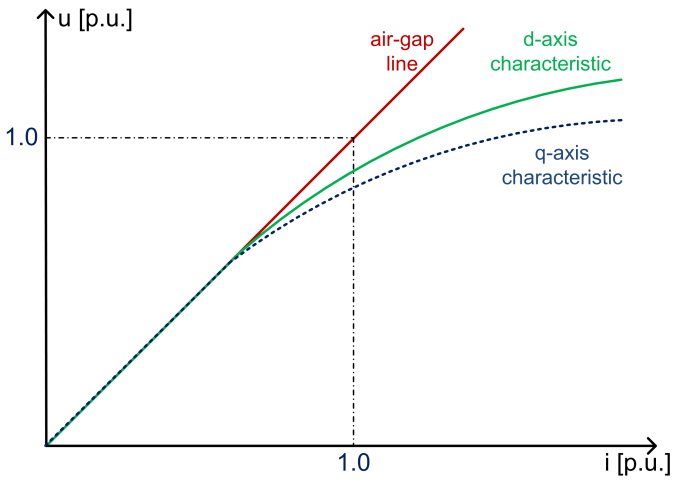

Figure 6.6: d- and q-axis saturation characteristics

When entering the saturation data in the table, the data has to be based on the non-reciprocal system of the appropriate axis which yields a slope of the air-gap line equal to one. For example, when entering d-axis saturation data a non-reciprocal system based on the unsaturated value of the d-axis mutual reactance needs to be used. For the q-axis, a non-reciprocal system based on the unsaturated value of the q-axis mutual reactance needs to be used. When using the quadratic or the exponential function, the curve is automatically based on the corresponding non-reciprocal p.u. system.

The saturation of stator leakage reactance is a current-dependent saturation, i.e. high currents after short-circuits will lead to a saturation effect of the leakage reactance. Because the use of unsaturated subtransient reactances would therefore lead to underestimated maximum short circuit currents, it is recommended to use saturated values for x''_d and x''_q ("saturated" refers here to current saturation).

For all other parameters (transient and synchronous reactance), unsaturated values should be entered.

6.1.4.1 Saturation coefficient calculation

- Saturation curve defined using a quadratic or exponential function
  The function can be defined specifying the excitation current $i_{1.0p.u.}$ and $i_{1.2p.u.}$ needed to obtain $1.0\ p.u.$ and $1.2\ p.u.$ of the rated generator voltage under no-load conditions (Figure 6.5). With these values the parameters SG_{10} and SG_{12} can be calculated as:

$$SG_{10} = \frac{i_{1.0}}{i_0} - 1 \tag{113}$$

$$SG_{12} = \frac{i_{1.2}}{1.2 \cdot i_0} - 1 \tag{114}$$

  – Quadratic:
    Based on the two parameters SG_{10} and SG_{12}, a quadratic approximation is applied and the $csat$ coefficient is calculated as:

$$c_{sat} = \begin{cases} \dfrac{B_g \cdot (\psi_m - A_g)^2}{\psi_m} & \text{if } \psi_m > A_g \\ 0 & \text{if } \psi_m \leq A_g \end{cases} \tag{115}$$

    where:

$$A_g = \frac{1.2 - \sqrt{1.2 \cdot \dfrac{SG_{12}}{SG_{10}}}}{1 - \sqrt{1.2 \cdot \dfrac{SG_{12}}{SG_{10}}}} \tag{116}$$

$$B_g = \frac{SG_{10}}{(1 - A_g)^2} \tag{117}$$

  – Exponential:
    Based on the same parameters SG_{10} and SG_{12}, an exponential approximation is applied and the c_{sat} coefficient is calculated as:

$$c_{sat} = \frac{SG_{10} \cdot \psi_m^{exp}}{\psi_m} \tag{118}$$

    where the exponent is defined as:

$$exp = \frac{\ln\left(1.2 \cdot \dfrac{SG_{12}}{SG_{10}}\right)}{\ln(1.2)} \tag{119}$$

- Saturation curve defined using tabular input
  A smoothed curve is being created from the entered point-pairs and the *Smoothing Factor* (parameter $smoothfac$ in $[\%]$) c_{sat} is calculated as:

$$c_{sat} = \frac{f(x,y,\psi_m)}{\psi_m} \tag{120}$$

  with $x(i) = satv(i)$ and $y(i) = satse(i) \cdot satv(i)$.

  The calculation of the excitation current i_{fd} $[\%]$ from $satse$ $[p.u.]$ ($SG(u)$) and vice-versa is done according to:

$$\begin{aligned} i_{fd} &= (satse + 1) \cdot \psi_m \cdot 100 \\ satse &= \frac{i_{fd}/100}{\psi_m} - 1 \end{aligned} \tag{121}$$

6.1.4.2 Options for calculating the saturation factors

One of the following saturation options can be selected for the synchronous machine type in *PowerFactory*:

- *d- and q-axis (flux magnitude)* saturation

  This common saturation option is normally used for the round-rotor machine when only the open-circuit characteristic is available, which is normally the case (d-axis).

  Using the magnitude of the magnetisation flux (calculated according to Equation 74 or 87), the saturation coefficient c_{sat} is being determined. Then, the saturation factors are calculated as follows:

$$\begin{aligned} sat_d &= \frac{1}{1+c_{sat}} \\ sat_q &= \frac{1}{1+\dfrac{x_{aqu}}{x_{adu}} \cdot c_{sat}} \end{aligned} \tag{122}$$

  where the x_{adu} and x_{aqu} are the unsaturated values of the mutual reactances.

- *d-axis (flux magnitude)* saturation

  This option is normally used for the salient-rotor machine when only the open-circuit characteristic is available. The saturation coefficient is calculated same as in the previous options and the saturation factors have the following form:

$$\begin{aligned} sat_d &= \frac{1}{1+c_{sat}} \\ sat_q &= 1 \end{aligned} \tag{123}$$

- *d- and q-axis (flux components)* separate saturation

  When the characteristics for the d- and q-axis are available, a saturation coefficient is calculated from each characteristic. For this option, the magnitude of the magnetisation flux is not used, but its d- and q-axis components appropriately.

  The saturation factors are calculated as:

$$\begin{aligned} sat_d &= \frac{1}{1+c_{sat_d}} \\ sat_q &= \frac{1}{1+c_{sat_q}} \end{aligned} \tag{124}$$

- *d-axis (flux component, d-axis)* separate saturation

  This case is analogue to the *d-axis (flux magnitude)* case, with the difference that here, instead of the flux magnitude, the d-axis component of the magnetising flux is being used. Since the d-axis component has a different form compared to the magnitude of the magnetising flux, the saturation will be somewhat different.

  The saturation factors are calculated as in Equation 123.

6.1.5 Excitation system interfacing

All the quantities until now have been based on the standard “xadu” reciprocal p.u. system. The excitation current in the reciprocal system is being initialised as $i_{fd} = ((x_{ad} + x_l) \cdot i_d + \psi_d)/x_{ad}$.

For practicality reasons, another p.u. system is used for interfacing to the excitation system models. These p.u. system is usually referred to a non-reciprocal p.u. system (for more information refer to Chapter 8.6 in [1]).

The excitation current output signal i_e and the excitation voltage input signal v_e (both in the non-reciprocal system) are used for interfacing with the excitation system.

One of the non-reciprocal p.u. systems widely used is the no load, no saturation p.u.-system. In this system, excitation current of $i_e = 1\ p.u.$ is required to produce $1\ p.u.$ stator voltage on the air-gap line under no-load, steady-state and rated speed conditions. Excitation voltage of $v_e = 1\ p.u.$ is the corresponding excitation voltage. The values are higher with saturation.

The excitation current i_e (in the non-reciprocal p.u. system) is calculated from the excitation current i_{fd} (in the reciprocal p.u. system) as:

$$i_e = x_{adu} \cdot i_{fd} \tag{125}$$

From the excitation voltage v_e (in the non-reciprocal p.u. system), u_{fd} (in the reciprocal p.u. system) is calculated as:

$$v_{fd} = \frac{r_{fd}}{x_{adu}} \cdot v_e \tag{126}$$

The excitation voltage input signal is being initialised as:

$$v_e = i_e \tag{127}$$

6.1.5.1 Excitation system base modes in *PowerFactory*

By modifying the base equations with the parameter i_{fdBase} and $e_{fdBaseRatio}$ (ratio between the exciter rated voltage and the machine excitation rated voltage), additional non-reciprocal p.u. systems can be defined. With these two parameters, the equations for the excitation current and voltage (Equations 125 and 126) obtain a new form:

$$i_e = x_{adu} \cdot i_{fd} \cdot (1/i_{fdBase}) \tag{128}$$

$$v_{fd} = \frac{r_{fd}}{x_{adu}} \cdot v_e \cdot (i_{fdBase} \cdot e_{fdBaseRatio}) \tag{129}$$

and similarily, for the initialisation of excitation voltage input signal the following is obtained:

$$v_e = i_e \cdot (1/e_{fdBaseRatio}) \tag{130}$$

The user can select between three different excitation system base modes in the *RMS-Simulation* and *EMT-Simulation* pages of the *ElmSym*:

- Air gap line mode (no load system without saturation)

  This mode is the default in *PowerFactory* and it has been described above. In this mode $i_{fdBase} = 1$. This is the standard excitation base used by the IEEE.

- No load system with saturation mode

  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 for the machine with saturation. Excitation voltage of $v_e = 1\ p.u.$ is the corresponding excitation voltage.

  In this mode $i_{fdBase} = 1/sat_d$ where sat_d is being calculated for $1\ p.u.$ magnetisation voltage.

- Full load system with saturation mode

  Under full load, steady-state and rated speed conditions, excitation current of $i_e = 1\ p.u.$ is required to produce $1\ p.u.$ stator voltage for the machine with saturation. Excitation voltage of $v_e = 1\ p.u.$ is the corresponding excitation voltage.

  In this mode i_{fdBase} corresponds to the excitation current calculated for full load conditions (equal to v_{e_rated}).

The choice of the base system to be used should match with the system used by the excitation system.

In older versions of *PowerFactory* the rotor currents and fluxes of the standard model were based on the non-reciprocal p.u. system. For compatibility reasons, these quantities are still available only for the standard model:

$$\begin{aligned} i_D &= x_{adu} \cdot i_{1d} \\ i_Q &= x_{aqu} \cdot i_{1q} \\ i_x &= x_{aqu} \cdot i_{2q} \end{aligned} \tag{131}$$

$$\begin{aligned} \psi_e &= \frac{x_{adu}}{x_{fd\_loop\_u}} \cdot \psi_{fd} \\ \psi_D &= \frac{x_{adu}}{x_{1d\_loop\_u}} \cdot \psi_{1d} \\ \psi_Q &= \frac{x_{aqu}}{x_{1q\_loop\_u}} \cdot \psi_{1q} \\ \psi_x &= \frac{x_{aqu}}{x_{2q\_loop\_u}} \cdot \psi_{2q} \end{aligned} \tag{132}$$

where the reactance sums $x_{fd\_loop\_u}$, $x_{1d\_loop\_u}$, $x_{1q\_loop\_u}$ and $x_{2q\_loop\_u}$ are calculated as in Equation 66 where xad is being replaced with its unsaturated value $xadu$ and xaq with $xaqu$.

6.1.6 Delta Speed Input Signal

The input signal dw (delta speed) can be used to calculated sub-synchronous oscillations between DC links and synchronous generators. See also IEEE 1204 (Guide for planning DC links).

The speed can be modified with the additional input signal dw, e.g. connect to Fourier source. With the new signal it is possible to calculate the damping of a generator connected on a DC links over a frequency range.

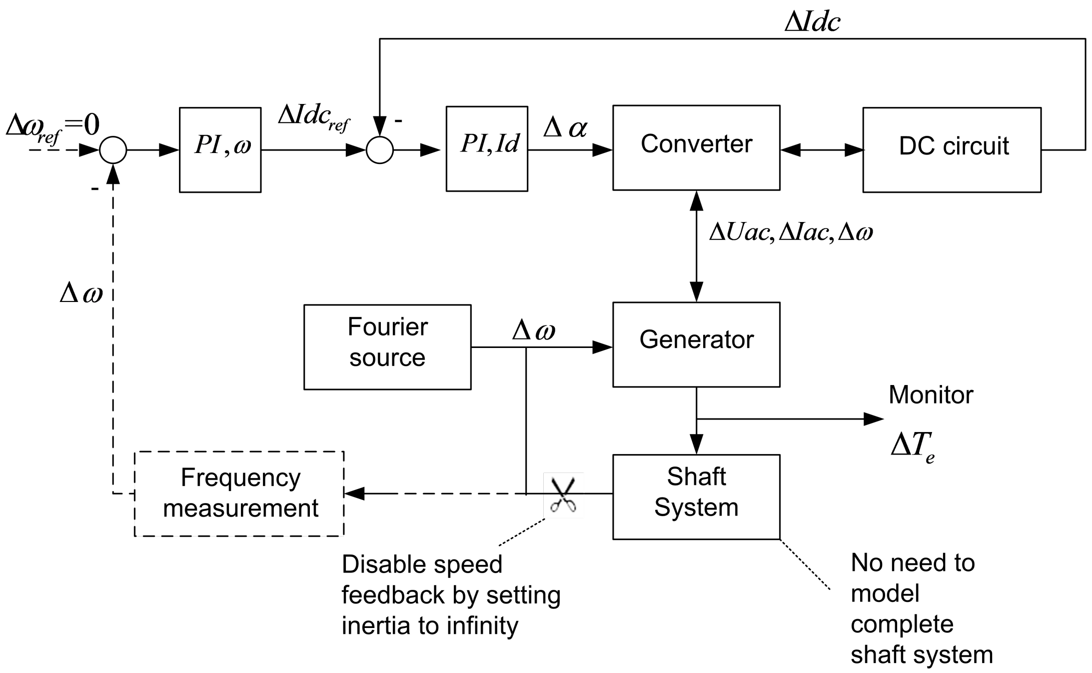

Figure 6.7: Application for Delta Speed input signal

If the dw input signal is connected, the parameter t_{ag} (Acceleration Time Constant) is internally set to ∞.

The input signal dw is per default initialised to zero and modifies the speed as $n' = n + dw$.

The dw input signal is available for the RMS- and the EMT-Simulation for all generator models except the classical model.

6.1.7 Integrated AVR for Motor Starting

When the synchronous machine is operating as a motor, the motor is starting, and the option *Use integrated AVR for motor starting* is activated, then the simplified AVR model shown in Figure 6.8 is used where:

- *rf_st* is the starting field resistance
- ie is the excitation current
- *speed_th* is the speed threshold, at which the excitation will be triggered
- *ve_const* is the constant value of excitation voltage
- ve is the excitation voltage

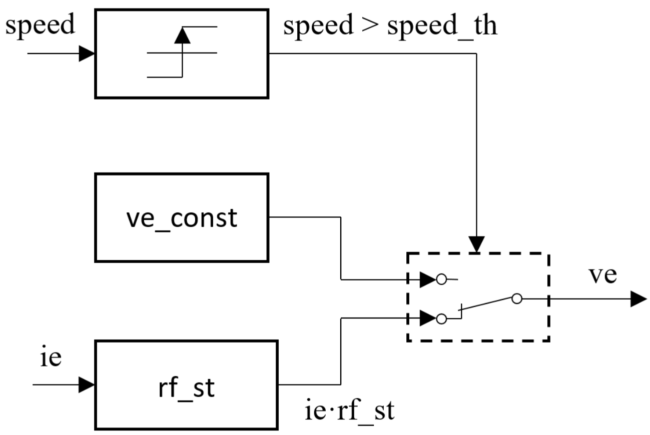

Figure 6.8: Integrated AVR for motor starting

The motor is considered to be starting when the simulation is performed and the motor speed is 0, or a motor starting command is performed using the dynamic simulation type. If the simulation is not considered a motor starting, then the corresponding input signal *ve* is used.

6.1.8 Inputs/Outputs/State Variables of the Dynamic Model

6.1.8.1 Stability Model (RMS)

Table 6.3: 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.
freflocal		Reference frequency of local reference machine	p.u.
dw		Delta speed	p.u.

Table 6.4: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
psifd	ψ_{fd}	Excitation flux	p.u.
psi1d	ψ_{1d}	Flux in 1d-damper winding, d-axis	p.u.
psi1q	ψ_{1q}	Flux in 1q-damper winding, q-axis	p.u.
psi2q	ψ_{2q}	Flux in 2q-damper winding, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.5: Output Definition of the RMS-Model

Parameter	Symbol	Description	Unit
ut	$\|u_t\|$	Terminal Voltage, Magnitude	p.u.
utr		Terminal Voltage, Real Part	p.u
uti		Terminal Voltage, Imaginary Part	p.u.
pgt		Electrical Power (based on rated active power)	p.u.
ie	i_e	Excitation Current (in non-reciprocal p.u. system)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed		Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
cur1	$\|i_t\|$	Positive-Sequence Current, Magnitude	p.u.
cur1r		Positive-Sequence Current, Real Part	p.u.
cur1i		Positive-Sequence Current, Imaginary Part	p.u.
P1		Positive-Sequence, Active Power	MW
Q1		Positive-Sequence, Reactive Power	Mvar
fe		Frequency Output ($fe = xspeed$)	p.u.
outofstep		Out of step (pole slip) is “1” if generator is out of step and “0” otherwise	

6.1.8.2 EMT-Model

Table 6.6: 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.
dw		Delta speed	p.u.

Table 6.7: State Variables Definition of the EMT-Model

Parameter	Symbol	Description	Unit
psifd	ψ_{fd}	Excitation flux	p.u.
psi1d	ψ_{1d}	Flux in 1d-damper winding, d-axis	p.u.
psi1q	ψ_{1q}	Flux in 1q-damper winding, q-axis	p.u.
psi2q	ψ_{2q}	Flux in 2q-damper winding, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.8: Output Definition of the EMT-Model

Parameter	Symbol	Description	Unit
ussd	u''_d	Subtransient Voltage, d-axis	p.u.
ussq	u''_q	Subtransient Voltage, q-axis	p.u.
ut	$\|u_t\|$	Terminal Voltage, Magnitude	p.u.
utr		Terminal Voltage, Real Part	p.u
uti		Terminal Voltage, Imaginary Part	p.u.
pgt		Electrical Power (based on rated active power)	p.u.
ie	i_e	Excitation Current (in non-reciprocal p.u. system)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed	n	Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
cur1	$\|i_t\|$	Positive-Sequence Current, Magnitude	p.u.
cur1r		Positive-Sequence Current, Real Part	p.u.
cur1i		Positive-Sequence Current, Imaginary Part	p.u.
P1		Positive-Sequence, Active Power	MW
Q1		Positive-Sequence, Reactive Power	Mvar
fe		Frequency Output ($fe = xspeed$)	p.u.

6.2 Model 3.3

The 3.3 model is a more detailed model compared to the standard model. It requires more input data and can be used for more detailed studies. In this case, the EMT model is to be preferred since there are no simplifications done as in the RMS model.

The rotor d-axis is modelled by three rotor loops representing the excitation and two damper windings. The rotor q-axis is also modelled with three rotor loops. According to the designation in [4], this model is referred to as 3.3 model. The model is based on [4] and [2]. Using high values for the impedance of certain branches, models with varying degrees of complexity can be simulated.

Figure 6.9 and Figure 6.10 show the equivalent circuit diagrams of the *PowerFactory* synchronous machine model 3.3, which is represented in a rotor reference system (Park coordinates, dq-reference frame).

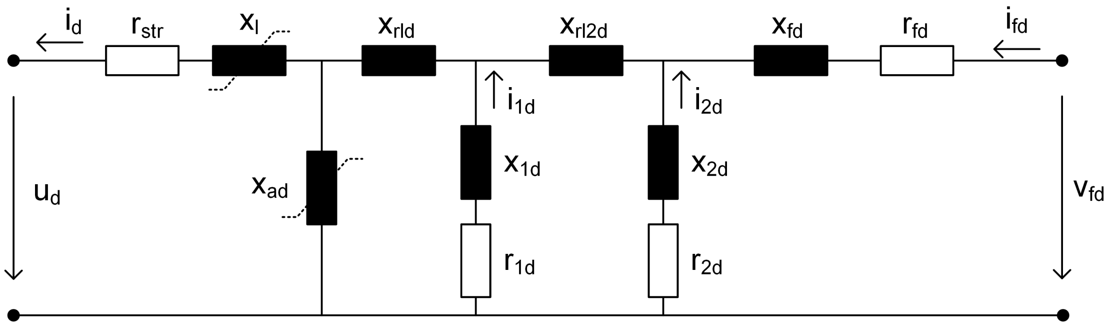

Figure 6.9: d-axis equivalent circuit

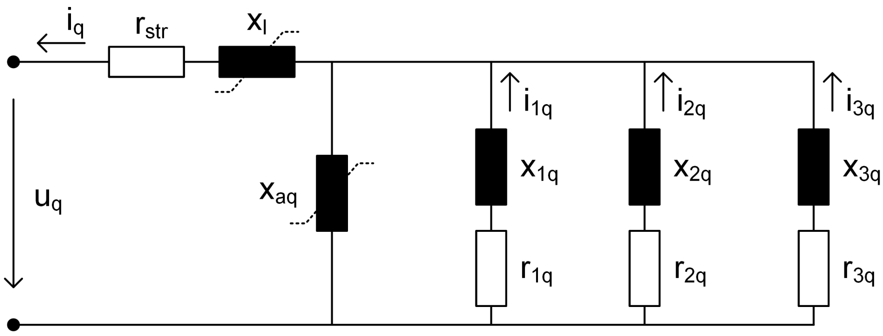

Figure 6.10: q-axis equivalent circuit

6.2.1 Input parameters and conversion

The 3.3 model can be used with operational reactances data as given in Table 6.9 or with equivalent circuit data (model parameters) as given in Table 6.10. Internally the model works with the equivalent circuit data. If operational reactances data is used, the data is converted to equivalent circuit data according to the conversion presented in [4].

Table 6.9: Input data from operational reactances

Name in PF	Symbol	Unit	Description
$rstr$	r_{str}	$p.u.$	Stator resistance
xl	x_l	$p.u.$	Stator leakage reactance
xad	x_{ad}	$p.u.$	Mutual (magnetising) reactance, d-axis
xaq	x_{aq}	$p.u.$	Mutual (magnetising) reactance, q-axis
$t1d, t2d, t3d$		s	Time constants d-axis
$t4d, t5d, t6d$		s	Time constants d-axis
$t7d, t8d$		s	Time constants d-axis
$t1q, t2q, t3q$		s	Time constants q-axis
$t4q, t5q, t6q$		s	Time constants q-axis

Table 6.10: Model parameters of the model 3.3 synchronous machine

Name in PF	Symbol	Unit	Description
$rstr$	r_{str}	$p.u.$	Stator resistance
xl	x_l	$p.u.$	Stator leakage reactance
xad	x_{ad}	$p.u.$	Mutual (magnetising) reactance, d-axis
xaq	x_{aq}	$p.u.$	Mutual (magnetising) reactance, q-axis
xrl	x_{rld}	$p.u.$	Coupling reactance of all d-axis rotor circuits
$xrl2d$	x_{rl2d}	$p.u.$	Coupling reactance between field and 2d damper winding
$x1d$	x_{1d}	$p.u.$	Reactance of 1d-damper winding (d-axis)
$r1d$	r_{1d}	$p.u.$	Resistance of 1d-damper winding (d-axis)
$x2d$	x_{2d}	$p.u.$	Reactance of 2d-damper winding (d-axis)
$r2d$	r_{2d}	$p.u.$	Resistance of 2d-damper winding (d-axis)
xfd	x_{fd}	$p.u.$	Reactance of field winding (d-axis)
rfd	r_{fd}	$p.u.$	Resistance of field winding (d-axis)
$x1q$	x_{1q}	$p.u.$	Reactance of 1q-damper winding (q-axis)
$r1q$	r_{1q}	$p.u.$	Resistance of 1q-damper winding (q-axis)
$x2q$	x_{2q}	$p.u.$	Reactance of 2q-damper winding (q-axis)
$r2q$	r_{2q}	$p.u.$	Resistance of 2q-damper winding (q-axis)
$x3q$	x_{3q}	$p.u.$	Reactance of 3q-damper winding (q-axis)
$r3q$	r_{3q}	$p.u.$	Resistance of 3q-damper winding (q-axis)

The synchronous reactances can be obtained as follows:

$$\begin{aligned} x_d &= x_l + x_{ad} \\ x_q &= x_l + x_{aq} \end{aligned} \tag{133}$$

6.2.2 Model equations

The rotor variables are referred to the stator windings and the equations are written using the rotor reference frame in generator orientation.

In the case of balanced RMS simulation, the available simulated values are positive sequence complex values. In the case of unbalanced RMS simulation, the available complex phase values for currents and voltages are first transformed into symmetrical components. For transforming to the dq-reference frame, the variables are shifted by multiplying with the transformation $\cos\varphi - \jmath \cdot \sin\varphi$. The voltages and currents available from the EMT simulation are first transformed from instantaneous values in the $\alpha\beta\gamma$ system using the Clarke transformation. The same transformation as above is used for transforming to the dq rotating reference frame.

The differential equations can be derived based on the equivalent circuit diagrams according to Figure 6.9 to Figure 6.10.

The *PowerFactory* synchronous machine model for RMS simulations uses the rotor currents, magnetisation fluxes, the speed n and the angle φ as state variables. The EMT model uses two more state variables (stator fluxes ψ_d and ψ_q).

The stator voltage equations can be described as follows:

$$
\begin{aligned}
u_d &= -r_{str} \cdot i_d - n \cdot \psi_q + \frac{1}{\omega_n} \cdot \frac{d\psi_d}{dt} \\
u_q &= -r_{str} \cdot i_q + n \cdot \psi_d + \frac{1}{\omega_n} \cdot \frac{d\psi_q}{dt} \\
u_0 &= -r_{str} \cdot i_0 + \frac{1}{\omega_n} \cdot \frac{d\psi_0}{dt}
\end{aligned} \tag{134}
$$

where n is the speed of the rotor and $\omega_n = 2 \cdot \pi \cdot f_{nom}$ is the nominal angular frequency.

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

$$
\begin{aligned}
0 &= r_{1d} \cdot i_{1d} + \frac{1}{\omega_n} \cdot \frac{d\psi_{1d}}{dt} \\
0 &= r_{2d} \cdot i_{2d} + \frac{1}{\omega_n} \cdot \frac{d\psi_{2d}}{dt} \\
v_{fd} &= i_{fd} \cdot r_{fd} + \frac{1}{\omega_n} \cdot \frac{d\psi_{fd}}{dt}
\end{aligned} \tag{135}
$$

$$
\begin{aligned}
0 &= r_{1q} \cdot i_{1q} + \frac{1}{\omega_n} \cdot \frac{d\psi_{1q}}{dt} \\
0 &= r_{2q} \cdot i_{2q} + \frac{1}{\omega_n} \cdot \frac{d\psi_{2q}}{dt} \\
0 &= r_{3q} \cdot i_{3q} + \frac{1}{\omega_n} \cdot \frac{d\psi_{3q}}{dt}
\end{aligned} \tag{136}
$$

For completing the model, the stator and rotor flux linkage equations in the d- and q-axis are required:

$$
\begin{aligned}
\psi_d &= -(x_l + x_{ad}) \cdot i_d + x_{ad} \cdot i_{1d} + x_{ad} \cdot i_{2d} + x_{ad} \cdot i_{fd} = \psi_{ad} - x_l \cdot i_d \\
\psi_q &= -(x_l + x_{aq}) \cdot i_q + x_{aq} \cdot i_{1q} + x_{aq} \cdot i_{2q} + x_{aq} \cdot i_{3q} = \psi_{aq} - x_l \cdot i_q
\end{aligned} \tag{137}
$$

$$
\begin{aligned}
\psi_{1d} &= \psi_{ad} + (x_{rld} + x_{1d}) \cdot i_{1d} + x_{rld} \cdot i_{2d} + x_{rld} \cdot i_{fd} \\
\psi_{2d} &= \psi_{ad} + x_{rld} \cdot i_{1d} + (x_{rld} + x_{rl2d} + x_{2d}) \cdot i_{2d} + (x_{rld} + x_{rl2d}) \cdot i_{fd} \\
\psi_{fd} &= \psi_{ad} + x_{rld} \cdot i_{1d} + (x_{rld} + x_{rl2d}) \cdot i_{2d} + (x_{rld} + x_{rl2d} + x_{fd}) \cdot i_{fd}
\end{aligned} \tag{138}
$$

$$
\begin{aligned}
\psi_{1q} &= \psi_{aq} + x_{1q} \cdot i_{1q} \\
\psi_{2q} &= \psi_{aq} + x_{2q} \cdot i_{2q} \\
\psi_{3q} &= \psi_{aq} + x_{3q} \cdot i_{3q}
\end{aligned} \tag{139}
$$

where ψ_{ad} and ψ_{aq} are the d- and q-axis components of the magnetising flux:

$$
\begin{aligned}
\psi_{ad} &= x_{ad} \cdot (-i_d + i_{1d} + i_{2d} + i_{fd}) \\
\psi_{aq} &= x_{aq} \cdot (-i_q + i_{1q} + i_{2q} + i_{3q})
\end{aligned} \tag{140}
$$

The electrical torque is calculated using the stator currents and stator fluxes and the rated power factor $cosn$:

$$
t_e = \frac{i_q \cdot \psi_d - i_d \cdot \psi_q}{cosn} \qquad [p.u.] \tag{141}
$$

6.2.2.1 Equations for the RMS model

The equations from Section 6.2.2 are used for the RMS model where several simplifications have been made for the stator voltage equations.

The stator dynamics are relatively fast for stability studies. Therefore, for RMS-simulations, the derivatives of the stator quantities are not considered in the equations. Taking into account this simplification, the stator voltage Equations 134 can be written as:

$$
\begin{aligned}
u_d &= -r_{str} \cdot i_d - n \cdot \psi_q \\
u_q &= -r_{str} \cdot i_q + n \cdot \psi_d
\end{aligned}
\tag{142}
$$

Similar as in the standard *PowerFactory* RMS model, additional simplification can be made to the model by modifying the effect of the speed variation on the stator voltages (option located on the *Advanced* tab of the *RMS-Simulation* page of the *TypSym* edit dialog). Depending on the option selected, Equation 142 is modified as follows:

- Effect of speed variation considered

  The equations have the form as already presented and the speed is considered in the equations.

- Effect of speed variation neglected

  The speed is set equal to the initial speed in both equations. It is assumed that the speed changes are small and they don't have a big effect on the stator voltage [1]. The model is then valid for speed deviations around initial speed.

The option *Considered* should not be used for direct motor starting applications since during starting there is a big difference between the speed of the machine and the network frequency. The simulated results without this option are similar to the results of the EMT model. For motor starting applications including variable speed drives the speed effect variation option should be considered.

For studies where the torque is of true interest, the EMT model is more appropriate.

In the case of unbalanced RMS simulation the same neutral, zero and negative sequence equations have to be satisfied as in Section 6.1.2.1.

For the unbalanced RMS simulation, the model 3.3 takes into account also a negative sequence torque into the equation of motion (Equation 95). The negative sequence torque is calculated as:

$$
t_{e2} = \frac{(r_{2sy} - r_{str}) \cdot \underline{i}_2^2}{cosn} \qquad [p.u.] \tag{143}
$$

The positive sequence torque t_{e1} is calculated according to Equation 141. The total electrical torque t_e is the sum of the positive and negative sequence torques:

$$
t_e = t_{e1} + t_{e2} \qquad [p.u.] \tag{144}
$$

6.2.2.2 Equations for the EMT model

For the EMT model, there are no changes made to the equations presented in Section 6.2.2.

For the EMT simulation, the neutral and zero sequence equations that have to be satisfied are the same as in Section 6.1.2.2.

6.2.2.3 Mechanical Equations, Rotor Angles and Delta Speed Input Signal

The mechanical equations, together with the definitions for mechanical torque, damping torque and acceleration time constant is described in Section 6.1.2.3.

The rotor angle definitions are identical to the definitions presented in Section 6.1.3.

The functionality of the delta speed input signal dw is given in Section 6.1.6.

6.2.3 Saturation

The model described so far is a purely linear model not considering any saturation effects. Generally, there exists saturation for all reactances of the synchronous machine model. However, for the purpose of system analysis, main flux saturation can be considered in the model by considering saturation of the mutual (magnetising) reactances x_{ad} and x_{aq}.

The main-flux saturation and the available options are identical to what is described in Section 6.1.4.

The saturation of stator leakage reactance is a current-dependent saturation, i.e. high currents after short-circuits will lead to a saturation effect of the leakage reactance. The modelling of the current dependency of the stator leakage reactance is supported by the Model 3.3 synchronous machine in *PowerFactory*. The data can be entered using tabular input of point-pairs of current and reactance. The data is then transformed to a smoothed curve with a piece-wise linear function using the dependency curve smoothing factor.

On every simulation step the stator reactance is determined from the curve for a specific value of the magnitude of the dq-stator current (zero sequence current is neglected):

$$xl = xl\_curve\left(\sqrt{i_d^2 + i_q^2}\right) \tag{145}$$

6.2.4 Excitation system interfacing

Refer to Section 6.1.5.

6.2.5 Integrated AVR for Motor Starting

Refer to Section 6.1.7.

6.2.6 Inputs/Outputs/State Variables of the Dynamic Model

6.2.6.1 Stability Model (RMS)

Table 6.11: 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.
freflocal		Reference frequency of local reference machine	p.u.
dw		Delta speed	p.u.

Table 6.12: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
i1d	i_{1d}	Current in 1d-damper winding, d-axis	p.u.
i2d	i_{2d}	Current in 2d-damper winding, d-axis	p.u.
ifd	i_{fd}	Current in field winding (excitation flux), d-axis	p.u.
i1q	i_{1q}	Current in 1q-damper winding, q-axis	p.u.
i2q	i_{2q}	Current in 2q-damper winding, q-axis	p.u.
i3q	i_{3q}	Current in 3q-damper winding, q-axis	p.u.
psiad	ψ_{ad}	Magnetisation flux, d-axis	p.u.
psiaq	ψ_{aq}	Magnetisation flux, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.13: Output Definition of the RMS-Model

Parameter	Symbol	Description	Unit
ut	u_t	Terminal Voltage	p.u.
utr		Terminal Voltage, Real Part	p.u
uti		Terminal Voltage, Imaginary Part	p.u.
pgt		Electrical Power (based on rated active power)	p.u.
ie	i_e	Excitation Current (in non-reciprocal p.u. system)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed		Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
cur1	$\|i_t\|$	Positive-Sequence Current, Magnitude	p.u.
cur1r		Positive-Sequence Current, Real Part	p.u.
cur1i		Positive-Sequence Current, Imaginary Part	p.u.
P1		Positive-Sequence, Active Power	MW
Q1		Positive-Sequence, Reactive Power	Mvar
fe		Frequency Output ($fe = xspeed$)	p.u.
outofstep		Out of step (pole slip) is “1” if generator is out of step and “0” otherwise	

6.2.6.2 EMT-Model

Table 6.14: 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.
dw		Delta speed	p.u.

Table 6.15: State Variables Definition of the EMT-Model

Parameter	Symbol	Description	Unit
i1d	i_{1d}	Current in 1d-damper winding, d-axis	p.u.
i2d	i_{2d}	Current in 2d-damper winding, d-axis	p.u.
ifd	i_{fd}	Current in field winding (excitation flux), d-axis	p.u.
i1q	i_{1q}	Current in 1q-damper winding, q-axis	p.u.
i2q	i_{2q}	Current in 2q-damper winding, q-axis	p.u.
i3q	i_{3q}	Current in 3q-damper winding, q-axis	p.u.
psiad	ψ_{ad}	Magnetisation flux, d-axis	p.u.
psiaq	ψ_{aq}	Magnetisation flux, q-axis	p.u.
psid	ψ_d	Stator flux, d-axis	p.u.
psiq	ψ_q	Stator flux, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.16: Output Definition of the EMT-Model

Parameter	Symbol	Description	Unit
ut	u_t	Terminal Voltage	p.u.
utr		Terminal Voltage, Real Part	p.u
uti		Terminal Voltage, Imaginary Part	p.u.
pgt		Electrical Power (based on rated active power)	p.u.
ie	i_e	Excitation Current (in non-reciprocal p.u. system)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed	n	Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
cur1	$\|i_t\|$	Positive-Sequence Current, Magnitude	p.u.
cur1r		Positive-Sequence Current, Real Part	p.u.
cur1i		Positive-Sequence Current, Imaginary Part	p.u.
P1		Positive-Sequence, Active Power	MW
Q1		Positive-Sequence, Reactive Power	Mvar
fe		Frequency Output ($fe = xspeed$)	p.u.

6.3 Classical Model

In comparison with the detailed model explained in Section 6.1, the classical model is a simplified model represented by a voltage behind an impedance. The equivalent circuit diagram is shown in Figure 6.11.

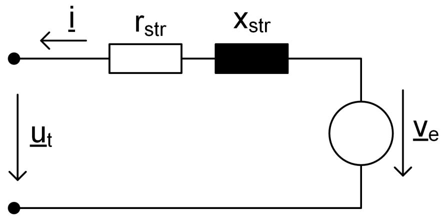

Figure 6.11: Classical model equivalent circuit

The classical synchronous machine model can be used for representing equivalents of parts of a system that are not represented in detail or for not so important machines.

The classical model normally refers to a model where v_e is constant. In *PowerFactory* the model is extended so that v_e is defined as a signal input (ve can be varied by a DSL model) and not a constant quantity.

The definitions of the rotor angles is the same as presented in Section 6.1.3.

Since it is a simplified model saturation is not taken into account.

6.3.1 Equations for the RMS model

The voltage equation that needs to be satisfied for the RMS simulation is:

$$\underline{u}_t = -(r_{str} + \jmath\, x_{str}) \cdot \underline{i}_t + v_e \angle \varphi \tag{146}$$

where the amplitude of v_e is initialised as:

$$v_e = \sqrt{(\underline{u}_t + (r_{str} + \jmath\, x_{str}) \cdot \underline{i}_t)^2} \tag{147}$$

Similar as in the standard *PowerFactory* RMS model, there is an option to neglect the rotor speed variation ($n = 1p.u.$) when calculating the stator flux (option located on the *Advanced* tab of the *RMS-Simulation* page of the *TypSym* edit dialogue):

$$\underline{\psi}_{str} = (\underline{u}_t + r_{str} \cdot \underline{i}_t)/\jmath\, n \tag{148}$$

In the case of unbalanced RMS simulation the same neutral, zero and negative sequence equations have to be satisfied as in Section 6.1.2.1.

The electrical torque is calculated using the stator current and stator fluxe and the rated power factor $cosn$:

$$t_e = \frac{\Im(\underline{i}_t) \cdot \Re(\underline{\psi}_{str}) - \Re(\underline{i}_t) \cdot \Im(\underline{\psi}_{str})}{cosn} \qquad [p.u.] \tag{149}$$

The other mechanical equations are identical to the equations of the detailed synchronous machine presented in Section 6.1.2.3. The model uses only two state variables:

- the speed of the machine n in $[p.u.]$;
- the angle φ in $[rad]$ which is initialised as in Equation 111 where x_q is replaced by x_{str}.

6.3.2 Equations for the EMT model

In addition to the two state variables used in the RMS model, the EMT model uses two more state variables for the stator flux. The following equations need to be satisfied:

$$\begin{aligned} \psi_d &= v_e\angle\varphi_q - x_{str} \cdot i_d \\ \psi_q &= -v_e\angle\varphi_d - x_{str} \cdot i_q \end{aligned} \tag{150}$$

$$\begin{aligned} u_d &= -r_{str} \cdot i_d - \psi_q + \frac{1}{\omega_n} \cdot \frac{d\psi_d}{dt} \\ u_q &= -r_{str} \cdot i_q + \psi_d + \frac{1}{\omega_n} \cdot \frac{d\psi_q}{dt} \end{aligned} \tag{151}$$

where the amplitude of $v_e\angle\varphi_d$ and $v_e\angle\varphi_q$ are the d and q component of v_e (calculated as in 147).

For the EMT model it is considered that the rotor speed variation is small and therefore it is neglected ($n = 1p.u.$ in equation 151).

In addition to the above, the neutral and zero sequence sequence equations that need to be satisfied are the same as in Section 6.1.2.2.

The mechanical equations are identical to the equations of the detailed synchronous machine presented in Section 6.1.2.3.

6.3.3 Integrated AVR for Motor Starting

The classical model does not support the integrated AVR for motor starting.

6.3.4 Inputs/Outputs/State Variables of the Dynamic Model

6.3.4.1 Stability Model (RMS)

Table 6.17: 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.
freflocal		Reference frequency of local reference machine	p.u.

Table 6.18: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.19: Output Definition of the RMS-Model

Parameter	Symbol	Description	Unit
ut	$\|u_t\|$	Terminal Voltage, Magnitude	p.u.
utr		Terminal Voltage, Real Part	p.u
uti		Terminal Voltage, Imaginary Part	p.u.
pgt		Electrical Power (based on rated active power)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed		Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
cur1	$\|i_t\|$	Positive-Sequence Current, Magnitude	p.u.
cur1r		Positive-Sequence Current, Real Part	p.u.
cur1i		Positive-Sequence Current, Imaginary Part	p.u.
P1		Positive-Sequence, Active Power	MW
Q1		Positive-Sequence, Reactive Power	Mvar
fe		Frequency Output ($fe = xspeed$)	p.u.
outofstep		Out of step (pole slip) is “1” if generator is out of step and “0” otherwise	

6.3.4.2 EMT-Model

Table 6.20: 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 6.21: State Variables Definition of the EMT-Model

Parameter	Symbol	Description	Unit
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.22: Output Definition of the EMT-Model

Parameter	Symbol	Description	Unit
ut	$\|u_t\|$	Terminal Voltage, Magnitude	p.u.
utr		Terminal Voltage, Real Part	p.u
uti		Terminal Voltage, Imaginary Part	p.u.
pgt		Electrical Power (based on rated active power)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed	n	Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
cur1	$\|i_t\|$	Positive-Sequence Current, Magnitude	p.u.
cur1r		Positive-Sequence Current, Real Part	p.u.
cur1i		Positive-Sequence Current, Imaginary Part	p.u.
P1		Positive-Sequence, Active Power	MW
Q1		Positive-Sequence, Reactive Power	Mvar
fe		Frequency Output ($fe = xspeed$)	p.u.

6.4 Asynchronous starting model

Compared to the 2.1 model (standard salient machine model), this model requires more input data because it contains additional impedance branches. The parameters of these branches are dependent of the square root of the slip and represent eddy-current effects of solid rotor. This model is suitable for motor starting simulations. For detailed analysis the EMT model is to be preferred since there are no simplification done as in the RMS model. For example, in studies where the torque is of true interest, the EMT model is more appropriate.

This model is based on [10]. More information can be found in [11], [12], [13]. In opposite to [10], where α dictates the imaginary part components of the eddy-current resistances, in *PowerFactory* the real and imaginary parts are to be entered directly. The parameters x_{1de}, r_{1de}, x_{fde}, r_{fde}, x_{1qe} and r_{1qe} are all dependent of $\sqrt{slip}$.

Figure 6.12 and Figure 6.13 show the equivalent circuit diagrams of the *PowerFactory* synchronous machine model representing eddy-current effects of solid rotor, written in a rotor reference system (Park coordinates, dq-reference frame).

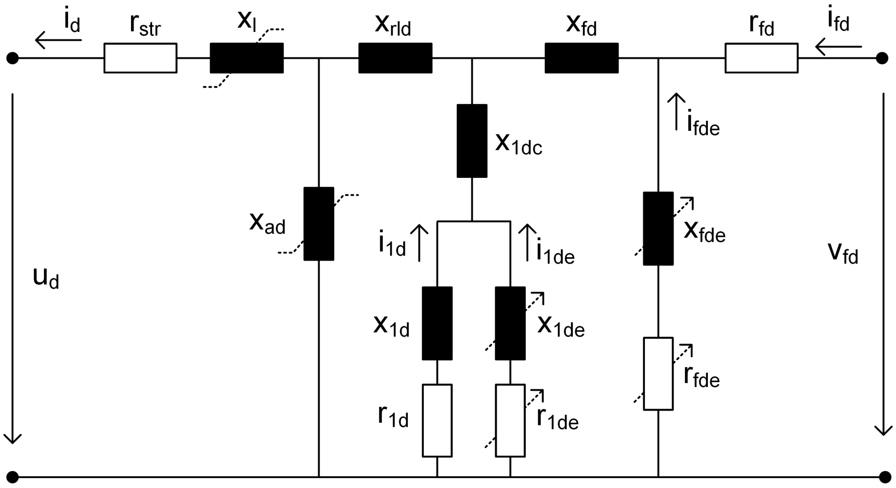

Figure 6.12: d-axis equivalent circuit

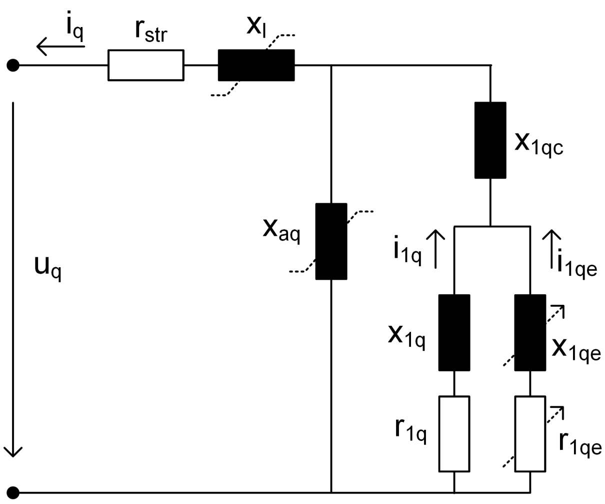

Figure 6.13: q-axis equivalent circuit

6.4.1 Input parameters

The model representing eddy-current effects can be used only with with equivalent circuit data (model parameters) as given in Table 6.23.

Table 6.23: Model parameters of the model 3.3 synchronous machine

Name in PF	Symbol	Unit	Description
$rstr$	r_{str}	$p.u.$	Stator resistance
xl	x_l	$p.u.$	Stator leakage reactance
xad	x_{ad}	$p.u.$	Mutual (magnetising) reactance, d-axis
xaq	x_{aq}	$p.u.$	Mutual (magnetising) reactance, q-axis
xrl	x_{rld}	$p.u.$	Coupling reactance of all d-axis rotor circuits
$x1dc$	x_{1dc}	$p.u.$	Coupling reactance between 1d-axis damper windings
$x1d$	x_{1d}	$p.u.$	Reactance of 1d-damper winding (d-axis)
$r1d$	r_{1d}	$p.u.$	Resistance of 1d-damper winding (d-axis)
$x1de$	x_{1de}	$p.u.$	Eddy-current reactance of 1d-damper winding for $slip = 1p.u.$ (d-axis)
$r1de$	r_{1de}	$p.u.$	Eddy-current resistance of 1d-damper winding for $slip = 1p.u.$ (d-axis)
xfd	x_{fd}	$p.u.$	Reactance of excitation (field) winding (d-axis)
rfd	r_{fd}	$p.u.$	Resistance of excitation (field) winding (d-axis)
$xfde$	x_{fde}	$p.u.$	Eddy-current reactance of excitation (field) winding for $slip = 1p.u.$ (d-axis)
$rfde$	r_{fde}	$p.u.$	Eddy-current resistance of excitation (field) winding for $slip = 1p.u.$ (d-axis)
$x1qc$	x_{1qc}	$p.u.$	Coupling reactance between 1q-axis damper windings
$x1q$	x_{1q}	$p.u.$	Reactance of 1q-damper winding (q-axis)
$r1q$	r_{1q}	$p.u.$	Resistance of 1q-damper winding (q-axis)
$x1qe$	x_{1qe}	$p.u.$	Eddy-current reactance of 1q-damper winding for $slip = 1p.u.$ (q-axis)
$r1qe$	r_{1qe}	$p.u.$	Eddy-current resistance of 1q-damper winding for $slip = 1p.u.$ (q-axis)

The synchronous reactances can be obtained as follows:

$$\begin{aligned} x_d &= x_l + x_{ad} \\ x_q &= x_l + x_{aq} \end{aligned} \tag{152}$$

6.4.2 Model equations

The rotor variables are referred to the stator windings and the equations are written using the rotor reference frame in generator orientation.

In the case of balanced RMS simulation, the available simulated values are positive sequence complex values. In the case of unbalanced RMS simulation, the available complex phase values for currents and voltages are first transformed into symmetrical components. For transforming to the dq-reference frame, the variables are shifted by multiplying with the transformation $\cos\varphi - \jmath \cdot \sin\varphi$. The voltages and currents available from the EMT simulation are first transformed from instantaneous values in the $\alpha\beta\gamma$ system using the Clarke transformation. The same transformation as above is used for transforming to the dq rotating reference frame.

Based on the equivalent circuit diagrams according to Figure 6.12 to Figure 6.13, the following differential equations can be derived.

The *PowerFactory* synchronous machine model for RMS simulations uses the rotor currents, magnetisation fluxes, the speed n and the angle φ as state variables. The EMT model uses two more state variables (stator fluxes ψ_d and ψ_q).

The stator voltage equations can be described as follows:

$$\begin{aligned} u_d &= -r_{str} \cdot i_d - n \cdot \psi_q + \frac{1}{\omega_n} \cdot \frac{d\psi_d}{dt} \\ u_q &= -r_{str} \cdot i_q + n \cdot \psi_d + \frac{1}{\omega_n} \cdot \frac{d\psi_q}{dt} \\ u_0 &= -r_{str} \cdot i_0 + \frac{1}{\omega_n} \cdot \frac{d\psi_0}{dt} \end{aligned} \tag{153}$$

where n is the speed of the rotor and $\omega_n = 2 \cdot \pi \cdot f_{nom}$ is the nominal angular frequency.

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

$$\begin{aligned} 0 &= r_{1d} \cdot i_{1d} + \frac{1}{\omega_n} \cdot \frac{d\psi_{1d}}{dt} \\ 0 &= r_{1de} \cdot i_{1de} + \frac{1}{\omega_n} \cdot \frac{d\psi_{1de}}{dt} \\ v_{fd} &= i_{fd} \cdot r_{fd} + \frac{1}{\omega_n} \cdot \frac{d\psi_{fd}}{dt} \\ 0 &= i_{fde} \cdot r_{fde} + \frac{1}{\omega_n} \cdot \frac{d\psi_{fde}}{dt} \end{aligned} \tag{154}$$

$$\begin{aligned} 0 &= r_{1q} \cdot i_{1q} + \frac{1}{\omega_n} \cdot \frac{d\psi_{1q}}{dt} \\ 0 &= r_{1qe} \cdot i_{1qe} + \frac{1}{\omega_n} \cdot \frac{d\psi_{1qe}}{dt} \end{aligned} \tag{155}$$

For completing the model, the stator and rotor flux linkage equations in the d- and q-axis are required:

$$\begin{aligned} \psi_d &= \psi_{ad} - x_l \cdot i_d \\ \psi_q &= \psi_{aq} - x_l \cdot i_q \end{aligned} \tag{156}$$

$$\begin{aligned} \psi_{1d} &= \psi_{ad} + x_{rld} \cdot (i_{fd} + i_{fde}) + (x_{rld} + x_{1dc}) \cdot i_{1de} + (x_{rld} + x_{1dc} + x_{1d}) \cdot i_{1d} \\ \psi_{1de} &= \psi_{ad} + x_{rld} \cdot (i_{fd} + i_{fde}) + (x_{rld} + x_{1dc}) \cdot i_{1d} + (x_{rld} + x_{1dc} + x_{1de}) \cdot i_{1de} \\ \psi_{fd} &= \psi_{ad} + x_{rld} \cdot (i_{1d} + i_{1de}) + (x_{rld} + x_{fd}) \cdot (i_{fd} + i_{fde}) \\ \psi_{fde} &= \psi_{ad} + (x_{rld} + x_{fd}) \cdot i_{fd} + (x_{rld} + x_{fd} + x_{fd}e) \cdot i_{fde} + x_{rld} \cdot (i_{1d} + i_{1de}) \end{aligned} \tag{157}$$

$$\begin{aligned} \psi_{1q} &= \psi_{aq} + x_{1qc} \cdot i_{1qe} + (x_{1qc} + x_{1q}) \cdot i_{1q} \\ \psi_{1qe} &= \psi_{aq} + x_{1qc} \cdot i_{1q} + (x_{1qc} + x_{1qe}) \cdot i_{1qe} \end{aligned} \tag{158}$$

where ψ_{ad} and ψ_{aq} are the d- and q-axis components of the magnetising flux:

$$\begin{aligned} \psi_{ad} &= x_{ad} \cdot (-i_d + i_{1d} + i_{1de} + i_{fd} + i_{fde}) \\ \psi_{aq} &= x_{aq} \cdot (-i_q + i_{1q} + i_{1qe}) \end{aligned} \tag{159}$$

The electrical torque is calculated using the stator currents and stator fluxes and the rated power factor $cosn$:

$$t_e = \frac{i_q \cdot \psi_d - i_d \cdot \psi_q}{cosn} \qquad [p.u.] \tag{160}$$

6.4.2.1 Equations for the RMS model

The equations from Section 6.4.2 are used for the RMS model where several simplifications have been made for the stator voltage equations.

The stator dynamics are relatively fast for stability studies. Therefore, for RMS-simulations, the derivatives of the stator quantities are not considered in the equations. Taking into account this simplification, the stator voltage Equations 153 can be written as:

$$\begin{aligned} u_d &= -r_{str} \cdot i_d - n \cdot \psi_q \\ u_q &= -r_{str} \cdot i_q + n \cdot \psi_d \end{aligned} \tag{161}$$

Similar as in the standard *PowerFactory* RMS model, additional modification can be made to the model by enabling/disabling the effect of the speed variation on the stator voltages (option $i\_speedVar$ on the *Advanced* tab of the *RMS-Simulation* page of *TypSym*). Depending on the option selected, Equation 161 is modified as follows:

- Effect of speed variation considered

  The equations have the form as already presented and the speed is considered in the equations.

- Effect of speed variation neglected

  The speed is set equal to the initial speed in both equations.

The option *Considered* should not be used for direct motor starting applications since during starting there is a big difference between the speed of the machine and the network frequency. The simulated results without this option are similar to the results of the EMT model. For motor starting applications including variable speed drives the speed effect variation option should be considered.

For studies where the torque is of true interest, the EMT model is more appropriate.

In the case of unbalanced RMS simulation the same neutral, zero and negative sequence equations have to be satisfied as in Section 6.1.2.1.

For the unbalanced RMS simulation, the model for asynchronous starting takes into account also a negative sequence torque into the equation of motion (Equation 95). The electrical torque t_e is the sum of the positive and negative sequence torques. The positive sequence torque t_{e1} is calculated according to 160. The negative sequence torque is calculated as:

$$t_{e2} = \frac{(r_{2sy} - r_{str}) \cdot \underline{i}_2^2}{cosn} \qquad [p.u.] \tag{162}$$

6.4.2.2 Equations for the EMT model

For the EMT model, there are no changes made to the equations presented in Section 6.4.2.

For the EMT simulation, the neutral and zero sequence sequence equations that have to be satisfied are the same as in Section 6.1.2.2.

When simulating asynchronous starting of a synchronous motor, the rotor angle (see 6.4.2.3) of the machine is initialised always with the same value when the circuit-breaker of the machine is open. This yields one of many possible solutions. The DC components of the simulated variables depend on the rotor position with respect to the terminal voltage where the machine will be connected. The DC components can be varied by changing the initial angle of the reference (for example: synchronous machine, voltage source, external grid) or by modifying the execution time of the circuit-breaker closing event.

6.4.2.3 Mechanical Equations, Rotor Angles and Delta Speed Input Signal

The mechanical equations, together with the definitions for mechanical torque, damping torque and acceleration time constant, are described in Section 6.1.2.3.

The rotor angle definitions are identical to the definitions presented in Section 6.1.3.

The functionality of the delta speed input signal dw is given in Section 6.1.6.

6.4.2.4 Saturation and parameter dependency

The model described so far is a purely linear model not considering any saturation effects. Generally, there exists saturation for all reactances of the synchronous machine model. However, for the purpose of system analysis, main flux saturation can be considered in the model by considering saturation of the mutual (magnetising) reactances x_{ad} and x_{aq}.

The main-flux saturation and the available options are as described in Section 6.1.4.

The saturation of stator leakage reactance is a current-dependent saturation, i.e. high currents after short-circuits will lead to a saturation effect of the leakage reactance. The modelling of the current dependency of the stator leakage reactance is supported by this model of the synchronous machine in *PowerFactory*. The data can be entered using tabular input of point-pairs of current and reactance. The data is then transformed to a smoothed curve with a piece-wise linear function using the dependency curve smoothing factor.

On every simulation step the stator reactance is determined from the curve for a specific value of the magnitude of the dq-stator current (zero sequence current is neglected):

$$xl = xl\_curve\left(\sqrt{i_d^2 + i_q^2}\right) \tag{163}$$

The additional impedance branches that are introduced to represent eddy-current effects, have parameters ($x_{1de}, r_{1de}, x_{fde}, r_{fde}, x_{1qe}$ and r_{1qe}) that are multiplied with the square root of the slip $\sqrt{slip}$. The values entered for this parameters in *TypSym* need to be for $slip = 100\%$. Internally the values are being kept and the dependent parameters are always updated according to:

$$\begin{aligned}
x_{1de} &= x_{1de_slip100\%} \cdot \sqrt{slip} \\
r_{1de} &= r_{1de_slip100\%} \cdot \sqrt{slip} \\
x_{fde} &= x_{fde_slip100\%} \cdot \sqrt{slip} \\
r_{fde} &= r_{fde_slip100\%} \cdot \sqrt{slip} \\
x_{1qe} &= x_{1qe_slip100\%} \cdot \sqrt{slip} \\
r_{1qe} &= r_{1qe_slip100\%} \cdot \sqrt{slip}
\end{aligned} \tag{164}$$

A threshold for the minimum slip is defined by using the parameter $slip_{min}$. By setting this parameter to 100%, the parameter dependency can be neglected.

6.4.2.5 Excitation system interfacing

Please refer to Section 6.1.5.

6.4.3 Integrated AVR for Motor Starting

Refer to Section 6.1.7.

6.4.4 Inputs/Outputs/State Variables of the Dynamic Model

6.4.4.1 Stability Model (RMS)

Table 6.24: 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.
freflocal		Reference frequency of local reference machine	p.u.
dw		Delta speed	p.u.

Table 6.25: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
i1d	i_{1d}	Current in 1d-damper winding, d-axis	p.u.
i1de	i_{1de}	Eddy-current in 1d-damper winding, d-axis	p.u.
ifd	i_{fd}	Current in field winding (excitation flux), d-axis	p.u.
ifde	i_{fde}	Eddy-current in field winding (excitation flux), d-axis	p.u.
i1q	i_{1q}	Current in 1q-damper winding, q-axis	p.u.
i1qe	i_{1qe}	Eddy-current in 1q-damper winding, q-axis	p.u.
psiad	ψ_{ad}	Magnetisation flux, d-axis	p.u.
psiaq	ψ_{aq}	Magnetisation flux, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.26: Output Definition of the RMS-Model

Parameter	Symbol	Description	Unit
ut	u_t	Terminal Voltage	p.u.
utr		Terminal Voltage, Real Part	p.u
uti		Terminal Voltage, Imaginary Part	p.u.
pgt		Electrical Power (based on rated active power)	p.u.
ie	i_e	Excitation Current (in non-reciprocal p.u. system)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed		Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
cur1	$\|i_t\|$	Positive-Sequence Current, Magnitude	p.u.
cur1r		Positive-Sequence Current, Real Part	p.u.
cur1i		Positive-Sequence Current, Imaginary Part	p.u.
P1		Positive-Sequence, Active Power	MW
Q1		Positive-Sequence, Reactive Power	Mvar
fe		Frequency Output ($fe = xspeed$)	p.u.
outofstep		Out of step (pole slip) is “1” if generator is out of step and “0” otherwise	

6.4.4.2 EMT-Model

Table 6.27: 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.
dw		Delta speed	p.u.

Table 6.28: State Variables Definition of the EMT-Model

Parameter	Symbol	Description	Unit
i1d	i_{1d}	Current in 1d-damper winding, d-axis	p.u.
i1de	i_{1de}	Eddy-current in 1d-damper winding, d-axis	p.u.
ifd	i_{fd}	Current in field winding (excitation flux), d-axis	p.u.
ifde	i_{fde}	Eddy-current in field winding (excitation flux), d-axis	p.u.
i1q	i_{1q}	Current in 1q-damper winding, q-axis	p.u.
i1qe	i_{1qe}	Eddy-current in 1q-damper winding, q-axis	p.u.
psiad	ψ_{ad}	Magnetisation flux, d-axis	p.u.
psiaq	ψ_{aq}	Magnetisation flux, q-axis	p.u.
psid	ψ_d	Stator flux, d-axis	p.u.
psiq	ψ_q	Stator flux, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.29: Output Definition of the EMT-Model

Parameter	Symbol	Description	Unit
ut	u_t	Terminal Voltage	p.u.
utr		Terminal Voltage, Real Part	p.u
uti		Terminal Voltage, Imaginary Part	p.u.
pgt		Electrical Power (based on rated active power)	p.u.
ie	i_e	Excitation Current (in non-reciprocal p.u. system)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed	n	Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
cur1	$\|i_t\|$	Positive-Sequence Current, Magnitude	p.u.
cur1r		Positive-Sequence Current, Real Part	p.u.
cur1i		Positive-Sequence Current, Imaginary Part	p.u.
P1		Positive-Sequence, Active Power	MW
Q1		Positive-Sequence, Reactive Power	Mvar
fe		Frequency Output ($fe = xspeed$)	p.u.

6.5 Single-phase model

Single-phase synchronous machines in the high-power range are mainly used as generators for the railway power supply in some countries [14]. The development of the single-phase dynamic models was supported by [15].

The rotor d-axis is modelled by two rotor loops representing the excitation (field) winding and the 1d-damper winding. The q-axis is modelled using one 1q-damper winding.

6.5.1 Input Parameters

The input parameters for the single-phase machine are the same as for the standard salient machine model without the x_{rlq} parameter. Please refer to subsection 6.1.1 of Section Standard Model.

The input resistances and reactances of a single-phase machine have double the values of a three-phase machines, whereas the time constants have the same values (please see Section **??**).

Note on the determination of the mutual magnetizing reactances: While the definition for the mutual magnetizing reactances for three-phase machines is $xad = 3/2 \cdot (lh + lh2)$ and $xaq = 3/2 \cdot (lh - lh2)$, for the single-phase machine is $xad = 1/2 \cdot (lh + lh2)$ and $xaq = 1/2 \cdot (lh - lh2)$. For both machines lh is the mean value of the magnetizing inductance and $lh2$ is the amplitude of the second harmonic of the magnetizing inductance for one stator phase. If measured the inductance of a stator phase is in front of a rotor pole $lh + lh2 + xl$ and in between rotor poles $lh - lh2 + xl$.

6.5.2 Model equations

The rotor variables are referred to the stator windings and the equations are written using the rotor reference frame in generator orientation.

In the case of unbalanced RMS simulation, the available complex phase values for currents and voltages are first transformed into symmetrical components. For transforming to the dq-reference frame, the variables are shifted by multiplying with the transformation $\cos\varphi - \jmath \cdot \sin\varphi$. The voltages and currents available from the EMT simulation are first transformed from instantaneous values in the $\alpha\beta\gamma$ system using the Clarke transformation. The same transformation as above is used for transforming to the dq rotating reference frame.

6.5.2.1 Equations for the RMS model

The stator dynamics are relatively fast for stability studies. Therefore, for RMS-simulations, the derivatives of the stator quantities are not considered in the equations. Taking into account this simplification, the stator voltage equations can be written as:

$$\begin{aligned} u_d &= -r_{str} \cdot i_d - n \cdot \psi_q \\ u_q &= -r_{str} \cdot i_q + n \cdot \psi_d \end{aligned} \tag{165}$$

Similar as in the standard *PowerFactory* RMS model, additional simplification can be made to the model by modifying the effect of the speed variation on the stator voltages (option located on the *Advanced* tab of the *RMS-Simulation* page of the *TypSym* edit dialog). Depending on the option selected, Equation 165 is modified as follows:

- Effect of speed variation considered

  The equations have the form as already presented and the speed is considered in the equations.

- Effect of speed variation neglected

  The speed is set equal to the initial speed in both equations. It is assumed that the speed changes are small and they don't have a big effect on the stator voltage [1]. The model is then valid for speed deviations around initial speed.

Using the reactance matrix:

$$\mathbf{X} = \begin{bmatrix} x_{ad} + x_{rl} + x_{1d} - \dfrac{x_{ad}^2}{2 \cdot x_d} & x_{ad} + x_{rl} - \dfrac{x_{ad}^2}{2 \cdot x_d} & 0 \\ x_{ad} + x_{rl} - \dfrac{x_{ad}^2}{2 \cdot x_d} & x_{ad} + x_{rl} + x_{fd} - \dfrac{x_{ad}^2}{2 \cdot x_d} & 0 \\ 0 & 0 & x_{aq} + x_{1q} - \dfrac{x_{aq}^2}{2 \cdot x_q} \end{bmatrix} \tag{166}$$

the following relationship between the fluxes and the rotor currents can be written:

$$\begin{bmatrix} \psi_{1d} - \dfrac{x_{ad}}{2 \cdot x_d} \cdot \psi_d \\ \psi_{fd} - \dfrac{x_{ad}}{2 \cdot x_d} \cdot \psi_d \\ \psi_{1q} - \dfrac{x_{aq}}{2 \cdot x_q} \cdot \psi_q \end{bmatrix} = \mathbf{X} \cdot \begin{bmatrix} i_{1d} \\ i_{fd} \\ i_{1q} \end{bmatrix} \tag{167}$$

where:

$$\begin{aligned} x_d &= x_l + \frac{x_{ad}}{2} \\ x_q &= x_l + \frac{x_{aq}}{2} \end{aligned} \tag{168}$$

The rotor currents can be now expressed using the inverse of the reactance matrix $\mathbf{B} = \mathbf{X}^{-1}$ as:

$$\begin{bmatrix} i_{1d} \\ i_{fd} \\ i_{1q} \end{bmatrix} = \mathbf{B} \cdot \begin{bmatrix} \psi_{1d} - \dfrac{x_{ad}}{2 \cdot x_d} \cdot \psi_d \\ \psi_{fd} - \dfrac{x_{ad}}{2 \cdot x_d} \cdot \psi_d \\ \psi_{1q} - \dfrac{x_{aq}}{2 \cdot x_q} \cdot \psi_q \end{bmatrix} \tag{169}$$

The stator flux equations in the d- and q-axis have the following form:

$$\begin{aligned} \psi_d &= -x_d \cdot i_d + x_{ad} \cdot (i_{1d} + i_{fd}) \\ \psi_q &= -x_q \cdot i_q + x_{aq} \cdot i_{aq} \end{aligned} \tag{170}$$

The rotor flux derivatives equations in the d- and q-axis have the following form:

$$\begin{aligned}\frac{d\psi_{fd}}{dt} &= (v_{fd} - r_{fd} \cdot i_{fd}) \cdot \omega_n \\ \frac{d\psi_{1d}}{dt} &= -r_{1d} \cdot i_{1d} \cdot \omega_n \\ \frac{d\psi_{1q}}{dt} &= -r_{1q} \cdot i_{1q} \cdot \omega_n\end{aligned} \tag{171}$$

The electrical torque is calculated using the stator currents and stator fluxes and the rated power factor $cosn$:

$$t_e = \frac{i_q \cdot \psi_d - i_d \cdot \psi_q}{cosn} \qquad [p.u.] \tag{172}$$

6.5.2.2 Equations for the EMT model

The stator voltage equation used for the EMT model is the following:

$$u_s = -r_{str} \cdot i_s + \frac{1}{\omega_n} \cdot \frac{d\psi_s}{dt} \tag{173}$$

where $\omega_n = 2 \cdot \pi \cdot f_{nom}$ is the nominal angular frequency.

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

$$\begin{aligned}0 &= r_{1d} \cdot i_{1d} \cdot \omega_n + \frac{d\psi_{ad}}{dt} + (x_{rl} + x_{1d}) \cdot \frac{di_{1d}}{dt} + x_{rl} \cdot \frac{di_{fd}}{dt} \\ v_{fd} \cdot \omega_n &= r_{fd} \cdot i_{fd} \cdot \omega_n + \frac{d\psi_{ad}}{dt} + x_{rl} \cdot \frac{di_{1d}}{dt} + (x_{rl} + x_{fd}) \cdot \frac{di_{fd}}{dt} \\ 0 &= r_{1q} \cdot i_{1q} \cdot \omega_n + \frac{d\psi_{aq}}{dt} + x_{1q} \cdot \frac{di_{1q}}{dt}\end{aligned} \tag{174}$$

The stator and rotor flux equations in the d- and q-axis are:

$$\begin{aligned}\psi_s &= \psi_d \cdot \cos\varphi - \psi_q \cdot \sin\varphi \\ 0 &= \psi_d \cdot \sin\varphi + \psi_q \cdot \cos\varphi \\ \psi_d &= \psi_{ad} - x_l \cdot i_d \\ \psi_q &= \psi_{aq} + x_l \cdot i_q\end{aligned} \tag{175}$$

$$\begin{aligned}\psi_{1d} &= \psi_{ad} + (x_{rl} + x_{1d}) \cdot i_{1d} + x_{rl} \cdot i_{fd} \\ \psi_{fd} &= \psi_{ad} + x_{rl} \cdot i_{1d} + (x_{rl} + x_{fd}) \cdot i_{fd} \\ \psi_{1q} &= \psi_{aq} + x_{1q} \cdot i_{1q}\end{aligned} \tag{176}$$

where ψ_{ad} and ψ_{aq} are the d- and q-axis components of the magnetising flux:

$$\begin{aligned}\psi_{ad} &= x_{ad} \cdot (-i_d + i_{1d} + i_{fd}) \\ \psi_{aq} &= x_{aq} \cdot (-i_q + i_{1q})\end{aligned} \tag{177}$$

The electrical torque is calculated as the sum of the partial derivatives of the flux equations versus the angle times the current flowing in the winding:

$$\begin{aligned}t_e = -2 \cdot ((x_{ad} - x_{aq})/2 \cdot \sin(2\varphi + \pi) \cdot i_s^2 - x_{ad} \cdot \cos(\varphi + \pi/2) \cdot i_s \cdot i_{fd} \\ - x_{ad} \cdot \cos(\varphi + \pi/2) \cdot i_s \cdot i_{1d} + x_{aq} \cdot \sin(\varphi + \pi/2) \cdot i_s \cdot i_{1q})/cosn\end{aligned} \tag{178}$$

where $cosn$ is the rated power factor.

6.5.2.3 Mechanical Equations, Rotor Angles and Delta Speed Input Signal

The mechanical equations, together with the definitions for mechanical torque, damping torque and acceleration time constant is described in Section 6.1.2.3.

6.5.3 Saturation

Saturation is not supported by the single-phase machine model.

6.5.4 Excitation system interfacing

Refer to Section 6.1.5.

6.5.5 Inputs/Outputs/State Variables of the Dynamic Model

6.5.5.1 Stability Model (RMS)

Table 6.30: 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.
freflocal		Reference frequency of local reference machine	p.u.
dw		Delta speed	p.u.

Table 6.31: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
psifd	ψ_{fd}	Field (excitation) flux	p.u.
psi1d	ψ_{1d}	Flux in 1d-damper winding	p.u.
psi1q	ψ_{1q}	Flux in 1q-damper winding	p.u.
psid	ψ_d	Stator Flux, d-axis, d-axis	p.u.
psiq	ψ_q	Stator Flux, q-axis	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.32: Output Definition of the RMS-Model

Parameter	Symbol	Description	Unit
pgt		Electrical Power (based on rated active power)	p.u.
ie	i_e	Excitation Current (in non-reciprocal p.u. system)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed		Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
fe		Frequency Output ($fe = xspeed$)	p.u.
outofstep		Out of step (pole slip) is “1” if generator is out of step and “0” otherwise	

6.5.5.2 EMT-Model

Table 6.33: 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.
dw		Delta speed	p.u.

Table 6.34: State Variables Definition of the EMT-Model

Parameter	Symbol	Description	Unit
i1d	i_{1d}	Current in 1d-damper winding, d-axis	p.u.
ifd	i_{fd}	Current in field winding (excitation flux), d-axis	p.u.
i1q	i_{1q}	Current in 1q-damper winding, q-axis	p.u.
psiad	ψ_{ad}	Magnetisation flux, d-axis	p.u.
psiaq	ψ_{aq}	Magnetisation flux, q-axis	p.u.
psid	ψ_d	Stator flux, d-axis	p.u.
psiq	ψ_q	Stator flux, q-axis	p.u.
psis	ψ_s	Stator flux	p.u.
speed	n	Speed	p.u.
phi	φ	Rotor position angle	rad

Table 6.35: Output Definition of the EMT-Model

Parameter	Symbol	Description	Unit
pgt		Electrical Power (based on rated active power)	p.u.
ie	i_e	Excitation Current (in non-reciprocal p.u. system)	p.u.
xphi		Rotor Angle ($xphi = phi$)	rad
xspeed	n	Speed ($xspeed = speed$)	p.u.
xme	t_e	Electrical Torque	p.u.
xmt	t_m	Mechanical Torque	p.u.
fe		Frequency Output ($fe = xspeed$)	p.u.

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Appendices

A Base values for single- and three-phase machines

The impedance base is calculated using the rated voltage and rated apparent power as:

$$Z_{base} = \frac{ugn^2}{sgn} \qquad [\Omega] \qquad (179)$$

where:

- For three-phase machines:
  - sgn is the rated three-phase apparent power.
  - ugn is the rated line-line voltage.
- For single-phase machines:
  - sgn is the rated single-phase apparent power.
  - ugn is the rated line-line voltage for phase to phase connections and the rated line-ground voltage for phase to neutral connections.

  According to [14], the behaviour of the single-phase machine can be derived from the single-phase operation of a three-phase machine. Impedances of a single-phase machine have double the values of the impedances of a three-phase machine loaded between two phases. So, if a three-phase machine with equal base voltage and apparent power is used in two phase mode, the resistances and reactances have to be set to half of the values of the single phase machine. The transient and subtransient time constants have the same value.

The rotor variables are referred to the stator side.

The base torque is the ratio between the electrical active power and the nominal mechanical angular frequency:

$$t_{base} = \frac{sgn \cdot cosn \cdot 1e^6}{\omega_{mech\_n}} \qquad [Nm] \qquad (180)$$

$$\omega_{mech\_n} = \frac{\omega_n}{\texttt{polepairs}} \qquad \left[mech.\frac{rad}{s}\right] \qquad (181)$$

where the nominal angular frequency ω_n is calculated using the nominal frequency $Fnom$:

$$\omega_n = 2\pi \cdot Fnom \qquad \left[elec.\frac{rad}{s}\right] \qquad (182)$$

B Additional calculation parameters (RMS/EMT simulation)

In this appendix, the calculation of some additional parameters available for the RMS and EMT models is presented:

- $Ptspin$ is the *Total Turbine Power of Area* in MW and is calculated using all machines belonging to a synchronous area as:

$$Ptspin = \sum_{ElmSym}^{Synch.area} (s\colon pt \cdot t\colon sgn \cdot t\colon cosn \cdot e\colon ngnum) \tag{183}$$

- $Pnomspin$ is the *Total Nominal Power of Spinning Machines in Area* in MW and is calculated using all machines belonging to a synchronous area as:

$$Pnomspin = \sum_{ElmSym}^{Synch.area} (t\colon sgn \cdot t\colon cosn \cdot e\colon ngnum) \tag{184}$$

- $Pmaxspin$ is the *Total Maximum Power of Spinning Machines in Area* in MW and is calculated using all machines belonging to a synchronous area as:

$$Pmaxspin = \sum_{ElmSym}^{Synch.area} c\colon Pmax \tag{185}$$

  where $c\colon Pmax$ is the smaller value between $e\colon Pmax\_uc \cdot e\colon ngnum$ and $t\colon sgn \cdot t\colon cosn \cdot e\colon pmaxratf \cdot e\colon ngnum$.

- $Presspin$ is the *Spinning Reserve of Area* in MW and is calculated using all machines belonging to a synchronous area as:

$$Presspin = Pmaxspin - Ptspin \tag{186}$$

- $Tagav$ is the *System Inertia of Area* in s and is calculated using all machines belonging to a synchronous area as:

$$Tagav = \left(\sum_{ElmSym}^{Synch.area} (c\colon Tag \cdot t\colon sgn \cdot t\colon cosn \cdot e\colon ngnum) \right) \Big/ Pnomspin \tag{187}$$

- $dorhz$ is the *Speed Deviation* in Hz and is calculated as:

$$dorhz = (s\colon speed + s\colon dw - 1) \cdot F_{nom} \tag{188}$$

Table B.1 lists the parameters used in the parameter calculation.

Table B.1: List of parameters

Symbol	**Parameter**	**Location**	**Description**	**Unit**
$s\colon pt$	pt	Signal	Turbine Power	p.u.
$t\colon sgn$	sgn	Type	Rated Apparent Power	MVA
$t\colon cosn$	cosn	Type	Rated Power Factor	
$e\colon ngnum$	ngnum	Element	Number of parallel Machines	
$c\colon Pmax$	Pmax	Calculation	Upper limit of active power	MW
$e\colon Pmax\_uc$	Pmax_uc	Element	Maximum Active Power Limit	MW
$e\colon pmaxratf$	pmaxratf	Element	Rating Factor (Active Power)	
$c\colon Tag$	Tag	Calculation	Acceleration Time Constant	s
$s\colon speed$	speed	Signal	Speed of the machine	p.u.
$s\colon dw$	dw	Signal	Delta Speed	p.u.

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