POWERFACTORY

PowerFactory 2021

Technical Reference

Asynchronous Machine

ElmAsm, TypAsmo

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

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Contents

1 General Description

All resistances and reactances of the model need to be entered for $slip = 0$ in $p.u.$ values. 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.

1.1 Equivalent Circuit Models

The model is represented as the classical asynchronous machine model with a frequency (or slip) dependent rotor impedance (see the equivalent circuit in Figure 1.1).

Stator voltages and currents in these equivalent circuit diagrams are represented as instantaneous phasors in a steady reference frame. Rotor voltages and currents are represented in a reference frame that rotates with mechanical frequency. Hence, all quantities in these equivalent circuits are represented in their “natural” reference frame. The rotor impedance is referred to the stator side, and thus the “rotating transformer” in Figure 1.1 does not show any winding ratio.

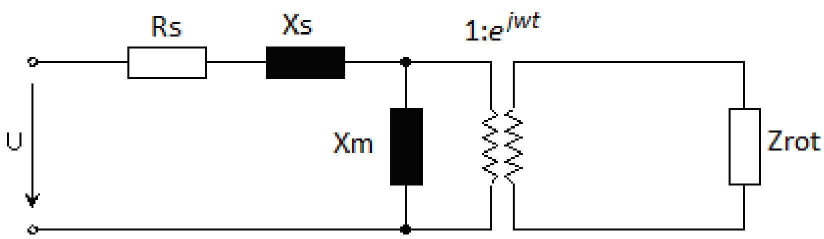

Figure 1.1: General asynchronous machine equivalent circuit

The stator winding resistance R_s, the stator leakage reactance X_s, the magnetizing reactance X_m and the rotor impedance Z_{rot} characterise the model.

As mentioned above, Z_{rot} can be frequency dependent, which allows the modelling of asynchronous machines over a wide speed (or slip) range. *PowerFactory* offers several ways to model a frequency dependent rotor impedance Z_{rot}. The rotor impedance models vary in detail and complexity and should be carefully selected depending on the types of studies to be performed and the availability of input data.

The rotor impedance models are described in the following sections.

1.1.1 Single Cage Model

The single cage model is the simplest of the rotor impedance models. The model is characterised by a single R-L branch with a slip dependent rotor resistance (see Figure 1.2. The advantage of this model is its simplicity, particularly when manufacturer data is incomplete or unavailable.

This model is adequate for describing wound rotor motors, however it is unsuitable for motor starting studies with squirrel cage motors. This is because the single cage model cannot describe the torque-speed characteristics of a squirrel cage motor over the full range of slip values (as a result of the current displacement effect). When applying the single cage model, either the starting characteristics or the full-load characteristics are modelled accurately, but not both [1].

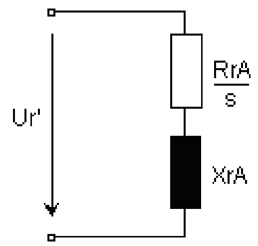

Figure 1.2: Single cage rotor model

1.1.2 Single Cage Model with Current Displacement (Squirrel Cage)

Squirrel cage rotors exhibit current displacement on starting and at low speeds (i.e. at high slip) due to the skin effect. The current displacement effect can be modelled by adding an additional R-L branch in parallel to the single cage rotor (see Figure 1.3). The additional R-L branch is modelled to represent the squirrel cage rotor on starting, where the rotor leakage reactance predominates. As the speed increases, the influence of the additional R-L branch decreases.

An additional series R-L element ($RrA0/s$ and $XrA0$ in Figure 1.3) represents a user-defined rotor leakage impedance, which provides additional modelling flexibility. By default, the rotor leakage impedance is set to zero.

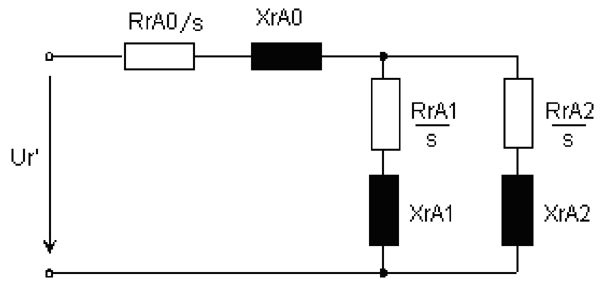

Figure 1.3: Squirrel cage (current displacement effect) rotor model

1.1.3 Double Cage Model

The double cage rotor is modelled in a similar way to the squirrel cage rotor with two parallel R-L branches representing the outer (A) and inner (B) cages (see Figure 1.4). There key difference is that in the double cage model, a rotor leakage reactance (Xrm) is included in lieu of $RrA0/s$ and $XrA0$.

1.1.4 Double Cage Model with Current Displacement

A deep bar double cage rotor, where the outer cage exhibits current displacement on starting, can be modelled by applying a double cage model with current displacement. Altogether, the frequency dependence of the rotor impedance can be approximated by up to three parallel R-L branches (see Figure 1.5).

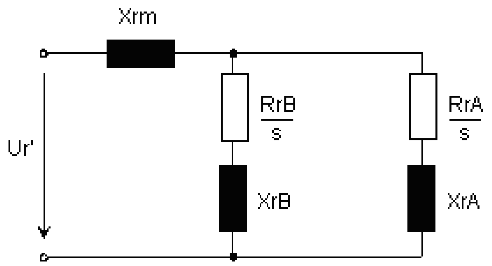

Figure 1.4: Double cage rotor model

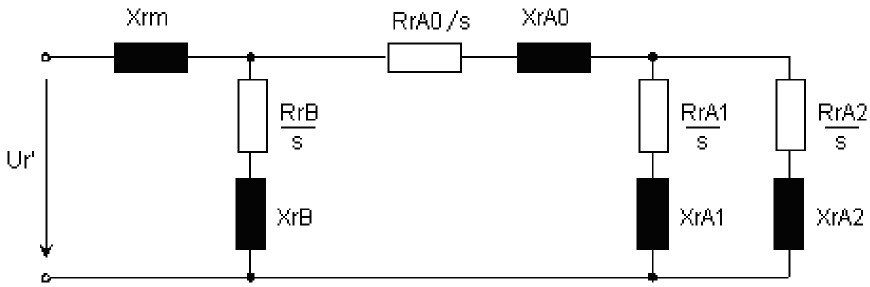

Figure 1.5: Double cage rotor model (with current displacement)

1.2 Motor Data Input

Motor data can be entered into the asynchronous machine type *TypAsmo* either by directly specifying the resistances and reactances of the equivalent circuit diagrams (*Electrical Parameter* option) or by specifying characteristic points on the torque-slip and current-slip curves of the machine (*Slip-Torque/Current Characteristic* option).

On the advanced tab of the Load Flow page, there are curves showing the torque-speed and current-speed characteristics of the machine (see Figure 1.6). These characteristics are always calculated using the steady state equations of the equivalent circuit. Hence, they truly represent the machine characteristics. The torque-speed characteristic can be exported for a user defined supply voltage level by using the *Export Torque-Speed Characteristic to Clipboard* button. The exported data is available in the Windows Clipboard for further external processing.

1.2.1 Electrical Parameters Option

If motor electrical parameter data is available, then this data can be entered directly into the asynchronous motor type (in the Load Flow tab) by selecting the *Electrical Parameter* input mode.

Sometimes motor manufacturers supply measured test values of the equivalent rotor impedance according to Figure 1.1 at different motor speeds (or slip-values), typically at no-load (i.e. close to synchronous speed) and at locked rotor / stand still. For such cases, *PowerFactory* offers a pocket calculator to convert these test measurements into equivalent circuit parameters for two parallel R-L branches (i.e. for rotors with current displacement). The pocket calculator can be accessed when the input mode is *Electrical Parameters* and the *Consider Current Displacement (Squirrel Cage Rotor)* options are selected (see Figure 1.7).

The general formula that relates the equivalent rotor impedance to equivalent circuit parameters

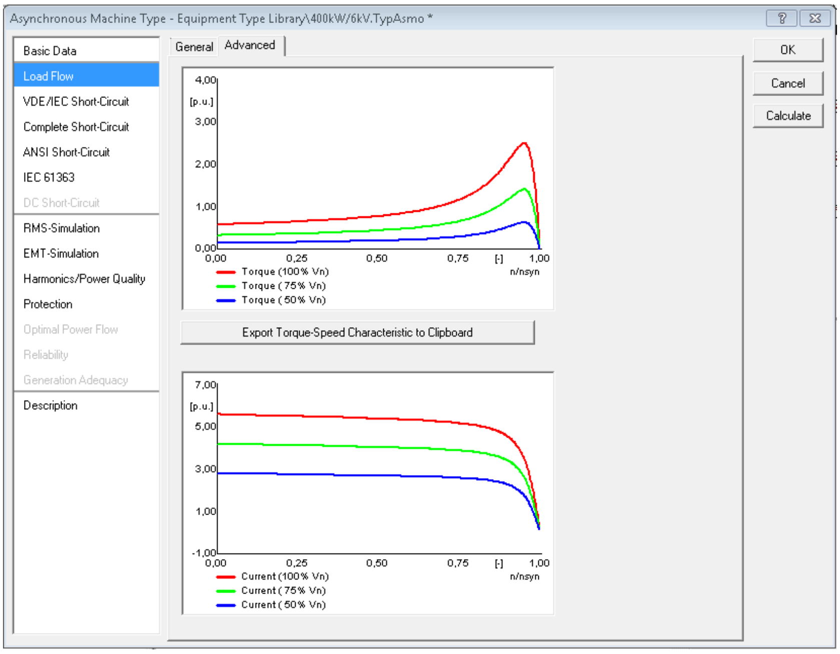

Figure 1.6: Speed-Torque and Speed-Current characteristic for different voltages

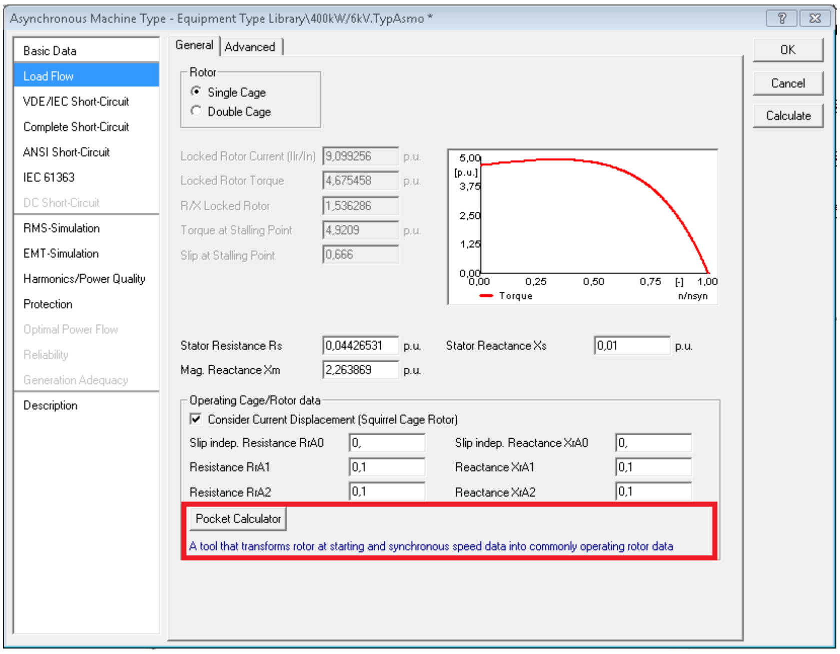

Figure 1.7: Pocket calculator for asynchronous machine

of a rotor circuit approximated by two ladder circuits (as in Figure 1.3) is:

$$R_r(s) = \frac{R_{A1} \cdot R_{A2}\,(R_{A1} + R_{A2}) + s^2 \cdot \left(R_{A1} \cdot X_{A2}^2 + R_{A2} \cdot X_{A1}^2\right)}{\left(R_{A1} + R_{A2}\right)^2 + s^2 \cdot \left(X_{A1} + X_{A2}\right)^2} \tag{1}$$

$$X_r(s) = \frac{R_{A1}^2 \cdot X_{A2} + R_{A2}^2 \cdot X_{A1} + s^2 \cdot (X_{A1} + X_{A2}) \cdot X_{A1} \cdot X_{A2}}{\left(R_{A1} + R_{A2}\right)^2 + s^2 \cdot \left(X_{A1} + X_{A2}\right)^2} \tag{2}$$

The slip-independent rotor leakage impedance (RrA0 and XrA0) is assumed to be zero in this case.

The values at stand-still (s=1) and synchronous speed (s=0) are:

$$R_r(0) = \frac{R_{A1} \cdot R_{A2}}{(R_{A1} + R_{A2})} \tag{3}$$

$$X_r(0) = \frac{R_{A1}^2 \cdot X_{A2} + R_{A2}^2 \cdot X_{A1}}{\left(R_{A1} + R_{A2}\right)^2} \tag{4}$$

$$R_r(1) = \frac{R_{A1} \cdot R_{A2} \cdot (R_{A1} + R_{A2}) + \left(R_{A1} \cdot X_{A2}^2 + R_{A2} \cdot X_{A1}^2\right)}{\left(R_{A1} + R_{A2}\right)^2 + \left(X_{A1} + X_{A2}\right)^2} \tag{5}$$

$$X_r(1) = \frac{R_{A1}^2 \cdot X_{A2} + R_{A2}^2 \cdot X_{A1} + (X_{A1} + X_{A2}) \cdot X_{A1} \cdot X_{A2}}{\left(R_{A1} + R_{A2}\right)^2 + \left(X_{A1} + X_{A2}\right)^2} \tag{6}$$

This set of non-linear equations can be solved by an iterative procedure. In the pocket calculator, these equations are solved using a Newton-Raphson algorithm.

The problem is highly simplified using the following substitution:

$$R_{A2} = \frac{R_{A1} \cdot R_r(0)}{(R_{A1} - R_r(0))} \tag{7}$$

$$X_{A2} = \frac{X_{A1} \cdot X_x}{(X_{A1} - X_x)} \tag{8}$$

The auxiliary variable X_x can directly be calculated from the given values for Z_{rot} and is defined by:

$$X_x = \frac{X_r(1)^2 - \left(R_r(1) - R_r(0)\right)^2}{X_r(0) - X_r(1)} \tag{9}$$

The Newton-Rahpson algorithm in the pocket calculator uses the following initial values:

$$R_{A1} = \frac{1}{5} \cdot R_{A2} \tag{10}$$

$$X_{A1} = \frac{5}{2} \cdot X_{A2} \tag{11}$$

1.2.2 Slip-Torque/Current Characteristic Option

If the input mode is set to *Slip-Torque/Current Characteristic*, the parameters of the equivalent circuit diagram are estimated (using an in-built parameter estimation algorithm) from the following set of motor performance parameters:

- Nominal operating point (Basic Data page parameters)
- Torque at stalling point (maximum or breakdown torque)
- Locked Rotor (Starting) torque (for double cage or single cage with current displacement)
- Locked Rotor (Starting) current (for double cage or single cage with current displacement)

The rated mechanical power, the rated power factor, the efficiency at rated operation and the rated speed of the machine specify the nominal operating point.

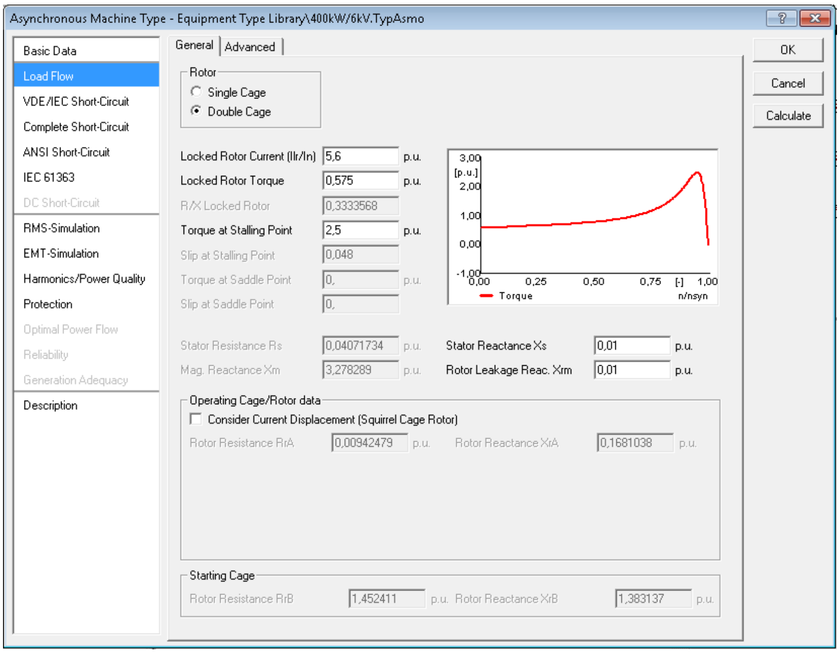

Figure 1.8: Load flow page of asynchronous machine type

Pressing the **Calculate** button starts the parameter estimation algorithm which converts the performance parameters to equivalent circuit electrical parameters. The algorithm aims to solve for the following parameters:

- Single cage model: R_s, X_m, R_{rA}, X_{rA}
- Squirrel cage model: R_s, X_m, R_{rA1}, X_{rA1}, R_{rA2}, X_{rA2}
- Double cage model: R_s, X_m, R_{rA}, X_{rA}, R_{rB}, X_{rB}
- Double cage model with current displacement: R_s, X_m, R_{rA1}, X_{rA1}, R_{rB}, X_{rB}

The following parameters are input parameters and therefore assumed to be known:

- Single cage model: X_s

- Squirrel cage model: X_s, R_{rA0}, X_{rA0}
- Double cage model: X_s, X_{rm}
- Double cage model with current displacement: X_s, R_{rA0}, X_{rA0}, R_{rA2}, X_{rA2}

The parameter estimation algorithm solves a non-linear least squares problem using the Newton-Raphson method. For single cage models, the problem formulation is as per the four equations below:

$$f_1(\mathbf{x}) = \cos\phi - \mathrm{Re}(S(s_f)) = 0 \tag{12}$$

$$f_2(\mathbf{x}) = \sin\phi - \mathrm{Im}(S(s_f)) = 0 \tag{13}$$

$$f_3(\mathbf{x}) = T_b - T(s_{max}) = 0 \tag{14}$$

$$f_4(x) = \eta fl - \eta(s_f) = 0 \tag{15}$$

For squirrel cage and double cage models, the following two equations are added to the problem formulation:

$$f_5(\mathbf{x}) = T_{lr} - T(s = 1) = 0 \tag{16}$$

$$f_6(\mathbf{x}) = I_{lr} - I(s = 1) = 0 \tag{17}$$

$$\tag{18}$$

where $\cos\phi s$ is the full load power factor (p.u.)
Ss is the motor complex power at slip s (p.u.)
s_f is the full load slip (p.u.)
ηfl is the motor full load efficiency (p.u.)
Ss is the motor complex power at slip s (p.u.)
T_b is the motor breakdown torque (p.u.)
T_{lr} is the motor locked rotor torque (p.u.)
I_{lr} is the motor locked rotor current (p.u.)

If the parameter estimation algorithm fails, one of two corresponding error messages will appear:

- Estimated parameter inconsistent. Check nominal operating point.

  This message means that at least one electrical parameter has been estimated having an inconsistent value. Default values have been used for the inconsistent parameters. First of all the data entered on the basic data page should be checked. The user should first try to find a solution using the single cage model. Only if motor start-up simulations are required, it is important to reproduce the speed-torque characteristic over the full range of slip values. For many applications, the single cage representation will be sufficient. Otherwise, we recommend to reduce the starting current, because measured starting currents are very often higher due to saturation of leakage reactance, which is not represented in the model.

- No convergence in iteration, parameter estimation used.

  This message means that the Newton-Raphson algorithm failed to converge and thus the input data could not be fully matched during the parameter estimation iterations. An estimate approximating the entered data is used instead. By analysing the speed-torque and speed-current characteristics, the user can verify how close the estimated parameters match the entered performance data (e.g. torque at stalling point, locked rotor current, locked rotor torque, etc).

2 Load Flow Analysis

For representing asynchronous machines in load flow analysis, the user has the choice between two representations (Bus type (*bustp*) parameter in *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 4.2).

Both calculation methods are based on the equivalent circuit diagram according to Figure 1.1 to Figure 1.5. The model equations are evaluated for steady state operating conditions during the load flow iterations.

The unbalanced Load Flow calculation requires in addition a negative and zero sequence model. The negative sequence model is based on the equivalent circuit diagrams already presented where the rotor resistances are divided by $(2 - slip)$ instead of only s. The normalised difference between the air-gap MMF and the rotor speed in the negative sequence system is $(2 - slip)$.

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 the asynchronous machine *ElmAsm* dialog.

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 r_{radd} is calculated so that the defined slip is being reached. The signal r_{radd} can be displayed in the results box of the machine.

2.1 Load Flow analysis when using Doubly Fed Induction Machine model

If the *Machine Type* is set to *Doubly Fed Induction Machine*, the Load Flow model is much simpler and the machine dispatches the entered data from the parameters $pgini$ and $qgini$.

2.1.1 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

2.1.1.1 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:

$$Q = Q_0 + K \cdot \Delta Q_{SCO} \tag{19}$$

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

2.1.1.2 Voltage Q-Droop control

Figure 2.1 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.

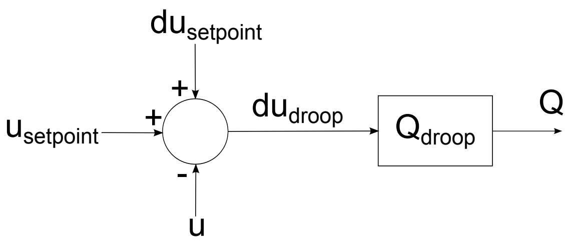

Figure 2.1: Voltage Q-Droop Control

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 2.2. 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.

$$u = u_{setpoint} - \Delta u_{droop} \tag{20}$$

$$\Delta u_{droop} = \frac{Q - Q_{setpoint}}{Q_{droop}} \tag{21}$$

$$Q_{droop} = \frac{S_r \cdot 100}{ddroop} \tag{22}$$

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 rate apparent power
- $ddroop$ is the voltage droop value specified in percentage

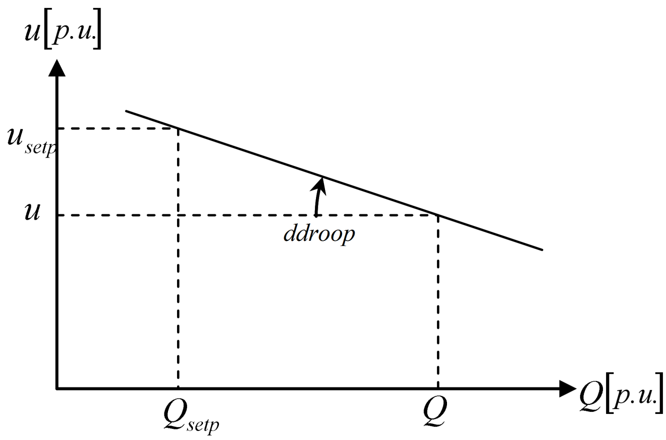

Figure 2.2: Voltage Q-Droop Control

2.1.1.3 Voltage Iq-Droop

The block diagram for this option is shown in Figure 2.3. 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.

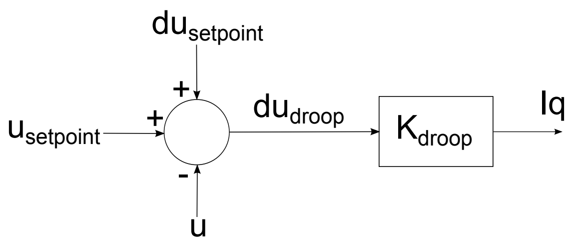

Figure 2.3: Voltage Iq-Droop Control

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

$$u = u_{setpoint} + du_{setpoint} - \Delta u_{droop} \tag{23}$$

$$\Delta u_{droop} = \frac{Iq - Iq_{setpoint}}{K_{droop} \cdot Ip_r} \tag{24}$$

$$K_{droop} = \frac{100}{ddroop} \tag{25}$$

with the reactive current setpoint:

$$Iq_{setpoint} = \frac{qgini \cdot ngnum}{\sqrt{3} \cdot U_{nom}} \tag{26}$$

and with the rated active current:

$$Ip_r = \frac{sgn \cdot ngnum \cdot cosn}{\sqrt{3} \cdot U_r} \tag{27}$$

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

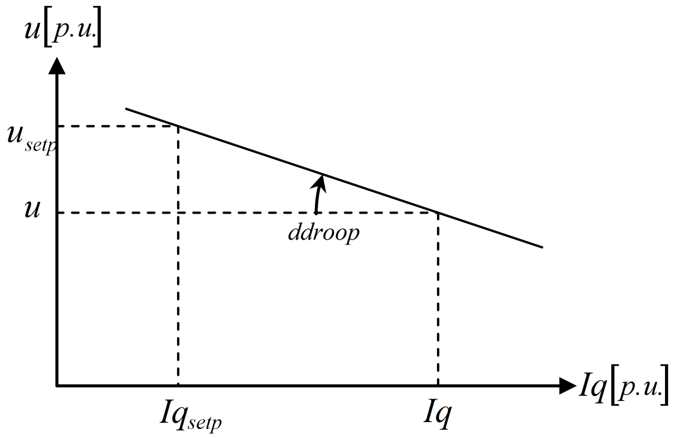

Figure 2.4: Voltage Iq-Droop Control

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

2.1.1.4 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.

2.1.1.5 Q(P)-Characteristic

The Q(P) characteristic is a reactive power control and follows a user-specified characteristic as shown in the picture 2.5.

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*).

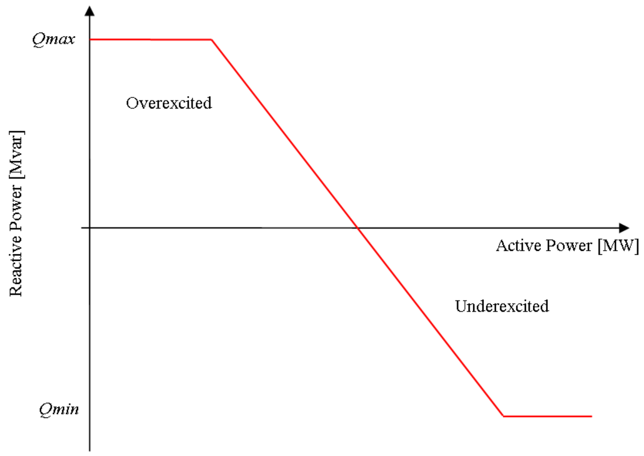

Figure 2.5: Q(P)-Characteristic

2.1.1.6 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 2.1.1.4). 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.

2.1.2 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:

$$P = f(windspeed) \tag{28}$$

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:

$$Pmax = Min(\ f(windspeed)\ or\ Pmax_{uc}) \tag{29}$$

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

3 Short-Circuit Calculation

3.1 VDE/IEC Short-Circuit

Asynchronous machines can be considered as one of the following in any VDE/IEC short-circuit calculation:

- No short-circuit contribution
- Static converter-fed drive
- Asynchronous machine

Additionally, machines configured as a *Doubly Fed Induction Generator (DFIG)* use a dedicated model for the short-circuit calculation according to IEC60909-2016 (see Section 3.1.4).

The common equivalent circuit is shown in Figure 3.1.

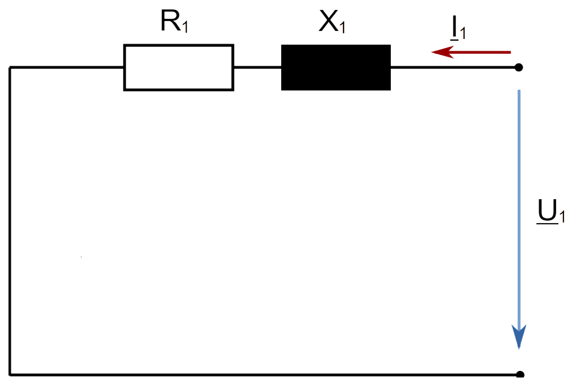

Figure 3.1: Equivalent positive sequence circuit for use in the VDE/IEC short-circuit calculation

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ is calculated as follows:

$$X_1 = \frac{|Z_1|}{\sqrt{1 + (R/X)^2}} \tag{30}$$

$$R_1 = R/X \cdot X_1 \tag{31}$$

where:

- $|Z_1|$ is the magnitude of the impedance in $[\Omega]$
- R/X is the R/X ratio

Details of the different configurations and the calculation of the impedance are given in the sections below. Asynchronous machines, as well as DFIGs, are only considered for the calculation of maximum short-circuit currents in the VDE/IEC short-circuit calculation and are always neglected when calculating minimum short-circuit currents.

3.1.1 No Short-Circuit Contribution

In this configuration, the asynchronous machine will not contribute to VDE/IEC short-circuit calculations.

3.1.2 Static Converter-Fed Drive

Asynchronous machines configured as a *Static Converter-Fed Drive* will only contribute to the subtransient and peak short-circuit currents.

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 3.1, is calculated as follows:

$$|Z_1| = \frac{1}{3} \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{32}$$

$$R/X = 0.1 \tag{33}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)

Steady-State and Breaking Current

As per IEC60909, static converter-fed drives do not contribute to breaking or steady-state currents.

Unbalanced Faults

As per IEC60909, static converter-fed drives are always neglected for unbalanced faults.

3.1.3 Asynchronous Machine

This is the default model for asynchronous machines. It used for motors and generators.

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 3.1, is calculated as follows:

$$|Z_1| = \frac{1}{I_{LR}/I_r} \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{34}$$

$$R/X = R/X \tag{35}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- I_{LR}/I_r is the locked rotor current in [p.u.] (*t:aiaznshc*)
- R/X is the R/X ratio (*t:rtoxshc*)

If the option *Consider Transient Parameter* (*t:i_trans*) is enabled, the locked rotor current and R/X ratio are calculated using load flow parameters, under the assumption that the slip $= 1.0$. The resulting values can be accessed via the parameters *t:aiazn* and *t:rtox*.

Steady-State and Breaking Current

As per IEC60909, asynchronous machines do not contribute to steady-state currents.

The breaking current contribution is calculated as follows:

$$I_b = \mu \cdot q \cdot I_k'' \tag{36}$$

Please refer to the corresponding IEC60909 standard for detailed information regarding the calculation of μ and q.

Unbalanced Faults

The equivalent circuits for the negative and zero sequence are shown in Figure 3.2.

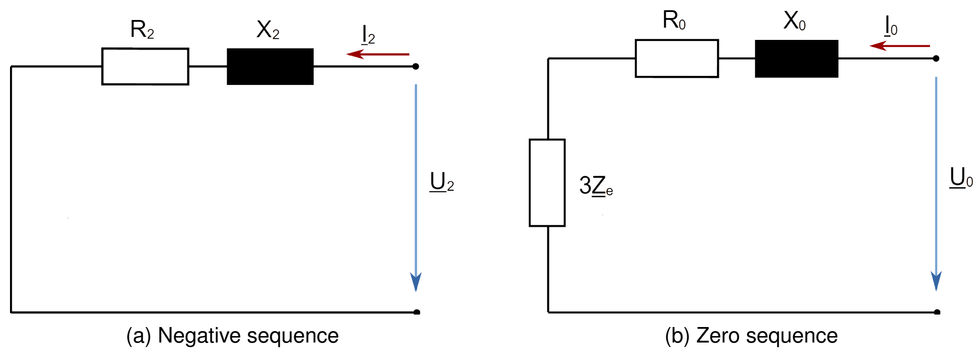

Figure 3.2: Equivalent negative and zero sequence circuits for use in the VDE/IEC short-circuit calculation

The impedance $\underline{Z}_2 = R_2 + j \cdot X_2$ is calculated as follows:

$$\underline{Z}_2 = \underline{Z}_1 \tag{37}$$

If the asynchronous machine is not grounded the zero sequence is considered to be open, otherwise the impedances $\underline{Z}_0 = R_0 + j \cdot X_0$ and $\underline{Z}_e$ are calculated as follows:

$$\underline{Z}_0 = (r_0 + j \cdot x_0) \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{38}$$

$$\underline{Z}_e = R_e + j \cdot X_e \tag{39}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- r_0 is the rated zero sequence resistance in [p.u.] (*t:rzero*)
- x_0 is the rated zero sequence reactance in [p.u.] (*t:xzero*)
- R_e is the grounding resistance in [Ω] (*e:Re*)
- X_e is the grounding reactance in [Ω] (*e:Xe*)

3.1.4 Doubly Fed Induction Generator

Asynchronous machines configured as *Generator* (*e:i_mot*) and *Doubly Fed Induction Machine* (*e:idfig*) will be considered as *Doubly Fed Induction Generator* when calculating a short-circuit according to IEC60909-2016. Older versions of the standard will use the *Asynchronous Machine* model.

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 3.1, is calculated as follows:

$$|Z_1| = \frac{\sqrt{2} \cdot \kappa_{WD} \cdot U_r}{\sqrt{3} \cdot i_{WD,max}} \tag{40}$$

$$R/X = R/X_{WD} \tag{41}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- κ_{WD} is the factor for the calculation of the peak current contribution (*e:kWD*)
- $i_{max,WD}$ is the maximum instantaneous current contribution in [kA] (*e:iWDmax*)
- R/X_{WD} is the R/X ratio of the doubly fed asynchronous generator (*e:rxWD*)

Note: The factor κ_{WD} may contain effects of the converter protection system and should not be confused with κ used in the calculation of the peak short-circuit current.

If the *Externally Modelled Unit Transformer* option is used, $i_{max,WD}$ is referred to the HV side of the transformer. The resulting impedance, $\underline{Z}_1$, is distributed as described in Section 3.1.5.

Breaking and Steady-State Current

For breaking and steady-state calculations, the *Doubly Fed Asynchronous Generator* uses the input value for the maximum steady-state contribution *e:ikWDmax* in [kA].

If the *Externally Modelled Unit Transformer* option is used, $I_{k,WD}$ is referred to the HV side of the transformer.

$$I_k = I_b = I_{k,WD} \tag{42}$$

Note: Asynchronous machines will always be neglected for the calculation of minimum short-circuit currents, hence the input value for the minimum steady-state contribution will not be used.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models shown in Figure 3.2 are used. However, dedicated sets of parameters for the negative sequence impedance and zero sequence impedance are used.

This changes the calculation of $\underline{Z}_2 = R_2 + j \cdot X_2$ and $\underline{Z}_0 = R_0 + j \cdot X_0$ as follows:

$$\underline{Z}_2 = (r_{2,iec} + j \cdot x_{2,iec}) \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{43}$$

$$\underline{Z}_0 = (r_{0,iec} + j \cdot x_{0,iec}) \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{44}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- $r_{2,iec}$ is the rated negative sequence resistance for DFIGs in [p.u.] (*e:r2iec*)
- $x_{2,iec}$ is the rated negative sequence reactance for DFIGs in [p.u.] (*e:x2iec*)
- $r_{0,iec}$ is the rated zero sequence resistance for DFIGs in [p.u.] (*e:r0iec*)
- $x_{0,iec}$ is the rated zero sequence reactance for DFIGs in [p.u.] (*e:x0iec*)

If the *Externally Modelled Unit Transformer* option is used, $\underline{Z}_2$ is referred to the HV side of the transformer as described in Section 3.1.5. The zero sequence is not distributed.

Note: Even with the *Externally Modelled Unit Transformer* option enabled, the per-unit system used for the negative sequence impedance remains that of the asynchronous machine.

3.1.5 Externally Modelled Unit Transformer

Input values obtained from manufacturers for *Doubly Fed Asynchronous Generators* are typically referred to the HV side of the generator unit transformer. In most cases, the asynchronous machine is assumed to model the whole unit; i.e. the rated voltage of the model is equal to the HV side of the unit transformer. However, if the network model requires the unit transformer to be modelled separately, this option can be used to facilitate this approach.

The following conditions must be met for a transformer to be considered a unit transformer:

- there must be exactly one transformer connected to the asynchronous machine;
- it must be a 2-winding transformer (*ElmTr2*);
- it must be a 3-phase transformer; and
- it must be explicitly marked as a unit transformer (*iblock* on the Short-Circuit VDE/IEC page).

With this option enabled and a unit transformer present, relevant equations are referred to the HV side of the transformer and assumed to be in the following form:

$$\underline{Z} = \underline{Z}_T + \left(\frac{U_{r,HV}}{U_{r,LV}}\right)^2 \cdot \underline{Z}_{AM} \tag{45}$$

where:

- $\underline{Z}$ is the impedance of the whole unit seen from the HV side of the unit transformer in [Ω]

- $\underline{Z}_T$ is the impedance of the unit transformer referred to the HV side in [Ω]
- $U_{r,HV}$ is the rated voltage on the HV side of the unit transformer in [kV] (*t:utrn_h*)
- $U_{r,LV}$ is the rated voltage on the LV side of the unit transformer in [kV] (*t:utrn_l*)
- $\underline{Z}_{AM}$ is the impedance of the asynchronous machine in [Ω]

Note: The impedance correction factor kT for unit transformers of *Doubly Fed Asynchronous Generators* is ignored; i.e. $kT = 1.0$.

3.2 Complete Short-Circuit

By default, asynchronous machines are considered as described in Section 3.2.1 in the complete short-circuit calculation. For machines configured as *Generator* (*e:i_mot*) and *Doubly Fed Induction Machine* (*e:idfig*), one of the following models can be configured:

- Equivalent synchronous machine
- Dynamic voltage support
- Doubly fed asynchronous generator

The common equivalent circuit is shown in Figure 3.3.

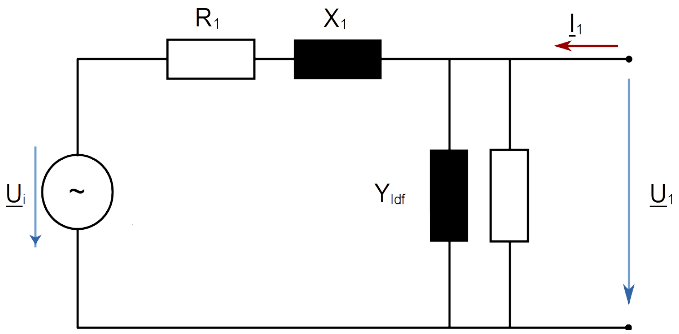

Figure 3.3: Equivalent positive sequence circuit for use in the complete short-circuit calculation

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ is calculated as follows:

$$X_1 = \frac{|Z_1|}{\sqrt{1 + (R/X)^2}} \tag{46}$$

$$R_1 = R/X \cdot X_1 \tag{47}$$

where:

- $|Z_1|$ is the magnitude of the impedance in $[\Omega]$
- R/X is the R/X ratio

The load flow admittance $\underline{Y}_{ldf} = G_{ldf} + j \cdot B_{ldf}$ and the internal voltage $\underline{U}_i$ depend on the initialisation of the complete short-circuit and the short-circuit model used. These are calculated as follows:

- With load flow initialisation:
  - Asynchronous Machine

$$\underline{Y}_{ldf} = j \cdot B_{comp,ldf} \tag{48}$$

$$\underline{U}_i = \underline{U}_{1,ldf} - \underline{Z}_1 \cdot (\underline{I}_{1,ldf} - \underline{Y}_{ldf} \cdot \underline{U}_{1,ldf}) \tag{49}$$

  - Doubly Fed Induction Generator

$$\underline{Y}_{ldf} = \frac{\underline{I}_{1,ldf}}{\underline{U}_{1,ldf}} \tag{50}$$

$$\underline{U}_i = \underline{U}_{1,ldf} \tag{51}$$

- Without load flow initialisation:

$$\underline{Y}_{ldf} = 0 \tag{52}$$

$$\underline{U}_i = c \cdot \frac{U_r}{\sqrt{3}} \tag{53}$$

where:

- $\underline{U}_{1,ldf}$ is the positive sequence pre-fault voltage in [kV]
- $\underline{I}_{1,ldf}$ is the positive sequence pre-fault current in [kA]
- $B_{comp,ldf}$ is the reactive power compensation from load flow in [S]
- c is the pre-fault voltage factor (Short-Circuit command input)
- U_r is the rated voltage in [kV] (*t:ugn*)

3.2.1 Asynchronous Machine

This is the default model for asynchronous machines. It used for motors and generators.

Subtransient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 3.3, is calculated as follows:

$$|Z_1| = \frac{1}{I_{LR}/I_r} \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{54}$$

$$R/X = R/X \tag{55}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- I_{LR}/I_r is the locked rotor current in [p.u.] (*t:aiaznshc*)
- R/X is the R/X ratio (*t:rtoxshc*)

If the option *Consider Transient Parameter* (*t:i_trans*) is enabled, the locked rotor current I_{LR}/I_r and R/X ratio are calculated using load flow parameters, under the assumption that the slip $=$ 1.0. The resulting values can be accessed via the parameters *t:aiazn* and *t:rtox*.

Transient Contribution

Asynchronous machines do not contribute to transient short-circuit currents. In complete short-circuit calculations without load flow initialisation, asynchronous machines are therefore neglected.

In complete short-circuit calculations with load flow initialisation, the parametrisation becomes completely load flow dependant. The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, the load flow admittance $\underline{Y}_{ldf} = G_{ldf} + j \cdot B_{ldf}$ and the internal voltage $\underline{U}_i$ are calculated as follows:

$$\underline{Y}_{ldf} = j \cdot B_{comp,ldf} \tag{56}$$

$$\underline{Z}_1 = \frac{\underline{U}_{1,ldf}}{\underline{I}_{1,ldf} - \underline{Y}_{ldf} \cdot \underline{U}_{1,ldf}} \tag{57}$$

$$\underline{U}_i = 0 \tag{58}$$

where:

- $\underline{U}_{1,ldf}$ is the positive sequence pre-fault voltage in [kV]
- $\underline{I}_{1,ldf}$ is the positive sequence pre-fault current in [kA]
- $B_{comp,ldf}$ is the reactive power compensation from the load flow in [S]

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 3.1.3 are used. For the calculation of transient contributions, the negative sequence impedance is kept constant; i.e. $\underline{Z}_2^{'} = \underline{Z}_2^{''} = \underline{Z}_1^{''}$.

3.2.2 Equivalent Synchronous Machine

Doubly fed induction generators configured using the option *Equivalent Synchronous Machine* allow input of an individual transient contribution per machine, while the subtransient contribution is derived from the machines characteristics. Both contributions, subtransient and transient, are considered as rotating contributions.

Subtransient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 3.3, is calculated as follows:

$$c = \frac{\sqrt{3} \cdot |\underline{U}_i|}{U_N} \tag{59}$$

$$|Z_1| = c \cdot \frac{1}{I_{LR}/I_r} \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{60}$$

$$R/X = R/X \tag{61}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- I_{LR}/I_r is the locked rotor current in [p.u.] (*t:aiaznshc*)
- R/X is the R/X ratio (*t:rtoxshc*)

If the option *Consider Transient Parameter* (*t:i_trans*) is enabled, the locked rotor current I_{LR}/I_r and R/X ratio are calculated using load flow parameters, under the assumption that the slip $=$ 1.0. The resulting values can be accessed via the parameters *t:aiazn* and *t:rtox*.

The voltage factor, c, is used in the calculation of $|Z_1|$ to ensure that the asynchronous machine will not contribute more than the specified subtransient short-circuit contribution, even with a fault at the terminals. This models the power electronic nature of the machine.

Transient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 3.3, is calculated as follows:

$$c = \frac{\sqrt{3} \cdot |\underline{U}_i|}{U_N} \tag{62}$$

$$|Z_k^{''}| = c \cdot \frac{1}{I_{LR}/I_r} \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{63}$$

$$|Z_k^{'}| = c \cdot \frac{U_r}{\sqrt{3} \cdot I_k^{'}} \tag{64}$$

$$R_1 = R/X \cdot \frac{|Z_k^{''}|}{\sqrt{1 + (R/X)^2}} \tag{65}$$

$$X_1 = \sqrt{|Z_k^{'}|^2 - {R_1}^2} \tag{66}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- I_{LR}/I_r is the locked rotor current in [p.u.] (*t:aiaznshc*)
- R/X is the R/X ratio (*t:rtoxshc*)
- $I_k^{'}$ is the transient short-circuit contribution in [kA] (*e:Iks*)

If the option *Consider Transient Parameter* (*t:i_trans*) is enabled, the locked rotor current I_{LR}/I_r and R/X ratio are calculated using load flow parameters, under the assumption that the slip $=$ 1.0. The resulting values can be accessed via the parameters *t:aiazn* and *t:rtox*.

The voltage factor, c, is used in the calculation of $|Z_1|$ to ensure that the asynchronous machine will not contribute more than the specified subtransient short-circuit contribution, even with a fault at the terminals. This models the power electronic nature of the machine.

The additional dependence on the subtransient short-circuit contribution is used to keep the resistive part of the impedance constant, so that the change in short-circuit contribution is modelled as a time-dependent reactance.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 3.1.3 are used. For the calculation of transient contributions, the negative sequence impedance is kept constant, i.e. $\underline{Z}_2^{'} = \underline{Z}_2^{''} = \underline{Z}_1^{''}$.

3.2.3 Dynamic Voltage Support

Doubly fed induction generators configured using the option *Dynamic Voltage Support* are similar to an *Equivalent Synchronous Machine*, but the transient contribution is modelled as a constant current injection. The subtransient contribution is considered as a rotating contribution.

Note: This model is deprecated and will be removed in future versions. A suitable alternative is the *Doubly Fed Asynchronous Generator*.

Subtransient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 3.3, is calculated as follows:

$$c = \frac{\sqrt{3} \cdot |\underline{U}_i|}{U_N} \tag{67}$$

$$|Z_1| = c \cdot \frac{1}{I_{LR}/I_r} \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{68}$$

$$R/X = R/X \tag{69}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- I_{LR}/I_r is the locked rotor current in [p.u.] (*t:aiaznshc*)
- R/X is the R/X ratio (*t:rtoxshc*)

If the option *Consider Transient Parameter* (*t:i_trans*) is enabled, the locked rotor current I_{LR}/I_r and R/X ratio are calculated using load flow parameters, under the assumption that the slip $=$ 1.0. The resulting values can be accessed via the parameters *t:aiazn* and *t:rtox*.

The voltage factor, c, is used in the calculation of $|Z_1|$ to ensure that the asynchronous machine will not contribute more than the specified subtransient short-circuit contribution, even with a fault at the terminals. This models the power electronic nature of the machine.

Transient Contribution

The transient contribution is modelled as a constant current injection, i.e. $|Z_1| = \infty$. For more information, see Section 3.2.5.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 3.1.3 are used. For the calculation of transient contributions, the negative sequence impedance is kept constant, i.e. $\underline{Z}_2^{'} = \underline{Z}_2^{''} = \underline{Z}_1^{''}$.

3.2.4 Doubly Fed Asynchronous Generator

This is the dedicated model for doubly fed induction generators. The subtransient contribution is considered as a rotating contribution and the transient contribution is modelled as a constant current injection.

Subtransient Contribution

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$, as shown in Figure 3.3, is calculated as follows:

$$|Z_1| = \frac{\sqrt{2} \cdot \kappa_{WD} \cdot U_r}{\sqrt{3} \cdot i_{WD,max}} \tag{70}$$

$$R/X = R/X_{WD} \tag{71}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- κ_{WD} is the factor for the calculation of the peak current contribution (*e:kWD*)
- $i_{max,WD}$ is the maximum instantaneous current contribution in [kA] (*e:iWDmax*)
- R/X_{WD} is the R/X ratio of the doubly fed asynchronous generator (*e:rxWD*)

Note: The factor κ_{WD} may contain effects of the converter protection system and should not be confused with κ used in the calculation of the peak short-circuit current.

If the *Externally Modelled Unit Transformer* option is used, $i_{max,WD}$ is referred to the HV side of the transformer. The resulting impedance $\underline{Z}_1$ is distributed as described in Section 3.1.5.

Transient Contribution

The transient contribution is modelled as a constant current injection, i.e. $|Z_1| = \infty$. For more information see Section 3.2.5.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 3.1.3 are used. However, dedicated sets of parameters for the negative sequence impedance and zero sequence are used.

This changes the calculation of $\underline{Z}_2 = R_2 + j \cdot X_2$ and $\underline{Z}_0 = R_0 + j \cdot X_0$ as follows:

$$\underline{Z}_2 = (r_{2,iec} + j \cdot x_{2,iec}) \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{72}$$

$$\underline{Z}_0 = (r_{0,iec} + j \cdot x_{0,iec}) \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{73}$$

where:

- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- $r_{2,iec}$ is the rated negative sequence resistance for DFIGs in [p.u.] (*e:r2iec*)
- $x_{2,iec}$ is the rated negative sequence reactance for DFIGs in [p.u.] (*e:x2iec*)
- $r_{0,iec}$ is the rated zero sequence resistance for DFIGs in [p.u.] (*e:r0iec*)
- $x_{0,iec}$ is the rated zero sequence reactance for DFIGs in [p.u.] (*e:x0iec*)

If the *Externally Modelled Unit Transformer* option is used, $\underline{Z}_2$ is referred to the HV side of the transformer and is distributed as described in Section 3.1.5. The zero sequence is not distributed.

Note: Even with the *Externally Modelled Unit Transformer* option enabled, the per-unit system used for the negative sequence impedance remains that of the asynchronous machine.

3.2.5 Constant Current Injection

Constant current injections inject a fixed positive sequence current at their terminals. The magnitude of the injected current depends on the voltage dip after the short-circuit calculation has been performed with only rotating machines participating. The angle of the injected current is chosen so that the additional voltage at the fault location, caused by the current injection, is in phase with the pre-fault voltage.

The magnitude of the injected current is calculated as follows:

$$
\begin{aligned}
I_{max} &= i_{max} \cdot I_r \\
\Delta u_1 &= \frac{|\underline{U}_{1,ldf}| - |\underline{U}_{1,rot}|}{U_r} \\
|I_1| &= \begin{cases} K \cdot \Delta u_1 \cdot I_{max} & \text{if } K \cdot \Delta u_1 < 1 \\ I_{max} & \text{if } K \cdot \Delta u_1 \geq 1 \end{cases}
\end{aligned} \tag{74}
$$

where:

- i_{max} is the maximum current injection in [p.u.] (*e:imax*)
- I_r is the rated current in [kA] ($I_r = S_r / (\sqrt{3} \cdot 1000 \cdot U_r)$)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- U_r is the rated voltage in [kV] (*t:ugn*)
- $\underline{U}_{1,ldf}$ is the positive sequence pre-fault voltage in [kV]
- $\underline{U}_{1,rot}$ is the positive sequence post-fault voltage from rotating machines in [kV]
- K is a scaling factor (*e:K*)

Note: The voltages are always measured at the machine terminal, including when the *Externally Modelled Unit Transformer* option is enabled.

Current Iteration

The magnitude of the injected current depends on the voltage dip from rotating machines. In most cases, the injected current will cause an increase in the terminal voltage. Hence, there will be a discrepancy between the final voltage at the terminal and the voltage used to calculate the injection. The *Current Iteration* option in the Short-Circuit command attempts to rectify this issue by re-calculating the voltage dip with the additional voltage caused by the converter injection. This is an iterative process, as the voltage increase at the terminal is also influenced by network topology and other injections.

The iterative process only adapts the magnitude of the injected current $|I_1|$, not the phase angle.

3.3 ANSI Short-Circuit

Asynchronous machines in any configuration are represented by the equivalent circuit shown in Figure 3.4 in the ANSI short-circuit calculation.

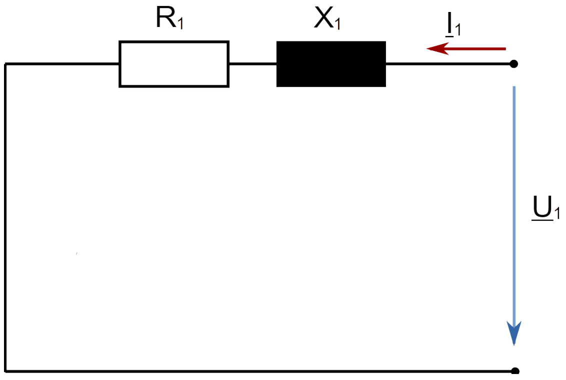

Figure 3.4: Equivalent positive sequence circuit for use in the ANSI short-circuit calculation

The impedance $\underline{Z}_1 = R_1 + j \cdot X_1$ is calculated as follows:

$$|Z_1| = k \cdot \frac{1}{I_{LR}/I_r} \cdot \frac{{U_r}^2 \cdot 1000}{S_r} \tag{75}$$

$$X_1 = \frac{|Z_1|}{\sqrt{1 + (R/X)^2}} \tag{76}$$

$$R_1 = R/X \cdot X_1 \tag{77}$$

where:

- k is a motor size dependent scaling factor
- U_r is the rated voltage in [kV] (*t:ugn*)
- S_r is the rated apparent power in [kVA] (*t:sgn*)
- I_{LR}/I_r is the locked rotor current in [p.u.] (*t:aiaznshc*)
- R/X is the R/X ratio (*t:rtoxshc*)

For more information regarding the motor size dependent scaling factor, please refer to the corresponding ANSI or IEEE standards.

Momentary Current Contribution

For the calculation of momentary currents, the model is considered as described above.

Interrupting Current Contribution

For the calculation of interrupting currents, the model is considered as described above.

30-Cycle Current Contribution

For the calculation of 30-cycle currents, the model is neglected.

Unbalanced Faults

For unbalanced faults, the negative and zero sequence models described in Section 3.1.3 are used.

3.4 IEC 61363

Asynchronous machines in any configuration are considered as *Equivalent Motors* in the IEC61363 short-circuit calculation. Please refer to the standard for further information.

4 Harmonics

The asynchronous machine model for harmonic analysis can directly be derived from the equivalent circuits according to Figures 1.1 to 1.5 if the option *Consider Transient Parameter* is selected. Otherwise, the input data for the locked rotor current ratio and the R/X locked rotor ratio are being used for calculating the impedances. In this case the effect of slip dependence is neglected in the model. The impedance calculation is done analogue to what is described in Section 3.2 and shown in Figure 4.1.

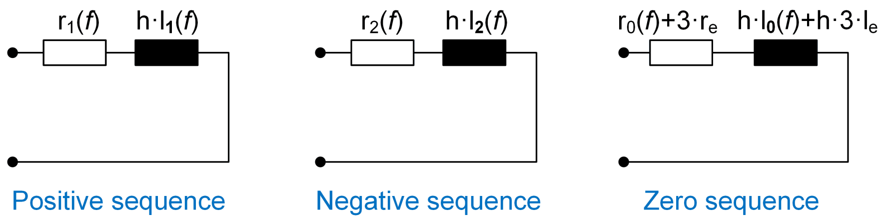

Figure 4.1: Harmonic load flow impedance model

The per unit values of the inductances and reactances are equivalent for frequency f equal to the base frequency $f_{base} = f_{nom}$:

$$x = \frac{\omega}{\omega_{base}} \cdot \frac{L}{L_{base}} \quad \left[\frac{\Omega}{\Omega}\right] = \frac{2 \cdot \pi \cdot f}{2 \cdot \pi \cdot f_{nom}} \cdot \frac{L}{L_{base}} \quad \left[\frac{\Omega}{\Omega}\right] = \frac{f}{f_{nom}} \cdot l = l \quad [p.u.] \tag{78}$$

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

$$z(f) = r(f) + \jmath \cdot x(f) = r(f) + \jmath \cdot \frac{f}{f_{nom}} \cdot l(f) = r(f) + \jmath \cdot h \cdot l(f) \tag{79}$$

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

This frequency dependency of the impedance can be considered by using characteristics. Several types of characteristics can be applied to the resistances and reactances shown in the Harmonic calculation tab of *TypAsmo*:

- 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:

$$\begin{aligned} r_1(f) &= r_1 \cdot k(f) = r_1 \cdot \left((1-a) + a \cdot (f/f_{nom})^b\right) \\ r_1(f) &= r_1 \cdot k(f) = r_1 \cdot \left(1 + a \cdot ((f/f_{nom}) - 1)^b\right) \end{aligned} \tag{80}$$

If the constant PQ model has been used, then internally a parallel susceptance is connected to the machine (Figure 4.2).

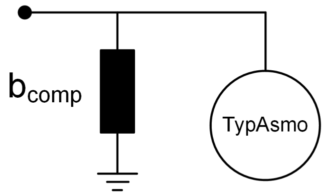

Figure 4.2: *DIgSILENT* TypAsmo PQ model

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

$$b_{comp} = \frac{q_{comp}}{|\underline{u}_s| \cdot S_r} \tag{81}$$

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.

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

4.1 Harmonic analysis when using Doubly Fed Induction Machine model

For frequency sweep calculation the DFIG machine is represented by an *Impedance* model. This impedance is calculated according to Section 3.2.

In addition to the *Impedance* model (equivalent to the model described in 3.2), two additional models are available for harmonic load flow calculation: *Norton Equivalent* and *Ideal Current Source*.

The equivalent circuits of *Impedance* and the *Norton Equivalent* model for harmonics are shown in Figures 4.1 and 4.3, respectively.

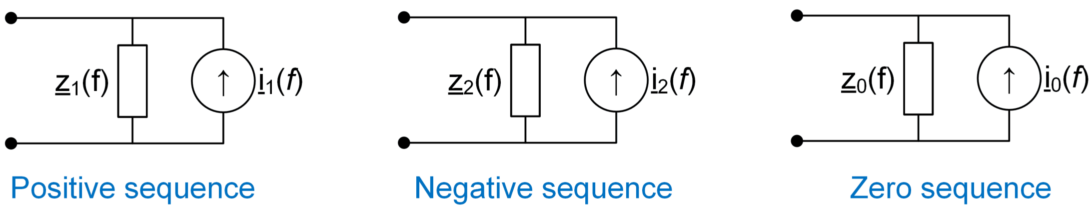

Figure 4.3: Harmonic load flow Norton equivalent model

For the two current source models, the harmonic currents can be defined in an *Harmonic Sources TypHmccur* object. The spectrum of harmonic infeeds may be entered according to one of the options: balanced, unbalanced or according to IEC 61000. The harmonic currents given in the harmonic voltage source object can be referred to the fundamental or rated current of the asynchronous machine. If *Rated Current* is selected then the phase angle is used from the initial bus voltage angle obtained from load flow. More information regarding the definition of harmonic current sources can be found in the corresponding chapter of the User Manual.

5 Stability/Electromagnetic Transients (RMS/EMT Simulation)

5.1 General Equations

The dynamic models for RMS (stability) and EMT-simulations can be derived from the equivalent circuits according to Figure 1.1 to Figure 1.5.

The *PowerFactory* RMS model uses the rotor fluxes as state variables. The EMT model, in addition to the rotor fluxes, uses the stator currents. This choice leads to the best decomposition of time frames and has therefore the best numerical properties.

The voltage equations of an asynchronous machine model with a number of n R-L rotor-loops expressed in an arbitrary rotating reference frame where ω is unspecified are the following:

$$\underline{u}_S = r_S \cdot \underline{i}_S + \frac{1}{\omega_n} \cdot \frac{d\underline{\psi}_S}{dt} + j\,\frac{\omega}{\omega_n} \cdot \underline{\psi}_S \tag{82}$$

$$\mathbf{0} = \mathbf{r_R} \cdot \underline{\mathbf{i}}_R + \frac{1}{\omega_n} \cdot \frac{d\underline{\mathbf{\Psi}}_R}{dt} + j\,\frac{\omega - \omega_R}{\omega_n} \cdot \underline{\mathbf{\Psi}}_R \tag{83}$$

where:

- $\underline{\mathbf{\Psi}}_R$ is a rotor flux vector of dimension equal to the number of rotor-loops n (refer to Section 5.1.1-5.1.3);
- $\underline{\mathbf{i}}_R$ is a rotor-current vector of dimension n; and
- $\mathbf{r_R}$ is a n×n resistance matrix;
- $\underline{u}_S$, $\underline{i}_S$ and $\underline{\psi}_S$ are stator voltage, current and flux;
- $\omega_n = \frac{d\ phi}{dt} = 2 \cdot \pi \cdot fnom$ is nominal angular frequency;
- ω_R is rotor speed.

Note that a bold letter represents a vector or a matrix.

The flux linkage equations are the following:

$$\underline{\psi}_S = x_{SS} \cdot \underline{i}_S + \mathbf{x}_{SR}^T \cdot \underline{\mathbf{i}}_R \tag{84}$$

$$\underline{\mathbf{\Psi}}_R = \mathbf{x}_{RS} \cdot \underline{i}_S + \mathbf{x}_{RR} \cdot \underline{\mathbf{i}}_R \tag{85}$$

For formulating the asynchronous machine equations with stator current and rotor flux as state variables, the flux linkage equations must be solved for the non-state variables, which are stator flux and rotor currents.

Equation 85 can be expressed as:

$$\underline{\mathbf{i}}_R = -\mathbf{x}_{RR}^{-1} \cdot \mathbf{x}_{RS} \cdot \underline{i}_S + \mathbf{x}_{RR}^{-1} \cdot \underline{\mathbf{\Psi}}_R \tag{86}$$

and when substituted into equation 84, the following is obtained for the stator flux:

$$\underline{\psi}_S = x'' \cdot \underline{i}_S + \mathbf{x}_{SR}^T \mathbf{x}_{RR}^{-1} \cdot \underline{\mathbf{\Psi}}_R \tag{87}$$

where :

$$x'' = x_{SS} - \mathbf{x}_{SR}^T \cdot \mathbf{x}_{RR}^{-1} \cdot \mathbf{x}_{RS} \tag{88}$$

If equation 87 is substituted into equation 82, the stator-voltage equation results in:

$$\underline{u}_S = r_S \cdot \underline{i}_S + j\,\frac{\omega_{ref}}{\omega_n} \cdot x'' \cdot \underline{i}_S + \frac{x''}{\omega_n} \cdot \frac{d\underline{i}_S}{dt} + j\,\frac{\omega_{ref}}{\omega_n} \cdot \underline{\psi}'' + \frac{1}{\omega_n} \cdot \frac{d\underline{\psi}''}{dt} \tag{89}$$

where the subtransient flux is defined as:

$$\underline{\psi}'' = \mathbf{x}_{SR}^T \cdot \mathbf{x}_{RR}^{-1} \cdot \underline{\mathbf{\Psi}}_R \tag{90}$$

Main flux saturation is not represented in the model.

5.1.1 Single Cage Model

The flux-linkage and the resistance matrices of the single cage model according to Figure 1.1 and Figure 1.2 can be expressed as follows:

$$x_{SS} = x_S + x_m \tag{91}$$

$$\mathbf{x}_{SR}^T = x_m \tag{92}$$

$$\mathbf{x}_{RS} = x_m \tag{93}$$

$$\mathbf{x}_{RR} = x_{rA} + x_m \tag{94}$$

$$\mathbf{r}_R = R_{rA} \tag{95}$$

where:

- x_m is the magnetising reactance in p.u.;
- x_s is stator reactance in p.u.;
- x_{rA} is rotor reactance in p.u..

5.1.2 Squirrel Cage Model

The flux-linkage and the resistance matrices of the squirrel cage rotor model according to Figure 1.1 and Figure 1.3 are the following:

$$x_{SS} = x_S + x_m \tag{96}$$

$$\mathbf{x}_{SR}^T = \begin{bmatrix} x_m & x_m \end{bmatrix} \tag{97}$$

$$\mathbf{x}_{RS} = \begin{bmatrix} x_m \\ x_m \end{bmatrix} \tag{98}$$

$$\mathbf{x}_{RR} = \begin{bmatrix} x_{rA1} + x_{rA0} + x_m & x_{rA0} + x_m \\ x_{rA0} + x_m & x_{rA2} + x_{rA0} + x_m \end{bmatrix} \tag{99}$$

$$\mathbf{r}_R = \begin{bmatrix} R_{rA0} + R_{rA1} & R_{rA0} \\ R_{rA0} & R_{rA0} + R_{rA2} \end{bmatrix} \tag{100}$$

5.1.3 Double Cage Model

The flux-linkage and resistance matrices of the double cage model with three R-L-rotor loops according to Figure 1.1 and Figure 1.5 are the following:

$$x_{SS} = x_S + x_m \tag{101}$$

$$\mathbf{x}_{SR}^T = \begin{bmatrix} x_m & x_m & x_m \end{bmatrix} \tag{102}$$

$$\mathbf{x}_{RS} = \begin{bmatrix} x_m \\ x_m \\ x_m \end{bmatrix} \tag{103}$$

$$\mathbf{x}_{RR} = \begin{bmatrix} x_{rA1} + x_{rA0} + x_{rm} + x_m & x_{rA0} + x_{rm} + x_m & x_{rm} + x_m \\ x_{rA0}x_{rm} + x_m & x_{rA2} + x_{rA0}x_{rm} + x_m & x_{rm} + x_m \\ x_{rm} + x_m & x_{rm} + x_m & x_{rB} + x_{rm} + x_m \end{bmatrix} \tag{104}$$

$$\mathbf{r}_R = \begin{bmatrix} R_{rA0} + R_{rA1} & R_{rA0} & 0 \\ R_{rA0} & R_{rA0} + R_{rA1} & 0 \\ 0 & 0 & R_{rB} \end{bmatrix} \tag{105}$$

5.2 RMS Model

The available currents and voltages from the RMS simulation are referred to the global reference system ω_{ref} (fixed to the rotor of the reference machine). If the global reference system is used, ω becomes ω_{ref} in Equations 82 and 83 and the ratio ω_{ref}/ω_n is equal to the speed (frequency) of the reference machine f_{ref}.

For the stability analysis, a reduced asynchronous machine model is used in which the stator transients are neglected. This is done in accordance with the steady state models of some of the elements used in stability analysis. After neglecting the term containing $\frac{d\underline{\psi}_S}{dt}$ from equation 82, the following equation for the stator voltage is being obtained:

$$\underline{u}_S = r_S \cdot \underline{i}_S + j\,\frac{\omega_{ref}}{\omega_n} \cdot x'' \cdot \underline{i}_S + j\,\frac{\omega_{ref}}{\omega_n} \cdot \underline{\psi}'' \tag{106}$$

This is a voltage-behind-reactance representation of the equivalent circuit. The subtransient voltage is here defined as:

$$\underline{u}'' = j\,\frac{\omega_{ref}}{\omega_n} \cdot \underline{\psi}'' \tag{107}$$

The internal parallel shunt compensation susceptance b_{comp} (Figure 4.2) 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 81).

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 $\underline{z}_2$ which is slip dependent and it is calculated according to the equivalent circuit diagrams in Figure 1.1 to Figure 1.5 where the rotor resistance is divided by an equivalent slip of $2 - slip$ (the normalised difference between the air-gap MMF and the rotor speed in the negative sequence system is $2 - slip$ (Chapter 9.3 of [2])). The negative sequence equation is given in Equation 108.

$$\underline{i}_{s2} = \frac{\underline{u}_{s2}}{\underline{z}_2} \tag{108}$$

If the *Connection* of the machine is set to *YN* (type parameter $nslty$), the zero sequence impedance can be entered $z_0 = rzero + \jmath \cdot xzero$. 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:

$$\underline{u}_{s0} = \underline{z}_0 \cdot \underline{i}_{s0} + 3 \cdot \underline{z}_e \cdot \underline{i}_{s0} \tag{109}$$

$$\tag{110}$$

- 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

$$\underline{u}_{s0} = \underline{z}_0 \cdot \underline{i}_{s0} + \underline{u}_n \tag{111}$$

$$0 = 3 \cdot \underline{i}_{s0} + \underline{i}_n \tag{112}$$

  – Internal grounding impedance connected

$$\underline{u}_{s0} = \underline{z}_0 \cdot \underline{i}_{s0} + \underline{u}_n \tag{113}$$

$$\underline{u}_n = \underline{z}_e \cdot (3 \cdot \underline{i}_{s0} + \underline{i}_n) \tag{114}$$

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

$$\underline{u}_{s0} = \underline{z}_0 \cdot \underline{i}_{s0} + \underline{u}_n \tag{115}$$

$$0 = 3 \cdot \underline{i}_{s0} + \underline{i}_n \tag{116}$$

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:

$$\underline{z}_e = (Re + \jmath \cdot Xe)/Z_b \qquad [p.u.] \tag{117}$$

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

5.3 EMT Model

In the EMT model, *PowerFactory* uses a stationary reference frame ($\omega_{ref} = 0$) for expressing the stator equation. The rotor variables are expressed in the synchronous reference frame rotating with nominal frequency ω_n. This means that the rotor terms in the stator voltage equation will be referred to the stationary reference frame. For this transformation the angle phi is used. It is initialised with $0\ rad$ and is rotating with the nominal angular frequency $\omega_n = \frac{d\ phi}{dt} = 2 \cdot \pi \cdot fnom$.

The stator voltage equation in the EMT case can be similarly deducted as for the RMS case and has the following form:

$$\underline{u}_S = r_S \cdot \underline{i}_S + \frac{x''}{\omega_n} \cdot \frac{d\underline{i}_S}{dt} + \left(j\,\frac{\omega_n}{\omega_n} \cdot \underline{\psi}'' + \frac{1}{\omega_n} \cdot \frac{d\underline{\psi}''}{dt} \right) \cdot e^{jphi} \tag{118}$$

This equation corresponds to a voltage-behind-reactance equivalent circuit, with the following definition for the subtransient voltage:

$$\underline{u}'' = \left(j\,\frac{\omega_n}{\omega_n} \cdot \underline{\psi}'' + \frac{1}{\omega_n} \cdot \frac{d\underline{\psi}''}{dt} \right) \cdot e^{jphi} \tag{119}$$

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 117. The resistance is obtained as $r_{e\_z} = z_e.r$ and the inductance as $l_{e\_z} = z_e.i/(2 \cdot \pi \cdot f_{nom})$.

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:

$$u_{s\_\gamma} = (r_{0\_z} + 3 \cdot r_{e\_z}) \cdot i_{s\_\gamma} + (l_{0\_z} + 3 \cdot l_{e\_z}) \cdot \frac{di_{s\_\gamma}}{dt} \tag{120}$$

- 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

$$u_{s\_\gamma} = r_{0\_z} \cdot i_{s\_\gamma} + l_{0\_z} \cdot \frac{di_{s\_\gamma}}{dt} + u_n \tag{121}$$

$$0 = 3 \cdot i_{s\_\gamma} + i_n \tag{122}$$

  – Internal grounding impedance connected

$$u_{s\_\gamma} = r_{0\_z} \cdot i_{s\_\gamma} + l_{0\_z} \cdot \frac{di_{s\_\gamma}}{dt} + u_n \tag{123}$$

$$u_n = r_{e\_z} \cdot (3 \cdot i_{s\_\gamma} + i_n) + l_{e\_z} \cdot \left(3 \cdot \frac{di_{s\_\gamma}}{dt} + \frac{di_n}{dt}\right) \tag{124}$$

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

$$u_{s\_\gamma} = r_{0\_z} \cdot i_{s\_\gamma} + l_{0\_z} \cdot \frac{di_{s\_\gamma}}{dt} + u_n \tag{125}$$

$$0 = 3 \cdot i_{s\_\gamma} + i_n \tag{126}$$

5.4 Mechanical Equations

The model is completed by the mechanical equation:

$$J_{tot} \cdot \frac{d\,\omega_m}{dt} = M_e - M_m \tag{127}$$

where:

- J_{tot} is the total inertia in $kg \cdot m^2$;
- M_e is the electrical torque in $N \cdot m$;
- M_m is the mechanical torque in $N \cdot m$;
- ω_m is the angular frequency of the rotor in mechanical rad/s.

The rated mechanical torque is defined as:

$$xmtn = \frac{pgn}{\omega_m} = \frac{pgn}{\omega_{0m} \cdot (1 - slipn)} = \frac{pgn}{\frac{\omega_n}{nppol} \cdot (1 - slipn)} \tag{128}$$

where:

- pgn is the rated mechanical power of the machine;
- ω_{0m} is the angular frequency of the rotor in mechanical rad/s based on synch. speed;
- ω_n is the nominal electrical frequency of the network in rad/s;
- $nppol$ is the number of pole-pairs;
- $slipn$ is the nominal slip.

The mechanical equation for motors gets the following form if the rated mechanical torque is used as base:

$$\frac{J_{tot}}{xmtn} \cdot \frac{\omega_n}{nppol} \cdot \frac{d\,speed}{dt} \equiv tag_{tot} \cdot \frac{d\,speed}{dt} = -xme - xmt \tag{129}$$

where:

- tag_{tot} is the total acceleration time constant in s;
- xme is the electrical torque in p.u.;
- xmt is the mechanical torque in p.u.;
- $speed$ is the speed in p.u.

The electrical torque is based on the rated mechanical power and is calculated as:

$$xme = (\underline{i}_S.r \cdot \underline{\psi}_S.i - \underline{i}_S.i \cdot \underline{\psi}_S.r)/(cosn \cdot effic/\omega_n) \tag{130}$$

where:

- $cosn$ is the rated power factor;
- $effic$ is the efficiency at rated operation in p.u.

The total inertia J_{tot} consists of two parts: the inertia defined in the type and the mechanical load defined in the machine, calculated as follows:

$$J_{tot} = J_{type} + J_{me} \cdot g_{ratio}^2 \tag{131}$$

where:

- J_{type} is the inertia defined in the type;
- J_{me} is the inertia of the mechanical load defined in the machine;
- g_{ratio} is the gearbox ratio.

It follows that the total acceleration time constant tag_{tot} is:

$$tag_{tot} = tag_{type} + tag_m \cdot g_{ratio}^2 \tag{132}$$

where:

- tag_{type} is the acceleration time constant from the type;
- tag_m is the acceleration time constant associated to the mechanical load in the machine

And the conversion between the type inertia and the type acceleration time constant is then:

$$J_{type} = \frac{tag_{type} \cdot pgn}{(1 - slipn) \cdot \left(\frac{\omega_n}{nppol}\right)^2} \tag{133}$$

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

$$slip = \begin{cases} (1 - speed/f_e) \cdot 100 & [\%] \text{ RMS simulation} \\ (1 - speed) \cdot 100 & [\%] \text{ EMT simulation} \end{cases} \tag{134}$$

5.4.1 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:

$$xmt = \begin{cases} \frac{pt}{speed} \cdot speedn & [p.u.] \text{ for generators or pt connected} \\ xmdm & [p.u.] \text{ for motors with connected external mdm} \\ mdmlp \cdot speed^{mdmex} & [p.u.] \text{ for motors with internal (build in) mdm} \end{cases} \tag{135}$$

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

5.5 Initialization

All state variables of the model are initialized from a preceding load flow calculation so that a simulation starts from a steady state condition.

If the default orientation of the asynchronous machine is set to *Motor*, the mechanical load torque *xmdm* is initialized. In case of *Generator* orientation, the turbine power pt is used for establishing the active power balance of the model.

In case of a running machine, the proportional factor $mdmlp$ of the built-in mdm or analogous factors of separately modelled motor-driven machines are calculated during the initialization process. In case of a disconnected machine, e.g. if a motor start-up is simulated, the user-defined variable of the input dialog is used instead.

5.6 Additional functionality of the RMS and EMT simulations

The functionality of the asynchronous machine models can be extended for the RMS and EMT simulations by using several predefined parameters/signals that the user can change during the simulation.

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.
- The parameter x_{stadd} (in $[p.u.]$) is additional stator reactance added to the stator reactance. This parameter is used by the *Motor Starting* Command.
- The parameter r_{radd} (in $[p.u.]$) is additional rotor resistance added to the rotor resistance. This parameter is used 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.

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

5.7 RMS/EMT Simulation when using Doubly Fed Induction Machine model

In the DFIG machine model, the asynchronous machine model is mostly identical to what is described in Section 5.1. The power converter injecting controllable voltage at slip frequency to the rotor has been simplified. The configuration of the asynchronous machine with doubly fed induction machine option is shown in Figure 5.1. The rotor voltages and the reactive current of the grid-side converter can be controlled.

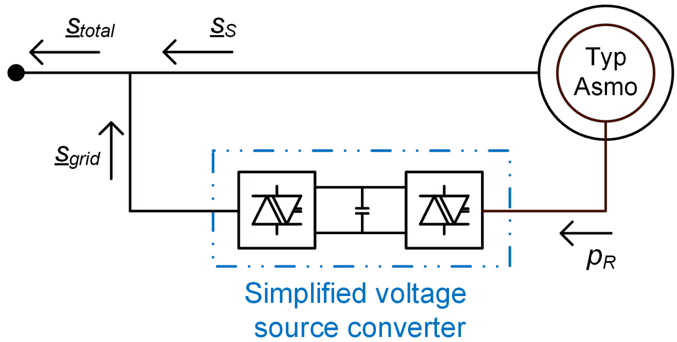

Figure 5.1: Configuration of the DFIG with simplified power converter

Taking into account the controllable rotor voltage in Equation 83, the following rotor voltage equation is obtained (Figure 5.2.):

$$\underline{\mathbf{u}}_{\mathbf{vsc}} = \mathbf{r_R} \cdot \underline{\mathbf{i}}_R + \frac{1}{\omega_n} \cdot \frac{d\underline{\mathbf{\Psi}}_R}{dt} + j\,\frac{\omega - \omega_R}{\omega_n} \cdot \underline{\mathbf{\Psi}}_R \tag{136}$$

where the rotor voltage $\underline{u}_{vsc}$ is equal to the voltage source converter voltage $\underline{u}_{vsc} = u_{sr} + \jmath u_{si}$. The voltages u_{sr} and u_{si} are input signals which can be used to control the rotor voltage.

If the option *Effect of frequency variation* (available on the *Advanced* tab of the *RMS-Simulation* page of the *TypAsmo* edit dialog) is disabled, it is assumed that the frequency changes are small and don't have a big effect on the stator voltage (the frequency is kept constant $\omega_{ref} = \omega_n$ in Equations 106 and 107). Else, the effect of frequency variation on the stator voltage is taken into account.

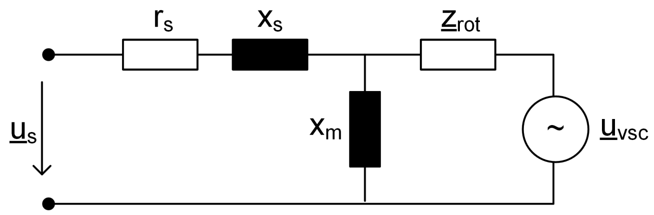

Figure 5.2: Asynchronous machine part of the DFIG model

The variables of the machine (currents, voltages,...) are expressed in a synchronous reference frame rotating with the global system reference (usually fixed to the rotor of the reference machine). The variables can be expressed in the rotor reference frame by shifting them using the rotating angle phi_m. This angle is initialised to zero, and its rotation depends on the speed of the machine i.e. its derivative is initialised and calculated as:

$$\frac{d\,phi_m}{dt} = 2 \cdot \pi \cdot f_{rnom} \cdot (speed - f_{ref}) \tag{137}$$

The variables are shifted to this reference frame by multiplying them with the transformation $e^{-\jmath \cdot phi_m}$. The output signals ird and irq are calculated using the internal rotor currents $\underline{i}_R$ as:

$$ird + \jmath\, irq = \underline{i}_R \cdot e^{-\jmath \cdot phi_m} \tag{138}$$

The calculation quantities urd and urq are similarly calculated as:

$$urd + \jmath\, urq = (usr + \jmath\, usi) \cdot e^{-\jmath \cdot phi_m} \tag{139}$$

The phase currents and voltages ira, irb, irc, ura, urb and urc are calculated from ird, irq, urd and urq using the inverse Clarke transformation.

Neglecting the losses, the active power of the stator p_S and rotor p_R can be expressed as:

$$p_S = \frac{\underline{s}_{total} \cdot r}{1 - slip/100} \tag{140}$$

$$p_R = -p_S \cdot slip/100 \tag{141}$$

where $\underline{s}_{total} = \underline{u}_t \cdot \underline{i}_t^*$ is the total apparent power expressed through the terminal voltage and current.

Since the power converter model has been simplified, the active power flowing out of the grid-side converter is equal to the rotor active power $p_{grid} = p_R$. The apparent power of the grid-side converter can be expressed as:

$$\underline{s}_{grid} = p_{grid} - \jmath\, i_{qgrid} \cdot |\underline{u}_t| \tag{142}$$

where i_{qgrid} is the input signal for controlling the reactive current of the grid-side converter (initialised to zero). In the RMS simulation the current is multiplied with $u_{t\ nom}/ugn \cdot sgn/1000$ where $u_{t\ nom}$ is the nominal voltage of the terminal, ugn is the rated voltage of the machine and sgn is the rated apparent power of the machine.

The DFIG model does not support neutral connections for both RMS and EMT simulations. The zero sequence equations remain the same. For the unbalanced RMS simulation, the negative sequence impedance $\underline{z}_2$ is a fix valued calculated using a negative sequence slip of $2 p.u.$.

5.7.1 Rotor protection

For limiting the rotor current and for influencing the speed-torque characteristic of the machine, the rotor additional resistance and reactance can be included. These can be inserted by changing the values of the input parameter $rradd$ and calculation parameter $xradd$ using *Parameter-Events*.

6 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 [3].

6.1 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.

6.1.1 Directly Online

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

6.1.2 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).

6.1.3 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}.

6.1.4 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 6.1).

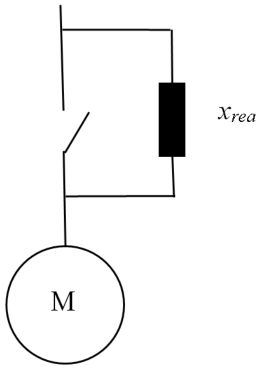

Figure 6.1: Additional Stator Reactance

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:

$$x_{stadd} = \frac{x_{rea}}{100} \cdot \frac{sgn}{ratedStr} \qquad [p.u.] \qquad (143)$$

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* $>=$.

6.1.5 Auto Transformer

The starting scheme of a motor using an auto transformer is shown in Figure 6.2. Initially, the star-contactor is closed and the by-pass switch is open.

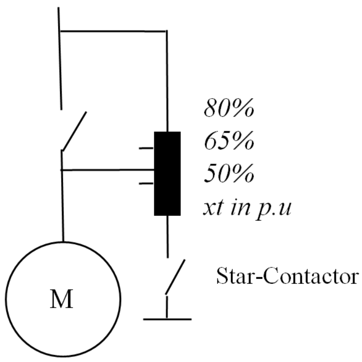

Figure 6.2: Auto Transformer Starting Method

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:

$$x_{stadd} = \frac{x_{rea}}{100} \cdot \frac{sgn}{ratedStr} \cdot \left(\frac{Tap}{100}\right)^2 \qquad [p.u.] \qquad (144)$$

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 143):

$$x_{stadd} = \frac{x_{rea}}{100} \cdot \frac{sgn}{ratedStr} \qquad [p.u.] \qquad (145)$$

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 $x_{stadd} = 0$.

A Parameters for Dynamic Models

Table A.1 describes the ratings and base values relevant for dynamic models (RMS and EMT) of the Asynchronous Machine.

Table A.1: Asynchronous Machine Base Values and Ratings

Symbol used in document	**Parameter name in *PowerFactory***	**Description**	**S.I. Unit**
sgn	sgn	Rated Apparent Power	VA
ugn	ugn	Rated Voltage, RMS	V
Z_b	-	Base Impedance eq. 146	Ohm
P_{en}	-	Rated Active Power, eq. 147	W
pgn	pgn	Rated Mechanical Power, eq. 148	W
$xmtn$	-	Rated Mechanical Torque, eq. 151	Nm
$cosn$	cosn	Rated Power Factor	-
η_r	effic	Efficiency at rated operation	%
$fnom$	frequ	Nominal Electrical Frequency (synchronous)	Hz
ω_n	-	Nominal Electrical Angular Frequency, eq.149	rad/s
$anend$	anend	Rated mechanical speed	rpm
s_n	-	Nominal Slip, eq. 150	-
$nppol$	nppol	Number of pole pairs	-

The following equations are used for computing various machine base values and ratings.

- Base Impedance:

$$Z_b = \frac{ugn^2}{sgn} \tag{146}$$

- Rated Active Power:

$$P_{en} = sgn \cdot cosn \tag{147}$$

- Rated Mechanical Power:

$$pgn = \frac{P_{en} \cdot \eta_r}{100} \tag{148}$$

- Nominal electrical angular frequency:

$$\omega_n = 2\pi \cdot fnom \tag{149}$$

- Nominal Slip:

$$slipn = \frac{\omega_n - \frac{2\pi}{60} \cdot anend \cdot nppol}{\omega_n} \tag{150}$$

- Rated Mechanical Torque:

$$xmtn = \frac{pgn}{\omega_m} = \frac{pgn}{\omega_{0m} \cdot (1 - slipn)} = \frac{pgn}{\frac{\omega_n}{nppol} \cdot (1 - slipn)} \tag{151}$$

Table A.2: Dynamic model signals (inputs, outputs and state variables) for *Standard Asynchronous Machine*

***PowerFactory* Parameter**	**Document Symbol**	**Unit**	**Base Value**	**Type**	**Description**
pt	pt	p.u.	pgn	IN	Turbine power
xmdm	xmt	p.u.	$xmtn$	IN	Mechanical load torque
rradd		p.u.	Z_b	IN	Additional rotor resistance
bcomp	b_{comp}	p.u.		IN	Compensation shunt susceptance (RMS only)
xspeed	$speed$	p.u.	ω_n	OUT	Mechanical speed
pgt		p.u.	P_{en}	OUT	Active power
xme	xme	p.u.	$xmtn$	OUT	Electrical torque
irot		p.u.		OUT	Rotor Current, magnitude
phi	phi	rad	-	OUT	Rotating angle for transferring between dq and $\alpha\beta$ system (EMT only)
speed	$speed$	p.u.	ω_n	STATE	Mechanical speed
psiA1_r		p.u.		STATE	Flux of loop A1, real
psiA1_i		p.u.		STATE	Flux of loop A1, imaginary
psiA2_r		p.u.		STATE	Flux of loop A2, real
psiA2_i		p.u.		STATE	Flux of loop A2, imaginary
psiB_r		p.u.		STATE	Flux of loop B, real
psiB_i		p.u.		STATE	Flux of loop B, imaginary

Table A.3: Dynamic model signals (inputs, outputs and state variables) - for Machine Type *Doubly Fed Induction Machine*

***PowerFactory* Parameter**	**Document Symbol**	**Unit**	**Base Value**	**Type**	**Description**
pt	pt	p.u.	pgn	IN	Turbine power
xmdm	xmt	p.u.	$xmtn$	IN	Mechanical load torque
rradd		p.u.	Z_b	IN	Additional rotor resistance
usr		p.u.		IN	Rotor voltage (voltage source converter)
usi		p.u.		IN	Rotor voltage (voltage source converter)
iqgrid		p.u.		IN	Reactive current of Grid-Side Converter
xspeed	$speed$	p.u.	ω_n	OUT	Mechanical speed
pgt		p.u.	P_{en}	OUT	Active power
xme	xme	p.u.	$xmtn$	OUT	Electrical torque
phi	phi	rad	-	OUT	Rotating angle for transferring between dq and $\alpha\beta$ system (EMT only)
ird	ird	p.u.		OUT	d-axis rotor current (referred to rotor angle)
irq	ird	p.u.		OUT	q-axis rotor current (referred to rotor angle)
xphim	phi_m	rad	-	OUT	Rotating angle with slip frequency
psis_r		p.u.		OUT	Stator Flux, Real Part
psis_i		p.u.		OUT	Stator Flux, Imaginary Part
psir_r		p.u.		OUT	Rotor Flux, Real Part
psir_i		p.u.		OUT	Rotor Flux, Imaginary Part
cosphim		-	-	OUT	cos(phim)
sinphim		-	-	OUT	sin(phim)
cosphi		-	-	OUT	cos(phi) (EMT only)
sinphi		-	-	OUT	sin(phi) (EMT only)
phim	phi_m	rad	-	STATE	Rotating angle with slip frequency
speed	$speed$	p.u.	ω_n	STATE	Mechanical speed
psiA1_r		p.u.		STATE	Flux of loop A1, real
psiA1_i		p.u.		STATE	Flux of loop A1, imaginary
psiA2_r		p.u.		STATE	Flux of loop A2, real
psiA2_i		p.u.		STATE	Flux of loop A2, imaginary
psiB_r		p.u.		STATE	Flux of loop B, real
psiB_i		p.u.		STATE	Flux of loop B, imaginary

Table A.4: Additional parameters (calculation parameters)

Parameter	**Unit**	**Base Unit**	**Description**
slip	%	$s_n \cdot 100$	Slip
xmem	p.u.	$xmtn$	Electrical torque (inverted sign)
xmt	p.u.	$xmtn$	Mechanical Torque
xradd	p.u.		Additional rotor reactance
addmt	p.u.	$xmtn$	Additional mechanical torque
ccomp	p.u.		Internal capacitance for compensating reactive power mismatch in case of PQ-load flow model (Standard model only)

B References

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