POWERFACTORY

PowerFactory 2021

Technical Reference

Saturable Asynchronous Machine

ElmAsm, TypAsm1

PF2021

POWER SYSTEM SOLUTIONS
MADE IN GERMANY

Publisher:
DIgSILENT GmbH
Heinrich-Hertz-Straße 9
72810 Gomaringen / Germany
Tel.: +49 (0) 7072-9168-0
Fax: +49 (0) 7072-9168-88
info@digsilent.de

Please visit our homepage at:
https://www.digsilent.de

December 1, 2020
PowerFactory 2021
Revision 1

Contents

1 General Description

This document describes the Asynchronous Machine model using the asynchronous machine type *TypAsm1* of DIgSILENT *PowerFactory*.

The *TypAsm1* model offers the following features:

- Stator iron losses can be modelled using the resistance r_{fe};
- Main Flux Saturation can be defined;
- Stator reactance can be varied in dependence of slip and current (leakage saturation);
- Rotor reactance can be varied in dependence of slip and current (leakage saturation);
- Rotor resistance can be varied in dependence of slip.

The model supports only single-cage rotors and the DFIG option is not supported. No parameter estimation is available and therefore only electrical parameters can be used as input to the model. The resistance r_{fe} is modelled in parallel with the magnetizing branch and can be used only for representing the stator iron losses (rotor iron losses cannot be correctly represented by this resistance and thus are neglected in this model).

Although the model is not strictly a double cage rotor model, the flexibility in the modelling of the slip dependence of the rotor leakage reactance and rotor resistance offers some possibility to cater for deep bar effects in the rotor.

All resistances and reactances of the model need to be entered for $slip = 0$ in $p.u.$ values (if dependency tables are not used). Additionally, all rotor resistances and reactances need to be referred to the stator side. If the rotor impedance referred to the stator is in absolute value, the base impedance for converting to $p.u.$ values is $Z_b = ugn^2/sgn$ where ugn is the rated voltage of the machine and sgn is the rated apparent power.

The equations and parameters of the Asynchronous Machine using *TypAsm1* are documented in the following sections.

2 Slip and Current Parameter Dependency

The following slip and current parameter dependencies have been implemented for all calculation models (except for the short-circuit model):

- Stator reactance x_{str} can vary with slip and current;
- Rotor reactance x_{rtr} can vary with slip and current;
- Rotor resistance r_{rtr} can vary with slip.

The leakage saturation effects can be modelled by using the current dependency.

The total stator reactance x_{str_tot} depends on the type of dependency selected:

$$x_{str\_tot} = \begin{cases} x_{str} & \text{no dependency} \\ x_{str} \cdot \left(1 + (c_s - 1) \cdot \dfrac{i_s}{i_{slim}}\right) - slip \cdot x_{str\_s} & \text{current and simple slip dep.} \\ x_{str} \cdot \left(1 + (c_s - 1) \cdot \dfrac{i_s}{i_{slim}}\right) - x_{str\_tab} & \text{current and slip dependency} \end{cases} \tag{1}$$

where:

- x_{str} is type parameter for $slip = 0$;
- c_s is stator reactance current dependency factor;
- i_s is the magnitude of the stator current;
- i_{slim} is the magnitude of the stator current for $s = 100\%$ and stator voltage value of $1p.u.$;
- $slip$ is the slip of the machine;
- x_{str_s} is slip dependent part of the stator reactance (type parameter);
- x_{str_tab} is slip dependent part of the stator reactance taken from the table for a certain slip;

From the above equation it is obvious that for $c_s = 1$, the current dependency is ignored, and that for $x_{str\_s} = 0$ the speed dependency is ignored.

Similar to the total stator reactance, the total rotor reactance x_{rtr_tot} depends on the type of dependency selected:

$$x_{rtr\_tot} = \begin{cases} x_{rtr} & \text{no dependency} \\ x_{rtr} \cdot \left(1 + (c_r - 1) \cdot \dfrac{i_r}{i_{rlim}}\right) & \text{current dependency} \\ (x_{rtr} - x_{rtr\_tab}) \cdot \left(1 + (c_r - 1) \cdot \dfrac{i_r}{i_{rlim}}\right) & \text{current and slip dependency} \end{cases} \tag{2}$$

where:

- x_{rtr} is type parameter for $slip = 0$;
- c_r is rotor reactance current dependency factor;
- i_r is the magnitude of the rotor current;

- i_{rlim} is the magnitude of the rotor current for $slip = 100\%$ and stator voltage value of $1p.u.$;
- $slip$ is the slip of the machine;
- x_{rtr_speed} is slip dependent part of the rotor reactance (type parameter);
- x_{rtr_tab} is slip dependent part of the rotor reactance taken from the table for a certain slip;

The rotor resistance can be only defined as slip dependent:

$$r_{rtr} = \begin{cases} r_{rtr} & \text{no dependency} \\ r_{rtr\_tab} & \text{slip dependency.} \end{cases} \tag{3}$$

where:

- r_{rtr} is type parameter for $slip = 0$;
- $slip$ is the slip of the machine;
- r_{rtr_tab} is slip dependent rotor resistance taken from the table for a certain slip;

When calculating the magnitude of stator and rotor currents for the purpose of leakage saturation, the positive sequence current is used. Only in the case of the EMT simulation, the dq current is being used (without the zero component).

By selecting the option *Limit the Current for Calculating Stator and Rotor Current Dependency* (i_curlim) in the RMS/EMT tab of *TypAsm1*, the currents i_s and i_r are limited to i_{slim} and i_{rlim}, respectively, when calculating x_{str_tot} and x_{rtr_tot} (only for simulations).

When the parameter slip dependency is being used, a curve is created from the entered point-pairs data in the table which is rounded using the curve smoothing factor $depSmoothFac$ in $[\%]$. The curve is piecewise linear where the corner points of the given intervals are rounded using a trigonometric function interpolation. The range around the corners which are rounded is defined by the percentage entered in the curve smoothing factor.

The main flux saturation is described in section 6.4.

3 Load Flow Analysis

The *TypAsm1* model is being considered for AC balanced, AC unbalanced and DC Load Flow calculations.

For representing asynchronous machines in load flow analysis, the user has the choice between two representations (*bustp* parameter *ElmAsm*):

- AS - Slip Iteration

  For the *AS* method, active power, mechanical power or mechanical torque need to be entered by the user as input and the corresponding slip and reactive power are products from the Load Flow calculation.

- PQ - Constant P-Q

  For the *PQ* method, the reactive power has also to be entered. In this case, the corresponding slip and an additional reactive power compensation is being calculated which compensates the reactive power mismatch. The reactive power compensation is a shunt (parameter $qcomp$) connected in parallel to the machine (Figure 5.1).

Both calculation methods are based on the equivalent circuit diagram according to Figure 3.1 for the positive sequence model. The model equations are evaluated for steady state operating conditions during the load flow iterations.

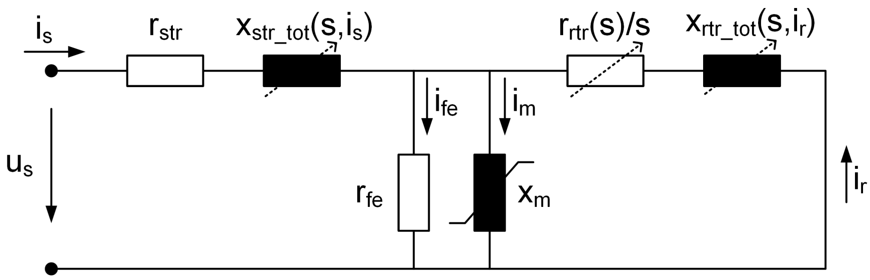

Figure 3.1: *DIgSILENT* asynchronous Machine TypAsm1 Load-Flow Model

If the *Connection* of the machine is set to *YN* (type parameter $nslty$), the zero sequence parameters $rzero$ and $xzero$ can be entered. In this case, also the internal grounding impedance and neutral connection information can be defined in the tab *Grounding/Neutral Conductor* of the *Basic Data* page of *ElmAsm*.

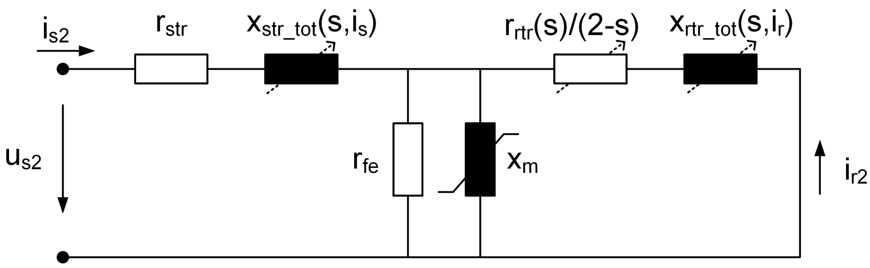

Figure 3.2: *DIgSILENT* TypAsm1 Negative - Sequence Load-Flow Model

The unbalanced Load Flow calculation requires also a negative and zero sequence model. The negative sequence model is based on the equivalent circuit diagram according to Figure

3.2. The normalised difference between the air-gap MMF and the rotor speed in the negative sequence system is $2 - slip$ (Chapter 9.3 of [1]), and therefore the rotor resistance is divided by $2 - slip$. The calculation of the leakage saturation and the slip dependence of the parameters, for the usage in the negative sequence circuit, is carried out same as in the case of the positive sequence model (using positive sequence current and using slip).

The zero sequence model is built by using the zero sequence impedance $\underline{z}_0 = rzero + \imath \cdot xzero$). As in the positive sequence case, the model equations are evaluated in steady state operating conditions during the load flow iterations.

The Load Flow model takes into account the slip and current dependency of the stator and rotor reactances and the slip dependence of the rotor resistance as described in the Slip and Current Parameter Dependency Section. The main flux saturation is also included in the Load Flow model. For more information how the saturation is calculated please refer to section 6.4.

If the *Machine Type* (*Basic Data* page of *ElmAsm*) is set to *with Variable Rotor Resistance*, a constant slip value can be set or a slip characteristic dependent on the active power can be defined (*Load Flow* page). In this case an additional rotor resistance is calculated r_{radd} so that the defined slip is being reached. The signal r_{radd} can be displayed in the results box of the machine.

The loading for the balanced case is calculated according to Equation 4 (positive sequence) and for the unbalanced case according to Equation 5 (symmetrical components) where $ngnum$ is number of parallel machines parameter and sgn is the rated apparent power.

$$loading = \frac{|\underline{u}_s \cdot \underline{i}_s^*|}{ngnum \cdot sgn/1000} \cdot 100 \qquad [\%] \tag{4}$$

$$loading = \frac{|(\underline{u}_{s1} \cdot \underline{i}_{s1}^* + \underline{u}_{s2} \cdot \underline{i}_{s2}^* + \underline{u}_{s0} \cdot \underline{i}_{s0}^*)/3|}{ngnum \cdot sgn/1000} \cdot 100 \qquad [\%] \tag{5}$$

The slip at maximum (breakdown) torque $slipk$ is being calculated using the Thevenin's equivalent impedance of the machine excluding the rotor circuit (maximum torque occurs when the power transferred to r_{rtr}/s is maximum):

$$slipk = \frac{r_{rtr}}{\sqrt{z_{th.r}^2 + (z_{th.i} + x_{rtr})^2}} \cdot 100 \qquad [\%] \tag{6}$$

$$\underline{z}_{th} = (r_{fe}||jx_m)||(r_{str} + jx_{str}) \qquad [p.u.] \tag{7}$$

For the *DC Load Flow*, only the active power is being taken into account.

3.1 Signals

The signals used in the Load Flow Analysis are presented in Table 3.1.

Table 3.1: Signals (Load Flow Analysis)

Name	Symbol	Unit	Type	Description
$slip$		$\%$	OUT	Slip
$rradd$	r_{radd}	$p.u.$	OUT	Additional Rotor Resistance

3.2 Calculation parameters

The calculation parameters used in the Load Flow Analysis are presented in Table 3.2.

Table 3.2: Calculation parameters (Load Flow Analysis)

Name	Symbol	Unit	Description
p		MW	Active Power (Electrical)
q		$Mvar$	Reactive Power
pm		MW	Mechanical Power
$qcomp$		$Mvar$	Reactive Power for Compensation
$ksat$	k_{sat}		Saturation Factor
$xmsat$	x_{msat}	$p.u.$	Saturated Magnetising Reactance
$rrtr$	r_{rtr}	$p.u.$	Rotor Resistance (including slip dependency if enabled)
$xstr\_tot$	x_{str_tot}	$p.u.$	Total Stator reactance (including dependencies)
$xrtr\_tot$	x_{rtr_tot}	$p.u.$	Total Rotor reactance (including dependencies)
$islim$	i_{slim}	$p.u.$	Stator Current for Locked-Rotor and Nominal Voltage
$irlim$	i_{rlim}	$p.u.$	Rotor Current for Locked-Rotor and Nominal Voltage
$irtr$	i_{rtr}	$p.u.$	Rotor Current (Complex value)
$frnom$		Hz	Nominal Frequency
$loading$		$\%$	Loading of the Machine
$slipn$		$\%$	Nominal Slip
$slipk$		$\%$	Slip at Breakdown (Stalling) point
$speed$		$p.u.$	Speed
$zasm$		$p.u.$	Positive Sequence Impedance (Complex value)
$zasm2$		$p.u.$	Negative Sequence Impedance (Complex value)
$z0$		$p.u.$	Zero Sequence Impedance (Complex value)
ze		$p.u.$	Grounding Impedance (Complex value)
xme		$p.u.$	Electrical Torque
$xme1$		$p.u.$	Electrical Torque, Positive Sequence
$xme2$		$p.u.$	Electrical Torque, Negative Sequence
$zonewscale$			Wind generation zone scaling factor

4 Short-Circuit Analysis

In this section the short-circuit models of the asynchronous machine are described.

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

The IEC 60909 standard (equivalent to VDE 102/103) only calculates the subtransient time phase. For calculating DC time constants, transient or permanent short-circuit currents, the rules defined in the individual short-circuit standards are applied. Figure 4.1 shows the IEC 60909 short-circuit model of an asynchronous machine.

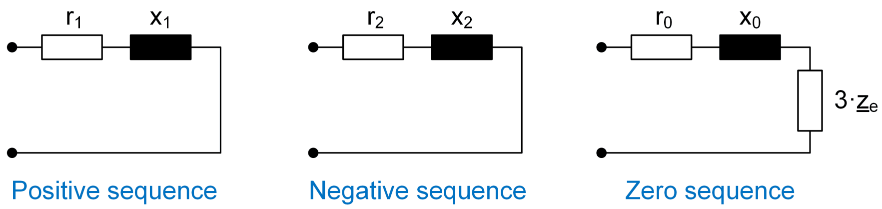

Figure 4.1: Asynchronous machine IEC 60909 short-circuit model

Depending on the selected options, several scenarios are possible for calculating the positive sequence impedance $\underline{z}_1 = r_1 + jx_1 = r_m + jx''_m$:

- Standard (User defined)

  In the standard case, the locked rotor current ratio ($aiaznshc$) and the r to x ratio ($rtoxshc$) are user defined and are used as following:

  $$\begin{aligned} z_1 &= 1/aiaznshc \\ rtox &= rtoxshc \end{aligned} \tag{8}$$

  The positive sequence impedance is calculated as:

  $$\begin{aligned} x_1 &= \frac{z_1}{\sqrt{1+rtox^2}} \\ r_1 &= x_1 \cdot rtox \end{aligned} \tag{9}$$

- Consider transient parameters

  In this case the parameters entered in the Load Flow tab are used for calculating the impedance $\underline{z}_1$ (slip is $1\ p.u.$).

- Static converter-fed drive (option located in ElmAsm)

  In the case of a static converter-fed drive, the subtransient impedance is fixed as well as the r to x ratio:

  $$\begin{aligned} z_1 &= 1/3 \\ r2x &= 0.1 \end{aligned} \tag{10}$$

  The positive sequence impedance is calculated same as in Equation 9.

The negative sequence impedance is set equal to the positive $\underline{z}_2 = \underline{z}_1$.

If the machine has *YN* connection (type parameter $nslty$), the zero sequence impedance $\underline{z}_0 = r_{zero} + \jmath \cdot x_{zero}$ 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 *ElmAsm*). The internal grounding impedance per unit values are calculated as $\underline{z}_e = (R_e + \jmath \cdot X_e)/z_b = r_e + \jmath \cdot x_e$ using the base impedance $z_b = ugn^2/sgn$ (ugn is the rated voltage of the machine and sgn is the rated apparent power).

4.2 Complete Short-Circuit Method

When using the *complete short-circuit method*, the internal voltage source is initialized by a preceding load flow calculation. This method calculates subtransient and transient fault currents using subtransient and transient voltage sources and impedances. Figure 4.2 shows the short-circuit subtransient model of an asynchronous machine. The transient model does not have the voltage source in the positive sequence.

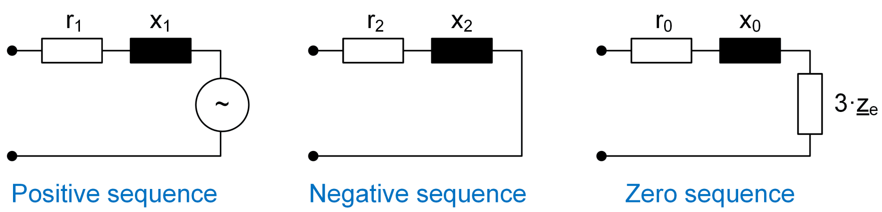

Figure 4.2: Asynchronous machine complete short-circuit subtransient model

The positive sequence impedance is calculated according to Equation 9. Depending on the selected options, several scenarios for calculation of the parameters are possible:

- Standard (User defined)

  In the standard case, the locked rotor current ratio ($aiaznshc$) and the r to x ratio ($rtoxshc$) are user defined and are used as following:

  $$\begin{aligned} z_1 &= 1/aiaznshc \\ rtox &= rtoxshc \end{aligned} \tag{11}$$

  The negative sequence impedance is set equal to the positive $\underline{z}_2 = \underline{z}_1$.

- Consider transient parameters

  In this case the parameters entered in the Load Flow tab are used for calculating the impedances.For calculating the subtransient positive sequence impedance a slip value of $1p.u.$ is being used. For the transient positive sequence impedance the slip determined by the load flow solution is being used.

  For the negative sequence impedances a slip value of $1p.u.$ is being used.

The zero and earthing impedances are calculated the same as for the IEC/VDE short-circuit.

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.

4.3 ANSI-C37 Short-Circuit

PowerFactory supports short-circuit calculation according to ANSI C-37. Similar to short-circuit calculations according to IEC60909, only subtransient fault currents are actually calculated.

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

4.4 Calculation parameters

The calculation parameters used in the Short-Circuit Analysis are presented in Table 4.1.

Table 4.1: Calculation parameters (Short-Circuit Analysis)

Name	Symbol	Unit	Description
$z1$		$p.u.$	Subtransient Impedance (1-Sequ.) (Complex value)
$r1$		$p.u.$	Subtransient Resistance
$x1$		$p.u.$	Subtransient Reactance
$z2$		$p.u.$	Subtransient Impedance (2-Sequ.) (Complex value)
$z0$		$p.u.$	Subtransient Impedance (0-Sequ.) (Complex value)
ze		$p.u.$	Grounding Impedance (Complex value)
uss		$p.u.$	Subtransient Voltage (Complex value)
Prm		MW	Rated Mechanical Power
$isremote$			Remote Contribution
$Icontrib$		kA	Contribution Current
$currcont$		$p.u.$	Contribution Current
$rradd$	r_{radd}	$p.u.$	Additional Rotor Resistance
$xstadd$	x_{stadd}	$p.u.$	Additional Stator Reactance
$autotap$		$p.u.$	Auto Transformer Tap

5 Harmonic Analysis

The asynchronous machine model for harmonic analysis can directly be derived from the equivalent circuits according to Figure 3.1. If the constant PQ model has been used, then internally a parallel susceptance is connected to the machine (Figure 5.1).

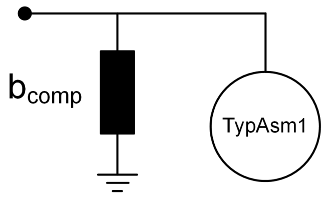

Figure 5.1: *DIgSILENT* TypAsm1 PQ model

The value of the susceptance is calculated from the reactive power compensation as follows:

$$b_{comp} = \frac{q_{comp}}{|\underline{u}_s| \cdot S_r} \tag{12}$$

where $|u_s|$ is the absolute value of the positive sequence terminal voltage and S_r is the rated apparent power of the machine in MVA. The susceptance is multiplied with the harmonic order when used in the harmonic analysis (as well as all other reactances).

For higher frequencies, the asynchronous machine impedance corresponds to the subtransient value. Only for frequencies around fundamental frequency, the actual slip dependence is important. This accurate representation is especially required for sub-synchronous resonance studies or self-excitation studies of asynchronous machines.

It is possible to neglect the effect of slip dependence by disabling the flag *consider transient parameters*.

No phase capacitances are included in the model. The phase capacitances cannot be ignored for frequencies higher than $1kHz$ in the case of asynchronous machines connected on a voltage higher than $10kV$.

5.1 Calculation parameters

The calculation parameters used in the Harmonic Analysis model are the same as for the Short-Circuit Analysis presented in Table 4.1.

6 RMS and EMT Simulation

The structure of the asynchronous machine model used for the RMS and EMT simulations is given in Figure 6.1. The base equations, for both the RMS and EMT model, which can be found in many references have been modified to account for the iron losses ([1], [2]).

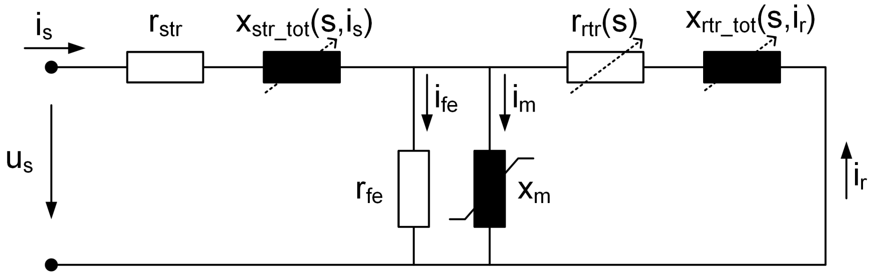

Figure 6.1: *DIgSILENT* TypAsm1 Dynamic model

The nominal asynchronous speed $speedn$ of the machine is calculated as a ratio between the rated asynchronous and nominal synchronous speed:

$$speedn = \frac{anend}{\frac{60 \cdot frnom}{nppol}} \qquad [p.u.] \tag{13}$$

where:

- $anend$ is the rated speed in rpm;
- $frnom$ is the nominal frequency in Hz;
- $nppol$ is the number of pole pairs.

The p.u. value of the speed of the machine is based on the synchronous speed.

The parameters x_{s_sum} and x_{r_sum} are the reactance sum of the stator and rotor circuit respectively:

$$x_{s\_sum} = x_{msat} + x_{str\_tot} \qquad [p.u.] \tag{14}$$

$$x_{r\_sum} = x_{msat} + x_{str\_tot} \qquad [p.u.] \tag{15}$$

6.1 RMS Electrical Equations

The available currents and voltages from the RMS simulation are referred to the global reference system (usually fixed to the rotor of the reference machine). In the case of balanced RMS simulation, the available values are positive sequence complex values and are directly used in the model. In the case of unbalanced RMS simulation, the available complex phase values for currents and voltages are first transformed into symmetrical components and then used in the model.

The stator transients are neglected in the RMS simulation model. The RMS model uses a local synchronously rotating reference frame for the variables. The variables are shifted (translated) to this reference frame using the angle φ_{ref} (in which case they get the notation "$_{loc}$") by multiplying with the transformation $e^{-\imath \cdot \varphi_{ref}}$. As for example:

$$\underline{\psi}_{R\_loc} = (\psi_{R\_r} + \imath \cdot \psi_{R\_i}) \cdot e^{-\imath \cdot \varphi_{ref}} = (\psi_{R\_r} + \imath \cdot \psi_{R\_i}) \cdot (\cos\varphi_{ref} - \imath \cdot \sin\varphi_{ref}) \tag{16}$$

The angle φ_{ref} is initialised with zero and keeps track of the frequency changes at the local bus where the machine is connected compared to the global reference frame. Its derivative is calculated as follows:

$$\frac{d\varphi_{ref}}{dt} = hpi \cdot (f_e - f_{ref}) \tag{17}$$

where f_e is the frequency of the terminal the machine is connected to, f_{ref} is the reference machine frequency and hpi is the nominal angular frequency calculated using the nominal frequency $frnom$ as:

$$hpi = 2 \cdot \pi \cdot frnom \qquad \left[\frac{rad}{s}\right] \tag{18}$$

The stator flux is calculated using the following equation:

$$\underline{\psi}_{S\_loc} = x_{s\_sum} \cdot \underline{i}_{s\_loc} + x_{msat} \cdot (\underline{i}_{r\_loc} - \underline{i}_{fe\_loc}) \qquad [p.u.] \tag{19}$$

The stator and rotor voltage equations have the following form:

$$\underline{u}_{s\_loc} = r_{str} \cdot \underline{i}_{s\_loc} + \imath \cdot f_e \cdot \underline{\psi}_{S\_loc} \tag{20}$$

$$0 = r_{rtr} \cdot \underline{i}_{r\_loc} + \imath \cdot \frac{slip}{100} \cdot f_e \cdot \underline{\psi}_{R\_loc} + \frac{1}{hpi} \cdot \frac{d\underline{\psi}_{R\_loc}}{dt} \tag{21}$$

The internal parallel shunt compensation susceptance b_{comp} (Figure 5.1) is defined as a signal and its value can be regulated using a DSL model (it is initialised from the load flow calculation according to equation 12).

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 takes into account the negative sequence impedance $\underline{z}_2$ which is calculated according to the equivalent circuit shown in Figure 3.2. Analogue as in the load flow model, the rotor resistance is divided by $2 - slip$ (the normalised difference between the air-gap MMF and the rotor speed in the negative sequence system is $2 - slip$ (Chapter 9.3 of [1])). The calculation of the leakage saturation and the slip dependence of the parameters, for the usage in the negative sequence equivalent impedance, is carried out same as in the case of the positive sequence model (using positive sequence current and using slip).

The negative sequence equation is given in Equation 22.

$$\underline{i}_{s2} = \frac{\underline{u}_{s2}}{\underline{z}_2} \tag{22}$$

If the *Connection* of the machine is set to *YN* (type parameter $nslty$), the zero sequence impedance can be entered $z_0 = rzero + \imath \cdot xzero$. For YN connections, the internal grounding impedance and neutral connection information can be defined in the *Grounding/Neutral Conductor* tab of the *Basic Data* page of *ElmAsm*.

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:

$$\underline{u}_{s0} = \underline{z}_0 \cdot \underline{i}_{s0} + 3 \cdot \underline{z}_e \cdot \underline{i}_{s0} \tag{23}$$

(24)

- 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

$$\underline{u}_{s0} = \underline{z}_0 \cdot \underline{i}_{s0} + \underline{u}_n \tag{25}$$
$$0 = 3 \cdot \underline{i}_{s0} + \underline{i}_n \tag{26}$$

  – Internal grounding impedance connected

$$\underline{u}_{s0} = \underline{z}_0 \cdot \underline{i}_{s0} + \underline{u}_n \tag{27}$$
$$\underline{u}_n = \underline{z}_e \cdot (3 \cdot \underline{i}_{s0} + \underline{i}_n) \tag{28}$$

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

$$\underline{u}_{s0} = \underline{z}_0 \cdot \underline{i}_{s0} + \underline{u}_n \tag{29}$$
$$0 = 3 \cdot \underline{i}_{s0} + \underline{i}_n \tag{30}$$

The complex value $\underline{z}_e$ is the internal grounding impedance calculated from the absolute values Re and Xe using the base impedance Z_b as:

$$\underline{z}_e = (Re + \imath \cdot Xe)/Z_b \qquad [p.u.] \tag{31}$$

where $Z_b = ugn^2/sgn$ (ugn is the rated voltage of the machine and sgn is the rated apparent power).

6.2 EMT Electrical Equations

For the EMT model *PowerFactory* uses a stationary reference frame for the stator variables and a synchronously rotating reference frame for the rotor variables. Most of the variables can be observed in both reference frames.

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. Consequently, the new obtained values are based on a stationary reference frame.

The angle φ is used for transforming between the stationary and rotating reference frames. It is initialised with $0\ [rad]$ and is rotating with the nominal angular frequency $hpi = 2 \cdot \pi \cdot frnom$.

The transformation of a certain variable from $\alpha\beta\gamma$ to a $dq0$ reference frame is carried out by multiplying it with the transformation:

$$e^{-\imath \cdot \varphi} = \cos\varphi - \imath \cdot \sin\varphi \tag{32}$$

The inverse transformation is used for transforming from a $dq0$ to a $\alpha\beta\gamma$ reference frame.

The stator flux and rotor flux equations have the following form:

$$\underline{\psi}_{S\_\alpha\beta} = x_{msat} \cdot \underline{i}_{m\_\alpha\beta} + x_{str\_tot} \cdot \underline{i}_{s\_\alpha\beta} \tag{33}$$
$$\underline{\psi}_{R\_dq} = x_{msat} \cdot \underline{i}_{m\_\alpha\beta} \cdot e^{-\imath \cdot \varphi} + x_{str\_tot} \cdot \underline{i}_{r\_dq} \tag{34}$$

The stator and rotor voltage equations have the following form:

$$\underline{u}_{s\_\alpha\beta} = r_{str} \cdot \underline{i}_{s\_\alpha\beta} + \frac{1}{hpi} \cdot \frac{d\underline{\psi}_{S\_\alpha\beta}}{dt} \tag{35}$$

$$0 = r_{rtr} \cdot \underline{i}_{r\_dq} + \imath \cdot (1 - speed) \cdot \underline{\psi}_{R\_dq} + \frac{1}{hpi} \cdot \frac{d\underline{\psi}_{R\_dq}}{dt} \tag{36}$$

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. The internal grounding parameters are calculated using the internal grounding impedance z_e calculated in Equation 31. The resistance is obtained as $r_{e\_z} = z_e.r$ and the inductance as $l_{e\_z} = z_e.i/hpi$.

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:

$$u_{s\_\gamma} = (r_{0\_z} + 3 \cdot r_{e\_z}) \cdot i_{s\_\gamma} + (l_{0\_z} + 3 \cdot l_{e\_z}) \cdot \frac{di_{s\_\gamma}}{dt} \tag{37}$$

- 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

$$u_{s\_\gamma} = r_{0\_z} \cdot i_{s\_\gamma} + l_{0\_z} \cdot \frac{di_{s\_\gamma}}{dt} + u_n \tag{38}$$

$$0 = 3 \cdot i_{s\_\gamma} + i_n \tag{39}$$

  – Internal grounding impedance connected

$$u_{s\_\gamma} = r_{0\_z} \cdot i_{s\_\gamma} + l_{0\_z} \cdot \frac{di_{s\_\gamma}}{dt} + u_n \tag{40}$$

$$u_n = r_{e\_z} \cdot (3 \cdot i_{s\_\gamma} + i_n) + l_{e\_z} \cdot \left(3 \cdot \frac{di_{s\_\gamma}}{dt} + \frac{di_n}{dt}\right) \tag{41}$$

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

$$u_{s\_\gamma} = r_{0\_z} \cdot i_{s\_\gamma} + l_{0\_z} \cdot \frac{di_{s\_\gamma}}{dt} + u_n \tag{42}$$

$$0 = 3 \cdot i_{s\_\gamma} + i_n \tag{43}$$

6.3 Mechanical Equations and Torque

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

$$\frac{dspeed}{dt} = \begin{cases} \dfrac{-xmt - xme}{tag} & [p.u.] \text{ for motors} \\[2ex] \dfrac{xmt - xme}{tag} & [p.u.] \text{ for generators} \end{cases} \tag{44}$$

where xmt is the mechanical torque, xme is the electrical torque and tag is the acceleration time constant.

From Equation 44 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 [3].

The slip is calculated as follows (f_e is the electrical frequency at the connection terminal):

$$slip = \begin{cases} (1 - speed/f_e) \cdot 100 & [\%] \text{ RMS simulation} \\[2ex] (1 - speed) \cdot 100 & [\%] \text{ EMT simulation} \end{cases} \tag{45}$$

6.3.1 Electrical Torque

For the balanced RMS simulation, the (positive sequence) electrical torque xme is calculated as ([2]):

$$xme = -\frac{x_{msat}}{x_{r\_sum}} \left(\Re(\underline{\psi}_{R\_loc}) \cdot \Im(\underline{i}_{s\_loc} - \underline{i}_{fe\_loc}) - \Im(\underline{\psi}_{R\_loc}) \cdot \Re(\underline{i}_{s\_loc} - \underline{i}_{fe\_loc}) \right) \quad [p.u.] \tag{46}$$

For the unbalanced RMS simulation, the torque is the sum of the positive and negative sequence torques $xme = xme1 + xme2$, where the negative sequence electrical torque $xme2$ is calculated analytically to the positive sequence torque with using negative sequence quantities (and slip of $2 - slip$).

In the EMT simulation, the torque is calculated analogue as in the balanced RMS simulation by using dq quantities.

Depending on the selected option for *Torque Based on* (type parameter $i\_torqueBase$), the torque base is the:

- Rated Mechanical Power divided with the Asynchronous Speed (mech.); or
- Rated Apparent Power divided with the Synchronous Speed (mech.).

If the base for the torque is selected as the *Rated Mechanical Power and Asynchronous Speed*, the torque xme is modified by dividing it by the parameter $torqueBase$:

$$torqueBase = cosn \cdot \frac{effic}{100} \cdot \frac{1}{speedn} \tag{47}$$

where with $cosn$ and $effic/100$ the base is changed to mechanical power ($pgn = sgn \cdot cosn \cdot effic/100$) and with $speedn$ to asynchronous speed.

6.3.2 Mechanical Torque

Mechanical loads can be defined in *PowerFactory* by connecting a so-called mdm model (motor-driven machine) to the input xmdm of the asynchronous machine. Such an external mdm model can either be defined by a DSL-model or by one of the already available models (MDM_1, MDM_3 or MDM_5). If no separate mdm model is defined, the asynchronous machine uses the speed-torque characteristic of the built-in mdm model.

When a generator is defined, the turbine power pt is being initialised using the initial value of xmt (which is initialised as $xmt = -xme$). If no external pt is defined, then the mechanical power remains constant during the simulation (the mechanical power remains constant and the torque changes). During the simulation, the mechanical torque of the generator is being updated from pt only if $speed > 0.001[p.u.]$. The turbine power pt is based on the active power pgn and synchronous speed.

The calculation of the mechanical torque xmt depends on if the machine is defined as a motor or as a generator and from the connected external signals:

$$xmt = \begin{cases} \dfrac{pt}{speed} \cdot \dfrac{cosn \cdot effic}{100} & [p.u.] \text{ for gen. or } pt \text{ connected and } i\_torqueBase = 0 \\ \dfrac{pt}{speed} \cdot speedn & [p.u.] \text{ for gen. or } pt \text{ connected and } i\_torqueBase = 1 \\ xmdm & [p.u.] \text{ for motors with external mdm connected} \\ mdmlp \cdot speed^{mdmex} & [p.u.] \text{ for motors with internal (build in) mdm} \end{cases} \tag{48}$$

where $mdmlp$ and $mdmex$ are the proportional factor and the exponent of the built-in motor-driven machine characteristic.

6.3.3 Moment of Inertia

The acceleration time constant tag, which is also referred as the mechanical starting time is equal to $tag = 2 \cdot H$ in $[s]$ where H is the inertia constant. The following equation is used for calculating tag depending on the base torque selected:

$$tag = \begin{cases} \dfrac{J_{tot} \cdot \omega_{0m}^2}{sgn \cdot 1000} & [s] \text{ Apparent power and synchronous speed as base} \\ \dfrac{J_{tot} \cdot \omega_{0m}^2}{pgn \cdot 1000} \cdot (1 - slipr) & [s] \text{ Mechanical power and asynchronous speed as base} \end{cases} \tag{49}$$

where:

- J_{tot} is the total moment of inertia consisting of the moment of inertia J defined in the type and the moment of inertia J_{me} of the mechanical load multiplied with the square of the gearbox ratio $gratio$ defined in the element:

$$J_{tot} = J + J_{me} \cdot gratio^2 \qquad \left[kg \cdot m^2\right] \tag{50}$$

- ω_{0m} is the rated mechanical angular frequency calculated as:

$$\omega_{0m} = 2 \cdot \pi \cdot \frac{frequ}{nppol} \qquad \left[mech.\frac{rad}{s}\right] \tag{51}$$

- $slipr$ is the rated slip of the machine:

$$slipr = 1 - \frac{nppol \cdot anend}{60 \cdot frequ} \qquad [p.u.] \tag{52}$$

For the purpose of torsional analysis, an appropriate model can be built using DSL.

6.4 Main Flux Saturation

Figure 6.2 shows a main flux saturation curve (full line). For the asynchronous machine this is the no-load saturation curve measured at synchronous speed. The linear line represents the air-gap line. The degree of saturation is the deviation of the no-load characteristic curve from the air-gap line.

The saturation curve of the main flux for *TypAsm1* can be defined by a:

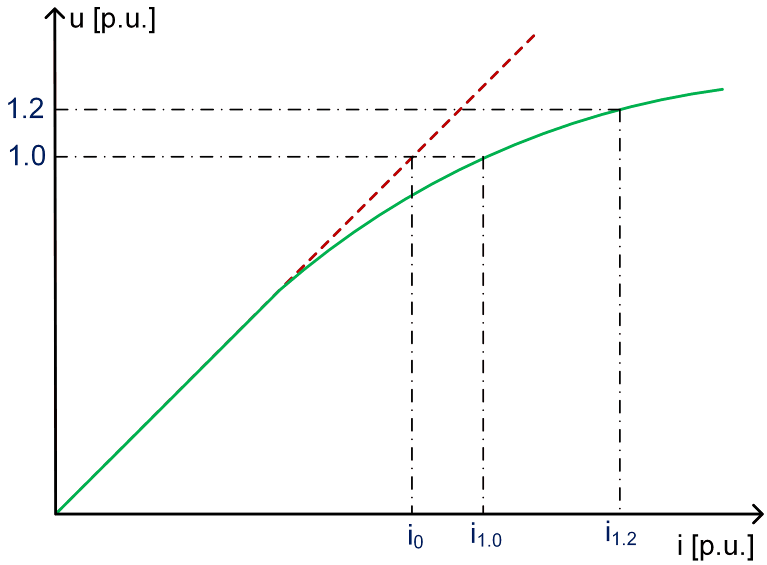

Figure 6.2: No-load saturation

- *Quadratic* function using parameters $SG10$ and $SG12$;
- *Exponential* function using parameters $SG10$ and $SG12$;
- smoothed curve with point-pairs of $Terminal\,Voltage$ and $No\,Load\,Current$ using Tabular input.

In all cases, a saturation factor k_{sat} is obtained with which the saturated magnetizing reactance can be calculated:

$$x_{msat} = x_m \cdot k_{sat} \qquad [p.u.] \tag{53}$$

In order to take into account only the current flowing through the magnetisation reactance when calculating the saturation factor, k_{sat} is being multiplied by a coefficient which is smaller or equal to one (calculated using a current divider for the magnetisation branch $i_{noload} = i_m + i_{fe}$).

There is no distinction made between the unsaturated magnetisation reactance x_m, in d- and q-axis (no saliency is considered for the rotor). Consequently, the no-load saturation function is considered to be representative for the total main flux.

For the RMS simulation, the flux magnitude is calculated using the electrical frequency f_e of the connected terminal as:

$$\underline{u}_m = \underline{u}_s - (r_{str} + \imath \cdot x_{str\_tot} \cdot f_e) \cdot \underline{i}_s \tag{54}$$

$$\psi_M = \sqrt{\left| \frac{\underline{u}_m \cdot e^{-\imath \cdot \varphi}}{\imath \cdot f_e} \right|} \tag{55}$$

In the EMT model, the flux magnitude is calculated from the magnetisation flux :

$$\underline{\psi}_m = \underline{\psi}_{S\_\alpha\beta} - x_{str\_tot} \cdot \underline{i}_{s\_\alpha\beta} \tag{56}$$

$$\psi_M = \sqrt{\left| \underline{\psi}_m \cdot e^{-\imath \cdot \varphi} \right|} \tag{57}$$

6.4.1 Quadratic and Exponential functions

The functions can be defined by specifying the currents $i_{1.0p.u.}$ and $i_{1.2p.u.}$ that are needed to obtain values of $1\ p.u$ and $1.2\ p.u.$ respectively, of the rated voltage under no-load conditions. With these values the parameters $SG10$ and $SG12$ are calculated as follows:

$$SG10 = \frac{i_{1.0}}{i_0} - 1 \tag{58}$$

$$SG12 = \frac{i_{1.2}}{1.2 \cdot i_0} - 1 \tag{59}$$

- **Quadratic**:
  Based on the two parameters SG10 and SG12, a quadratic approximation is applied and the $csat$ coefficient is calculated as:

$$csat = \begin{cases} \dfrac{B_g(\psi_M - A_g)^2}{\psi_M} & \text{if } \psi_M > A_g \\ 0 & \text{else} \end{cases} \tag{60}$$

  where:

$$A_g = \frac{1.2 - \sqrt{1.2 \cdot \dfrac{SG12}{SG10}}}{1 - \sqrt{1.2 \cdot \dfrac{SG12}{SG10}}} \tag{61}$$

$$B_g = \frac{SG10}{(1 - A_g)^2} \tag{62}$$

- **Exponential**:
  Based on the same parameters SG10/SG12, an exponential approximation is applied and the $csat$ coefficient is calculated as:

$$c_{sat} = SG10 \cdot \psi_M^{exp} \tag{63}$$

  where:

$$exp = \frac{ln(1.2 \cdot SG10/SG12)}{ln(1.2)} \tag{64}$$

The saturation factor k_{sat} is calculated using the $csat$ coefficient as:

$$k_{sat} = \frac{1}{1 + c_{sat}} \tag{65}$$

6.4.2 Tabular Input

The data from a no-load test measurement on the machine can be entered in a table using the measured data for the *Terminal Voltage* and *No Load Current*.

As in the case of the curves for the slip dependencies, a rounded curve, using the curve smoothing factor $satSmoothFac$ in $[\%]$, is created from the entered data. The curve is piecewise linear where the corner points of the given intervals are rounded using a trigonometric function interpolation. The range around the corners which are rounded is defined by the percentage entered in the curve smoothing factor.

For a certain amplitude of the magnetizing flux (approximated by using the magnetizing voltage), a value for the current $i_{curve} = f(\psi_M)$ is being read from the curve. The saturated value of the magnetizing reactance is then calculated as:

$$x_{msat} = \frac{\psi_M}{i_{curve}} \qquad [p.u.] \tag{66}$$

The saturation factor can be calculated using Equation 53.

6.5 Signals

The signals used in the RMS model are presented in Table 6.1. The signals used in the EMT model are presented in Table 6.2.

Table 6.1: Signals (RMS Simulation)

Name	Symbol	Unit	Type	Description
$xrtr\_tot$	x_{rtr_tot}	$p.u.$	STATE	Total Rotor reactance (including dependencies)
$psiR\_r$	ψ_{R_r}	$p.u.$	STATE	Rotor Flux, Real Part
$psiR\_i$	ψ_{R_i}	$p.u.$	STATE	Rotor Flux, Imaginary Part
$speed$		$p.u.$	STATE	Mechanical Speed
$phiref$	φ_{ref}	rad	STATE	Reference Angle
pt		$p.u.$	IN	Turbine Power
$xmdm$		$p.u.$	IN	MDM Torque
$fref$		$p.u.$	IN	Reference Frequency
$rradd$	r_{radd}	$p.u.$	IN	Additional Rotor Resistance
$bcomp$	b_{comp}	$p.u.$	IN	Compensation shunt susceptance
$xspeed$		$p.u.$	OUT	Mechanical Speed
xme		$p.u.$	OUT	Electrical Torque
pgt		$p.u.$	OUT	Electrical Power (rated to electrical active power)
$irot$		$p.u.$	OUT	Rotor Current (Magnitude)

6.6 Calculation parameters

The calculation parameters used in the RMS model are presented in Table 6.3. The calculation parameters used in the EMT model are presented in Table 6.4.

Table 6.2: Signals (EMT Simulation)

Name	Symbol	Unit	Type	Description
$xrtr\_tot$	x_{rtr_tot}	$p.u.$	STATE	Total Rotor reactance (including dependencies)
$psiS\_a$	ψ_{S_α}	$p.u.$	STATE	Stator Flux, alpha-component
$psiS\_b$	ψ_{S_β}	$p.u.$	STATE	Stator Flux, beta-component
$psiR\_d$	ψ_{R_d}	$p.u.$	STATE	Rotor Flux, d-Axis
$psiR\_q$	ψ_{R_q}	$p.u.$	STATE	Rotor Flux, q-Axis
ir_d	i_{r_d}	$p.u.$	STATE	Rotor Current, d-Axis
ir_q	i_{r_q}	$p.u.$	STATE	Rotor Current, q-Axis
$speed$		$p.u.$	STATE	Mechanical Speed
pt		$p.u.$	IN	Turbine Power
$xmdm$		$p.u.$	IN	MDM Torque
$rradd$	r_{radd}	$p.u.$	IN	Additional Rotor Resistance
phi	φ	rad	OUT	Reference Angle
$xspeed$		$p.u.$	OUT	Mechanical Speed
xme		$p.u.$	OUT	Electrical Torque
pgt		$p.u.$	OUT	Electrical Power (rated to electrical active power)
$irot$		$p.u.$	OUT	Rotor Current (Magnitude)

Table 6.3: Calculation parameters (RMS Simulation)

Name	Symbol	Unit	Description
$speedn$		$p.u.$	Nominal Asynchronous Speed
$rrtr$	r_{rtr}	$p.u.$	Rotor Resistance (including slip dependency if enabled)
$xradd$		$p.u.$	Additional Rotor Reactance
$xstadd$	x_{stadd}	$p.u.$	Additional Stator Reactance
$xstr\_tot$	x_{str_tot}	$p.u.$	Total Stator reactance (including dependencies)
xs_sum	x_{s_sum}	$p.u.$	Sum of Stator Circuit Reactances (including x_{msat})
xr_sum	x_{r_sum}	$p.u.$	Sum of Rotor Circuit Reactances (including x_{msat})
$frnom$		Hz	Nominal Frequency
fe	f_e	$p.u.$	Electrical Frequency
$slip$		$\%$	Slip
us_loc	$\underline{u}_{s\_loc}$	$p.u.$	Stator Voltage, Local reference (Complex value)
im_loc		$p.u.$	No-Load Current (Reactive), Local reference (Complex value)
ir_loc	$\underline{i}_{r\_loc}$	$p.u.$	Rotor Current, Local reference (Complex value)
ife_loc		$p.u.$	No-Load Current (Resistive), Local reference (Complex value)
$psiS\_loc$	$\underline{\psi}_{S\_loc}$	$p.u.$	Stator Flux, Local reference (Complex value)
$psiR\_loc$	$\underline{\psi}_{R\_loc}$	$p.u.$	Rotor Flux, Local reference (Complex value)
$islim$	i_{slim}	$p.u.$	Stator Current for Locked-Rotor and Nominal Voltage
$irlim$	i_{rlim}	$p.u.$	Rotor Current for Locked-Rotor and Nominal Voltage
xmt		$p.u.$	Mechanical Torque
$addmt$		$p.u.$	Additional Torque
$xmem$		$p.u.$	Electrical Torque (Motor)
$mdmlp$		$p.u.$	Proportional Factor of the build-in MDM
$mdmex$			Exponent of the build-in MDM
tag		s	Acceleration Time Constant
$psiM$	ψ_M	$p.u.$	Magnetizing Flux (Magnitude)
$ksat$	k_{sat}		Saturation Factor
$xmsat$	x_{msat}	$p.u.$	Saturated Magnetising Reactance

Table 6.4: Calculation parameters (EMT Simulation)

Name	**Symbol**	**Unit**	**Description**
$speedn$		$p.u.$	Nominal Asynchronous Speed
$rrtr$	r_{rtr}	$p.u.$	Rotor Resistance (including slip dependency if enabled)
$xradd$		$p.u.$	Additional Rotor Reactance
$xstadd$	x_{stadd}	$p.u.$	Additional Stator Reactance
$ccomp$		$p.u.$	Capacitance (Shunt for Compensation)
$xstr\_tot$	x_{str_tot}	$p.u.$	Total Stator reactance (including dependencies)
xs_sum	x_{s_sum}	$p.u.$	Sum of Stator Circuit Reactances (including x_{msat})
xr_sum	x_{r_sum}	$p.u.$	Sum of Rotor Circuit Reactances (including x_{msat})
$islim$	i_{slim}	$p.u.$	Stator Current for Locked-Rotor and Nominal Voltage
$irlim$	i_{rlim}	$p.u.$	Rotor Current for Locked-Rotor and Nominal Voltage
$frnom$		Hz	Nominal Frequency
$slip$		$\%$	Slip
us_alpha	u_{s_α}	$p.u.$	Stator Voltage, alpha-component
us_beta	u_{s_β}	$p.u.$	Stator Voltage, beta-component
us_gamma	u_{s_γ}	$p.u.$	Stator Voltage, gamma-component
is_alpha	i_{s_α}	$p.u.$	Stator Current, alpha-component
is_beta	i_{s_β}	$p.u.$	Stator Current, beta-component
is_gamma	i_{s_γ}	$p.u.$	Stator Current, gamma-component
us_dq		$p.u.$	Stator Voltage, dq-system (Complex value)
is_dq		$p.u.$	Stator Current, dq-system (Complex value)
im_dq		$p.u.$	No-Load Current (Reactive), dq-system (Complex value)
ife_dq		$p.u.$	No-Load Current (Resistive), dq-system (Complex value)
$psiS\_dq$		$p.u.$	Stator Flux, dq-system (Complex value)
xmt		$p.u.$	Mechanical Torque
$addmt$		$p.u.$	Additional Torque
$xmem$		$p.u.$	Electrical Torque (Motor)
$mdmlp$		$p.u.$	Proportional Factor of the build-in MDM
$mdmex$			Exponent of the build-in MDM
tag		s	Acceleration Time Constant
$psiM$	ψ_M	$p.u.$	Magnetizing Flux (Magnitude)
$ksat$	k_{sat}		Saturation Factor
$xmsat$	x_{msat}	$p.u.$	Saturated Magnetising Reactance

7 Motor starting

The *Motor Starting* command can be carried out by using a *Dynamic* or a *Static* simulation type. The dynamic motor starting supports balanced and unbalanced RMS simulations (for EMT simulation, the motor starting has to be configured manually).

In this section the different types of dynamic motor starting are described. Additional information is provided in reference [4].

7.1 Dynamic Motor Starting

The following starting methods are supported for the dynamic motor starting:

- Directly Online
- Star-Delta
- Variable Rotor Resistance
- Reactor
- Auto Transformer

The motor starting method can be selected in the *Motor Starting* tab of the *ElmAsm* element (*RMS-Simulation* page). If the option *Use Motor Starting* is not enabled, but anyway the *Motor Starting* command is executed, then the *Directly Online* method is used.

7.1.1 Directly Online

With the *Directly Online* method, the motor is turned on and connected directly to the network by the *Motor Starting* command.

7.1.2 Star-Delta Method

In the star-delta method, the motor is first connected in star configuration in order to reduce the voltage across its windings. While connected in star configuration, the input voltages and currents that are being fed to the model are divided with $\sqrt{3}$.

After the time specified in *Switch to D after* (parameter Tyd) or if the speed gets higher than the speed specified in *Switch to D at Speed* $>=$ (parameter $speedyd$), the configuration is changed to Delta (input voltages and currents are not modified anymore).

7.1.3 Variable Rotor Resistance

With this starting method, a user-specified table determines the additional rotor resistance at different times or for different speed values in the motor starting simulation. The changes of the additional rotor resistance can be monitored in the results of the simulation using the signal r_{radd}.

7.1.4 Reactor

With this method, the motor is connected initially to the network via a reactance x_{rea} and the by-pass switch is open (Figure 7.1).

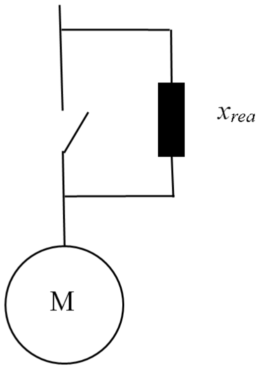

Figure 7.1: Additional Stator Reactance

This is implemented in such a way that the value of the additional stator reactance parameter x_{stadd} is calculated from $xrea$ and is considered by the equations of the motor. The additional stator reactance is calculated as:

$$x_{stadd} = \frac{x_{rea}}{100} \cdot \frac{sgn}{ratedStr} \qquad [p.u.] \tag{67}$$

where sgn is the type parameter *Rated Apparent Power* and $ratedStr$ is the *Rated Apparent Power* from the reactor. The parameter x_{stadd} can be monitored in the results of the simulation.

Depending on the option *Triggered by...* (parameter $iTrigg$), the by-pass switch is closed, short-circuiting the reactance x_{rea} and setting $x_{stadd} = 0$. This can be triggered using the time specified in *Bypass after* or after the motor speed has reached the value specified in *Bypass at speed* $>=$.

7.1.5 Auto Transformer

The starting scheme of a motor using an auto transformer is shown in Figure 7.2. Initially, the star-contactor is closed and the by-pass switch is open.

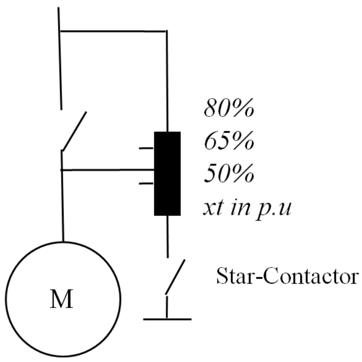

Figure 7.2: Auto Transformer Starting Method

The input voltages and currents of the asynchronous machine are modified to take into account the *Tap* ($autotap$) setting of the auto transformer by multiplying them with $autotap/100$. The additional stator reactance x_{stadd} is calculated from x_{rea} and is taken into the equations of the motor. The additional stator reactance is calculated as:

$$x_{stadd} = \frac{x_{rea}}{100} \cdot \frac{sgn}{ratedStr} \cdot \left(\frac{Tap}{100}\right)^2 \qquad [p.u.] \tag{68}$$

After the specified time in *Release Star Contactor after* or when the speed is greater than the value entered in *Release Star Contactor at speed* $>=$, the star contactor is opened. Since the by-pass switch is still open, the auto transformer reactance becomes (same as in Equation 67):

$$x_{stadd} = \frac{x_{rea}}{100} \cdot \frac{sgn}{ratedStr} \qquad [p.u.] \tag{69}$$

After the specified time in *Bypass after* or when the speed is greater than the value in *Bypass at speed* $>=$, the by-pass switch is closed, short-circuiting the additional reactance and therefore setting $x_{stadd} = 0$.

8 Additional functionality of the RMS and EMT simulations

The functionality of the asynchronous machine models can be increased for the RMS and EMT simulations by using some predefined parameters/signals that the user can change during the simulation. Initially these parameters are set to 0 so that they do not have any influence on the simulation and can be changed by DSL parameter events.

Here is a list and description of the additional parameters/signals:

- The parameter $addmt$ (in $[p.u.]$) is an additional mechanical torque which is added to the mechanical torque xmt.
- The parameter x_{stadd} (in $[p.u.]$) is additional stator reactance added to the total stator reactance x_{str_tot}. This parameter is being utilised by the *Motor Starting* Command.
- The parameter r_{radd} (in $[p.u.]$) is additional rotor resistance added to the rotor resistance r_{rtr}. This parameter is being utilised by the *Motor Starting* Command. Also it is being used in the *Load Flow* calculation when *with Variable Resistance* machine type is defined (*Basic Data* page of the element).
- The parameter x_{radd} (in $[p.u.]$) is additional rotor reactance added to the total rotor reactance x_{rtr_tot}.

All these parameters can be plotted and monitored during the RMS/EMT simulation.

A References

[1] P. Krause, O. Wasynczuk, S. Sudhoff, and S. Pekarek, *Analysis of Electric Machinery and Drive Systems*. Wiley, 2013.

[2] E. Levi, “Impact of iron loss on behavior of vector controlled induction machines,” *IEEE Transactions on Industry Applications*, vol. 31, Nov/Dec 1995.

[3] P. Kundur, *Power System Stability and Control*. McGraw-Hill, Inc, 1994.

[4] DIgSILENT GmbH, *Motor Startup Quick User Guide*, 2012.

List of Figures

List of Tables