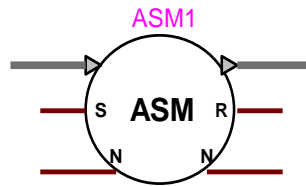


Asynchronous machine device



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1 Description

This device is currently used to represent 3 major types of 3-phase induction machines: single-squirrel-cage, double-squirrel-cage and wound-rotor.

1.1 The induction machine symbol

The induction machine device is a 3-phase device. Its symbol is automatically updated according to internal winding configurations. The following figure presents available device pins.

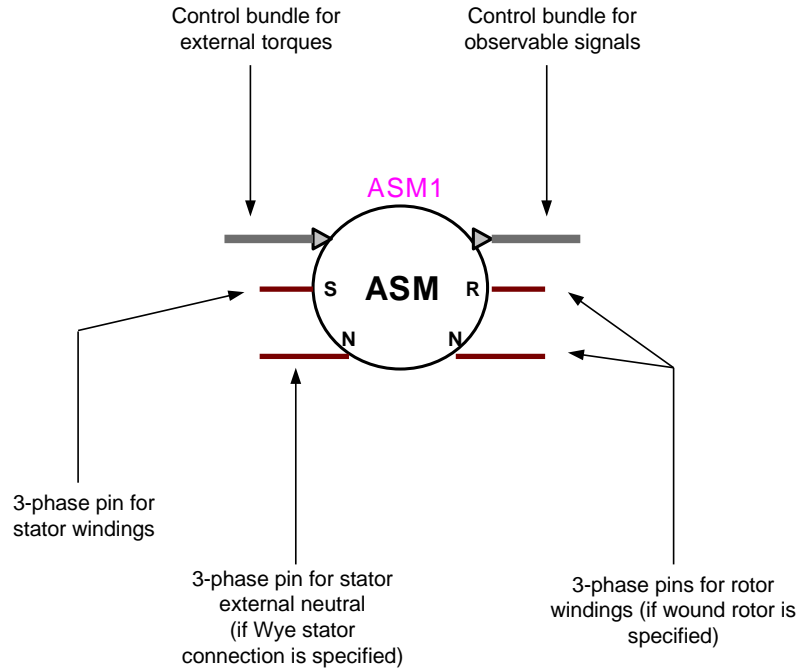


Figure 1 The induction machine

1.2 Theoretical summary

The following presentation is for an ideal 3-phase, p-poles induction machine. The fundamental approach is to consider an arrangement of three ideal sinusoidally distributed, without space harmonics, stator windings 120 degrees apart. The rotor is also given three windings. The power-invariant Park's transformation matrix \mathbf{P} is given by:

$$\mathbf{P} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} \cos \beta & \cos \left(\beta - \frac{2\pi}{3} \right) & \cos \left(\beta + \frac{2\pi}{3} \right) \\ \sin \beta & \sin \left(\beta - \frac{2\pi}{3} \right) & \sin \left(\beta + \frac{2\pi}{3} \right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (1)$$

The transformation equation from abc quantities to dq0 reference frame is given by:

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \mathbf{P} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (2)$$

where the variable x can be the phase voltages, currents, or flux linkages of the machine. The selected reference frame can be stationary ($\beta = 0$), fixed to the rotor ($\beta = \theta_r$) or synchronous ($\beta = \theta_b$). The q-axis of the dq0 system is located 90 degrees behind the direct axis (d-axis).

1.2.1 Variables used to define the induction machine model

The variables used in this model are defined in the following table. Electrical rotor variables are defined from the stator side.

Symbol	Description
V_d, V_q, V_{0s}	Stator voltages in dq0 domain
V_{D1}, V_{Q1}, V_{0r}	Rotor voltages in dq0 domain
i_d, i_q, i_{0s}	Stator currents in dq0 domain
i_{D1}, i_{Q1}, i_{0r}	Rotor currents in dq0 domain ($i_{0r} = 0$ for cage rotors)
i_{D2}, i_{Q2}	Second cage rotor currents in dq0 domain (only for double cage rotor)
R_s	Stator resistance
L_{ls}	Stator leakage inductance
R_{r1}	Rotor resistance
L_{r1}	Rotor leakage inductance
R_{r2}	Rotor resistance of the second cage (only for double cage rotor)
L_{r2}	Rotor leakage inductance of the second cage (only for double cage rotor)
L_{md}	d-axis linkage inductance
L_{mq}	q-axis linkage inductance
p	Number of poles
ω_r	Electrical speed (rad/s)
θ_r	Electrical angle (rad)
ω	Reference frame speed
ω_{rm}	Mechanical speed $\omega_{rm} = \left(\frac{2}{p}\right)\omega_r$
θ_{rm}	Mechanical angle $\theta_{rm} = \left(\frac{2}{p}\right)\theta_r$
ω_b	Base electrical speed (rad/s)
θ_b	Base electrical angle (rad)
ω_{bm}	Base mechanical speed $\omega_{bm} = \left(\frac{2}{p}\right)\omega_b$
θ_{bm}	Base mechanical angle $\theta_{bm} = \left(\frac{2}{p}\right)\theta_b$
s	Mechanical speed deviation (slip) $s = \frac{\omega_{bm} - \omega_{rm}}{\omega_{bm}}$
T_{eg}	Electromagnetic torque (Nm)

1.2.2 The different types of machines in dq0 domain

3 types of induction machines are currently available in EMTF. Their representation in the dq0 system is presented in the following figures.

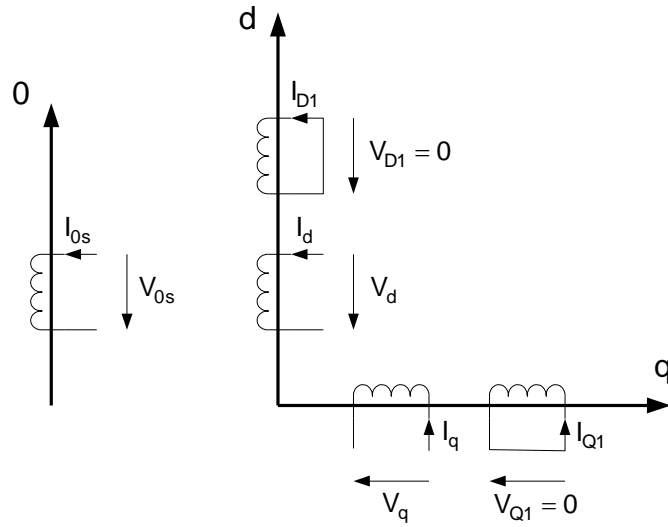


Figure 2 Single-cage machine model in the dq0 reference frame

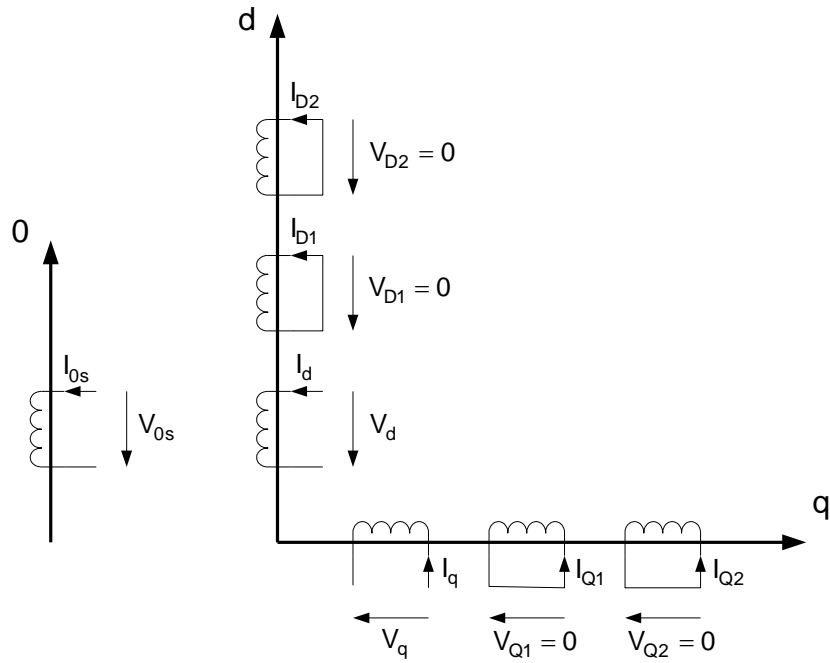


Figure 3 Double-cage machine model in the dq0 reference frame

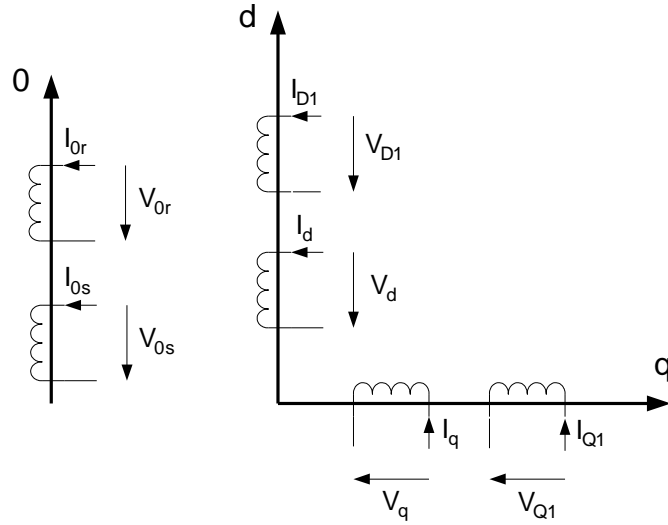


Figure 3 Wound-rotor machine model in the dq0 reference frame

1.2.3 Voltage equations

The following equations are written for double-cage and wound-rotor machines. The electromagnetic circuit structures of both the stator and the rotor are symmetric for most induction machines. As a consequence the following equations are only written for d-axis variables.

In matrix notation, the stator winding abc voltage equations can be represented as:

$$\mathbf{V}_s^{abc} = \frac{d\boldsymbol{\Psi}_s^{abc}}{dt} + \mathbf{R}_s \mathbf{I}_s^{abc} \quad (3)$$

When the Park's transformation is applied on equation (3) the d-axis equations for wound-rotor machines are given by:

$$\begin{bmatrix} v_d(t) \\ v_{D1}(t) \\ v_{0r}(t) \end{bmatrix} = - \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_{r1} & 0 \\ 0 & 0 & R_{r1} \end{bmatrix} \begin{bmatrix} i_d(t) \\ i_{D1}(t) \\ i_{0r}(t) \end{bmatrix} - \begin{bmatrix} \omega \Psi_q(t) \\ (\omega - \omega_r) \Psi_{Q1}(t) \\ 0 \end{bmatrix} - \begin{bmatrix} \frac{d\Psi_d}{dt}(t) \\ \frac{d\Psi_{D1}}{dt}(t) \\ \frac{d\Psi_{0r}}{dt}(t) \end{bmatrix} \quad (4)$$

For the double-cage machine case:

$$\begin{bmatrix} v_d(t) \\ 0 \\ 0 \end{bmatrix} = - \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_{r1} & 0 \\ 0 & 0 & R_{r2} \end{bmatrix} \begin{bmatrix} i_d(t) \\ i_{D1}(t) \\ i_{D2}(t) \end{bmatrix} - \begin{bmatrix} \omega \Psi_q(t) \\ (\omega - \omega_r) \Psi_{Q1}(t) \\ (\omega - \omega_r) \Psi_{Q2}(t) \end{bmatrix} - \begin{bmatrix} \frac{d\Psi_d}{dt}(t) \\ \frac{d\Psi_{D1}}{dt}(t) \\ \frac{d\Psi_{D2}}{dt}(t) \end{bmatrix} \quad (5)$$

where Ψ is the flux linkage.

1.2.4 Flux linkage relations

The dq0 flux linkages are obtained by applying Park's transformation to abc flux linkages. Coil inductances are divided into linkage inductances and leakage inductances $L_a = L_{ls}$ (stator leakage) or $L_a = L_{lr}$ (rotor leakage). As the induction machine is assumed to be symmetrical, the leakage inductances are the same for stator d and q-axis. The rotor d and q-axis leakage inductances are also be the same. As a consequence:

$$L_d = L_{md} + L_a$$

and

$$L_q = L_{mq} + L_a$$

For a wound-rotor:

$$\begin{bmatrix} \Psi_d(t) \\ \Psi_{D1}(t) \end{bmatrix} = - \begin{bmatrix} L_d = L_{md} + L_{ls} & L_{md} \\ L_{md} & L_d = L_{md} + L_{lr} \end{bmatrix} \begin{bmatrix} i_d(t) \\ i_{D1}(t) \end{bmatrix} \quad (6)$$

For a double-cage rotor:

$$\begin{bmatrix} \Psi_d(t) \\ \Psi_{D1}(t) \\ \Psi_{D2}(t) \end{bmatrix} = - \begin{bmatrix} L_d = L_{md} + L_{ls} & L_{md} & L_{md} \\ L_{md} & L_d = L_{md} + L_{lr1} & L_{md} \\ L_{md} & L_{md} & L_d = L_{md} + L_{lr2} \end{bmatrix} \begin{bmatrix} i_d(t) \\ i_{D1}(t) \\ i_{D2}(t) \end{bmatrix} \quad (7)$$

1.2.5 Equivalent circuits for time-domain solution

Substituting equation (6) into equation (4), gives the voltage equations:

$$v_d(t) = -R_s i_d - L_{ls} \frac{di_d(t)}{dt} - L_{md} \frac{d(i_{D1}(t) + i_d(t))}{dt} - \omega \Psi_q(t) \quad (8)$$

$$v_{D1}(t) = -R_{r1} i_{D1}(t) - (\omega - \omega_r) \Psi_{Q1}(t) - L_{lr1} \frac{di_{D1}(t)}{dt} - L_{md} \frac{d(i_{D1}(t) + i_d(t))}{dt} \quad (9)$$

The equivalent circuit for the wound-rotor is shown in Figure 4.

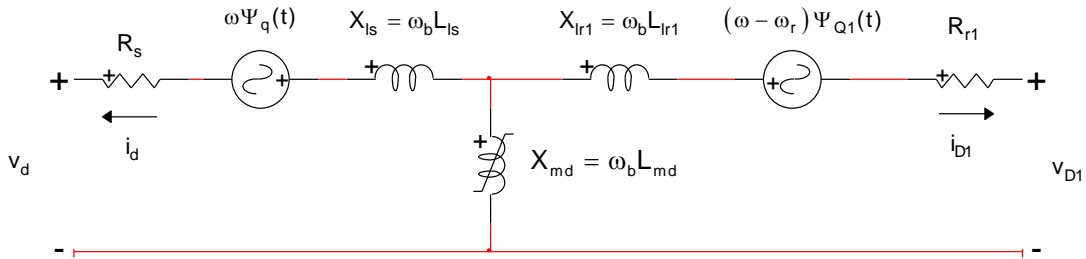


Figure 4 D-axis equivalent circuit of a wound-rotor machine for time-domain solution

In the same way, substituting equation (7) into equation (5), gives the voltage equations for the double-cage rotor.

$$v_d(t) = -R_s i_d - L_{ls} \frac{di_d(t)}{dt} - L_{md} \frac{d(i_{D1}(t) + i_{D2}(t) + i_d(t))}{dt} - \omega \Psi_q(t) \quad (10)$$

$$0 = -R_{r1} i_{D1}(t) - (\omega - \omega_r) \Psi_{Q1}(t) - L_{lr1} \frac{d[i_{D1}(t) + i_{D2}(t)]}{dt} - L_{md} \frac{d(i_{D1}(t) + i_{D2}(t) + i_d(t))}{dt} \quad (11)$$

$$0 = -R_{r2} i_{D2}(t) - (\omega - \omega_r) \Psi_{Q2}(t) - L_{lr2} \frac{di_{D2}(t)}{dt} - L_{md} \frac{d(i_{D1}(t) + i_{D2}(t) + i_d(t))}{dt} - (\omega - \omega_r) \Psi_{Q1}(t) - L_{lr1} \frac{d[i_{D1}(t) + i_{D2}(t)]}{dt} \quad (12)$$

The equivalent circuit is shown in Figure 5.

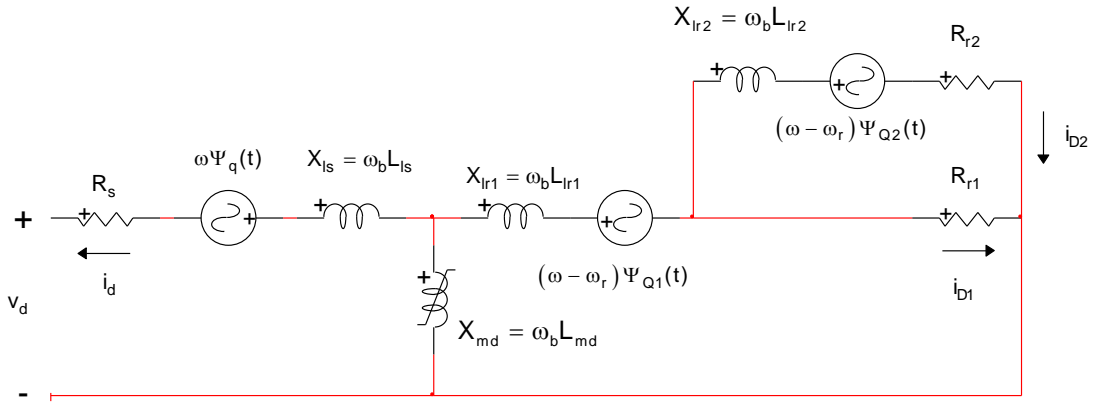


Figure 5 D-axis equivalent circuit of a double-cage rotor for time-domain solution

1.2.6 Equivalent circuit for steady-state solution

It is recalled that in an asynchronous reference frame the steady-state voltages are related by:

$$\tilde{V}_{ds} = -j\tilde{V}_{qs} \quad (13)$$

$$\tilde{V}_{dr} = -j\tilde{V}_{qr} \quad (14)$$

Appropriate substitution of these equations into equations (8) and (9) yields the steady-state voltage equations for wound-rotor :

$$\tilde{V}_d = -R_s \tilde{i}_d - jX_{ls} \tilde{i}_d - jX_{md} (\tilde{i}_d + \tilde{i}_{D1}) \quad (15)$$

$$\frac{\tilde{V}_{D1}}{s} = -\frac{R_{r1}}{s} \tilde{i}_{D1} - jX_{lr1} \tilde{i}_{D1} - jX_{md} (\tilde{i}_d + \tilde{i}_{D1}) \quad (16)$$

Where j is the complex number unit, s is the slip and the tilde denotes phasors.

The following equations are obtained for double-cage rotors:

$$\tilde{V}_d = -R_s \tilde{i}_d - jX_{ls} \tilde{i}_d - jX_{md} (\tilde{i}_d + \tilde{i}_{D1} + \tilde{i}_{D2}) \quad (17)$$

$$0 = -\frac{R_{r1}}{s} \tilde{i}_{D1} - jX_{lr1} (\tilde{i}_{D1} + \tilde{i}_{D2}) - jX_{md} (\tilde{i}_d + \tilde{i}_{D1} + \tilde{i}_{D2}) \quad (18)$$

$$0 = -\frac{R_{r2}}{s} \tilde{i}_{D2} - jX_{lr2} \tilde{i}_{D2} - jX_{lr1} (\tilde{i}_{D1} + \tilde{i}_{D2}) - jX_{md} (\tilde{i}_d + \tilde{i}_{D1} + \tilde{i}_{D2}) \quad (19)$$

In balanced steady-state operating mode, the network sees the induction machine as a positive sequence impedance whose value depends on the slip. The negative and zero sequence impedances are neglected during the steady-state initialization.

An equivalent circuit based on the phasor equations (15) and (16) for the wound-rotor case is shown in Figure 6.

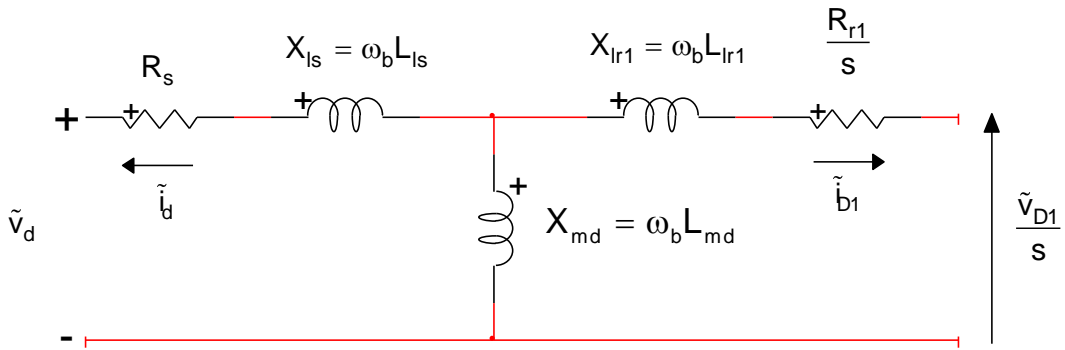


Figure 6 Equivalent circuit for steady-state behavior of induction machines with wound-rotor

The steady-state equivalent circuit for a double-cage rotor defined by equations (17), (18) and (19) is shown in Figure 7.

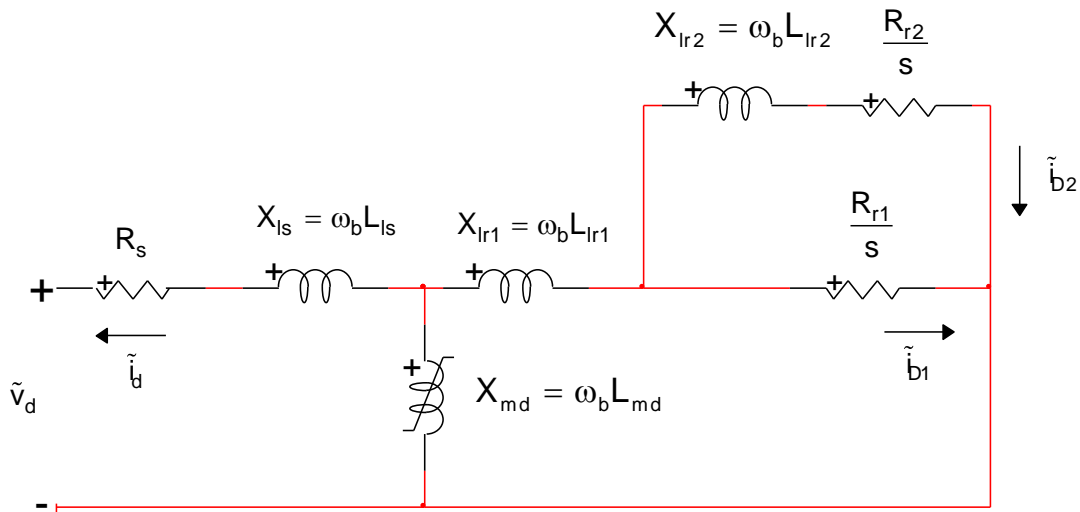


Figure 7 Equivalent circuit for steady-state behavior of induction machines with double-cage-rotor

1.2.7 Mechanical equations

For most of types of studies it may be necessary to take the speed variations into account. The simplest model for the mechanical part is the single mass representation as used in stability studies:

$$J \frac{d\omega_{rm}}{dt} + D\omega_{rm} = T_e - T_{turbine} \quad (20)$$

where:

- J is the moment of inertia of rotating turbine-generator mass
- ω_{rm} is the mechanical speed
- D is the damping coefficient for viscous and wind friction
- $T_{turbine}$ is the torque input to turbine

- T_e is the electromagnetic torque of the generator

Modeling the mechanical part of an induction machine with a single mass representation is not sufficiently accurate in some situations. In the case of wind turbines models, accurate results are obtained by increasing the number of masses which are used to represent the physical characteristics of mechanical system: low-speed shaft, gearbox, high-speed shaft and wind generator rotor.

The mechanical part of the induction machine model in EMTD is composed of a multimass system. An unlimited number of masses can be specified.

Each major element is considered to be a rigid mass connected to adjacent elements by mass less springs. An external torque can be applied on each individual mass. Figure 8 shows a typical 3-mass model representing a windmill drive train.

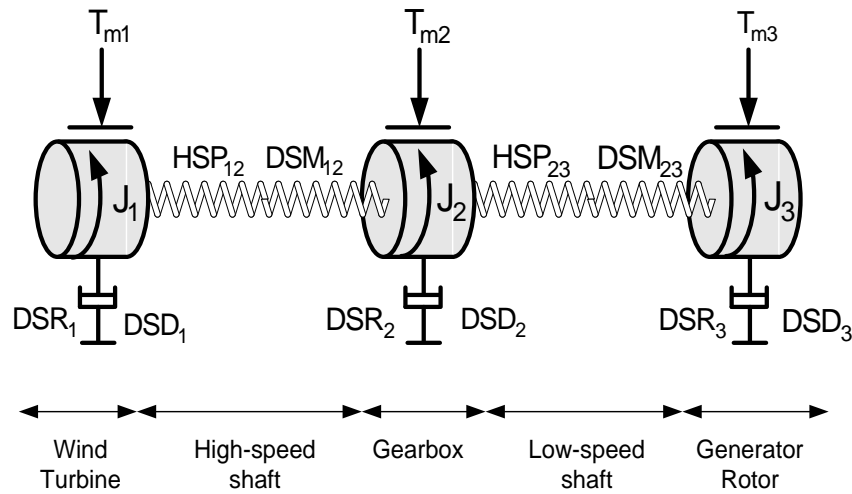


Figure 8 Mechanical part of a windmill drive train

The shaft/rotor system is assumed to be linear, which is reasonable for the small amplitudes of torsional vibrations. The n-spring-connected rotating masses are then described by the rotational form of Newton's second law:

$$\mathbf{J} \frac{d\boldsymbol{\omega}_{rm}}{dt} + \mathbf{D}\boldsymbol{\omega}_{rm} + \mathbf{HSP} \boldsymbol{\theta}_{rm} = \mathbf{T}_e - \mathbf{T}_{turbine} \quad (21)$$

where:

\mathbf{J} is the diagonal matrix of moments of inertia (J_1 , J_2 and J_3 in Figure 8)

$\boldsymbol{\omega}_{rm}$ is the vector of mechanical speeds

$\boldsymbol{\theta}_{rm}$ is the vector of angular positions

\mathbf{HSP} is the tridiagonal matrix of stiffness coefficients

\mathbf{D} is the tridiagonal matrix of damping coefficients

$\mathbf{T}_{turbine}$ is the vector of external torques applied to the turbine stages (T_{m1} , T_{m2} and T_{m3} in Figure 8)

\mathbf{T}_e is the vector of electromagnetic torques of generator (only one non-zero component).

The moment of inertia and the stiffness coefficients are normally available from design data. The spring action of the shaft section between masses $i-1$ and i creates a torque which is proportional to the angle twist $\theta_{m i} - \theta_{m i+1}$. The proportionality factor is the stiffness coefficient or spring constant HSP_{i+1} . This spring action torque acts in opposite directions on masses $i-1$ and i :

$$T_{\text{spring } i-1} = -T_{\text{spring } i} = \text{HSP}_{i-1 i} (\theta_{\text{rm } i-1} - \theta_{\text{rm } i}) \quad (22)$$

From equation (22) it can be seen that the **HSP** matrix has the following form (3 masses):

$$\mathbf{HSP} = \begin{bmatrix} \text{HSP}_{12} & -\text{HSP}_{12} & 0 \\ -\text{HSP}_{12} & \text{HSP}_{12} + \text{HSP}_{23} & -\text{HSP}_{23} \\ 0 & -\text{HSP}_{23} & \text{HSP}_{23} \end{bmatrix} \quad (23)$$

Three damping effects are included with the damping coefficients, namely the absolute speed self damping DSD_i of mass i , the mutual damping coefficient $\text{DSM}_{i+1 i}$ and the mutual damping coefficient $\text{DSM}_{i-1 i}$. The damping torque acting on mass i is therefore:

$$T_{\text{damping } i} = \text{DSD}_i \omega_{\text{rm } i} + \text{DSM}_{i-1 i} (\omega_{\text{rm } i} - \omega_{\text{rm } i-1}) + \text{DSM}_{i+1 i} (\omega_{\text{rm } i} - \omega_{\text{rm } i+1}) \quad (24)$$

From equation (24) it can be seen that **D** has the same structure as **HSP** except that the diagonal element is now $\text{DSD}_i + \text{DSM}_{i-1 i} + \text{DSM}_{i+1 i}$:

$$\mathbf{D} = \begin{bmatrix} \text{DSD}_1 + \text{DSM}_{12} & -\text{DSM}_{12} & 0 \\ -\text{DSM}_{12} & \text{DSD}_2 + \text{DSM}_{12} + \text{DSM}_{23} & -\text{DSM}_{23} \\ 0 & -\text{DSM}_{23} & \text{DSD}_3 + \text{DSM}_{23} \end{bmatrix} \quad (25)$$

Another damping coefficient, named speed deviation self damping for a given mass (DSR), is also available. By definition:

$$T_i = \text{DSR}_i (\omega_{\text{m } i} - \omega_{\text{bm}}) \quad (26)$$

where ω_{bm} is the base mechanical speed.

It is difficult to obtain realistic values for these damping coefficients. Fortunately, they have very little influence on the peak torque value during transient disturbances. However, even if all these damping coefficients are not used, research conducted on a simulated distribution network with an integrated wind farm, shows that the value of the Critical Clearing Time of a wind farm is much more realistic if the multi mass model is used.

1.2.8 Saturation

Machine saturation can be optionally included. Magnetizing and leakage inductances can saturate.

□ Saturation of the magnetizing inductances

Machine saturation can be optionally included. The saturation of the machine is in principle dependent on the electrical current in every circuit. That is why the induction machine model in EMTP can simulate saturation separately on d and q-axis but also can use the total saturation approach in which the total flux is the resulting flux of the d-q axis contributions.

For both saturation methods a piecewise linear approximation is used to take into account the saturation effect. The magnetization characteristic (d-axis voltage in pu vs d-axis current in A) can be defined with an unlimited number of segments. This monotonically increasing characteristic represents the saturation of the magnetization branch of the induction machine.

For the total saturation approach, the unsaturated mutual flux is given by:

$$\Psi_m = \sqrt{\Psi_{\text{md}}^2 + \Psi_{\text{mq}}^2} \quad (27)$$

This flux saturates to take into account the fact that fluxes in the two axes affect one another (cross-magnetization).

When the electromagnetic circuit structures of both the stator and the rotor are symmetric, as in most induction machines, the decoupled approach of saturation on d and q-axis may lead to unacceptable results.

□ Saturation of the leakage inductances

When induction motors start, they draw a current of between 5 and 10 times the full load current. With such high currents, the leakage flux associated with the stator and rotor conductors becomes high enough to magnetically saturate the surrounding iron. This reduces the stator and rotor leakage reactances, and causes the current and the torque to increase. This phenomenon is used to obtain the highest possible starting torque.

If the optional "Saturation of leakage inductances" is turned on, 50% of the stator and rotor leakage inductances are assumed to saturate as a function of the stator and rotor currents. Saturation is assumed to start when the current is greater than a specified saturation current I_{sat} . The saturable portion of the leakage reactance reduces as the current increases following the rule of the describing function given below. This model is given in [1].

The saturation describing function DF is a function of the ratio of the amplitude of the fundamental component of a sinusoid clipped at the saturation level over the full amplitude of the sinusoid. In EMTP the maximum instantaneous value among the 3 phase currents is used in the equation below:

$$DF(y) = \frac{2}{\pi} \left(\arcsin y + y\sqrt{1-y^2} \right) \quad y \leq 1 \quad (28)$$

$$DF(y) = 1 \quad y > 1$$

$$y = \left| \frac{I_{sat}}{I} \right|$$

Where I_{sat} is specified by the user and I is taken at each time-point solution as the maximum among the 3 phase currents. When the current is less than the saturation current, the reactance remains at its unsaturated value. When the current is 6 times the saturation current, the leakage reactance reduces to about 70% of its unsaturated value.

1.2.9 Skin effect in deep bars

Deep rectangular rotor bars are frequently used in the cage windings of large induction motors. In this type of rotor, the eddy current distribution in the bar changes with the frequency of the bar current. At high frequencies, the eddy currents cause the rotor bar current to flow mainly in the top portion of the bar. At low frequencies the bar current flows evenly throughout the whole bar. Thus, at motor startup, when the frequency is high, the effective resistance of the rotor bar is high. At the running speed, the rotor frequency is low and hence the effective rotor bar resistance is low.

The effective resistance and reactance of a deep rotor bar changes with frequency. The deep bar factor DF is defined as:

$$DF = d\sqrt{2\omega\mu_0\sigma} \quad (29)$$

where d is the thickness of deep bars and σ is the conductivity of the rotor bars,

The following equation gives the effective rotor impedance as a function of slip:

$$R_{r1} + jX_{lr1} = \frac{R_{r(slip=0)}}{2} \theta \frac{\sinh \theta + \sin \theta + j(\sinh \theta - \sin \theta)}{\cosh \theta - \cos \theta} \quad (30)$$

with the variable $\theta = \sqrt{s} DF$.

The deep rotor bar causes the resistance to increase as the slip increases and the reactance to decrease. EMTP uses the above equation in steady-state and time-domain computations. This theory is based on the work presented in [1].

1.3 The Nameplate input calculator

In this release of EMTP-RV, a nameplate input calculator is available. This option allows to determine the equivalent circuit parameters for three-phase induction motors and induction generators from their standard specifications:

- Full load power factor (%)
- Full load efficiency (%)
- Full load slip (%)
- Ratio of starting current to full load current (pu)

For motors with deep rotor bars or a double cage, the ratio of starting torque to full load torque is an additional requirement. The level of current at which the stator and rotor leakage reactances saturate may also be specified.

The Nameplate input calculator finds the equivalent circuit parameters and allows to load them into the “Circuit Parameters” section. Calculated data is available only in pu. The parameters can still be manually modified. The EMTP mode has access only to the parameters given in the “Circuit Parameters” section.

The calculation method is described [1]. It is similar to the EMTP-V3 “Type-40 induction machine” [2]. The new calculation method is slightly different from the Type-40 method:

- The parameter values can be changed after calculation.
- In EMTP-V3 the user had to enter 2 different starting currents. One starting current at rated voltage and one starting current at the reduced voltage VRED. VRED was given by the user. In the new version, the calculator only needs the starting current at rated voltage.

1.4 How to control the external mechanical torques

The external mechanical torque applied on each mass composing the mechanical shaft can be controlled in 2 ways: independent control on each mass or total control. If one option is chosen, the other is no more available.

□ Independent control of the external mechanical torques

In this case the external mechanical torque applied on each mass can be controlled. The corresponding control signals are available in the control bundle of the induction machine device if the torque control option Tm_i has been specified in the mechanical data form. These torques are negative for a generator and positive for a motor. If this option has been chosen and if no controlled torque signal has been selected for a mass i then no external torque is applied on this mass i.

□ Total control

The total mechanical torque applied on the mechanical shaft can be specified. The fraction of the total external mechanical torque which is associated with each mass in the mechanical data form is used to calculate the individual external torque applied on each mass.

If a steady-state initialization has been chosen the electromagnetic torque in steady-state is taken as the total external mechanical torque. In this case an external torque is applied on each mass in accordance with the fraction of total external mechanical torque associated with each mass. This constant torque will be taken as the total external torque as long as the “Controlled torque start time” is not exceeded.

1.5 Base quantities

Parameters of the induction machine model can be specified in fundamental units or in per units (pu). The base quantities with rms value of a p-pole, three phase induction machine with rated line-to-line rms voltage V_{rated} , rated value of angular frequency ω_b , and rated volt-ampere S_{rated} , are as follows :

- RMS line-to-line base voltage $V_b = V_{\text{rated}}$
- Base volt-ampere $S_b = S_{\text{rated}}$
- RMS Base current $I_b = \frac{S_b}{\sqrt{3}V_b}$
- Base impedance $Z_b = \frac{V_b^2}{S_b} = \frac{V_b}{\sqrt{3} I_b}$
- Base torque $T_b = \frac{p S_b}{2 \omega_b}$
- RMS Base flux $\Psi_b = \frac{V_b}{\omega_b}$

The voltage rating is line-to-line for wye-connections. For delta-connections it is necessary to multiply this voltage by $\sqrt{3}$ to assure that the base impedance Z_b is 3 times larger than in the wye-connection.

Current, voltage and flux base quantities are RMS values. As a consequence a $\sqrt{2}$ factor is applied on the instantaneous values of current, voltage and flux if pu is requested in scopes and observables.

2 Parameters

2.1 Main data

- **Rated power:** Total 3-phase power rating of the machine. Used in the definition of base values upon which pu machine parameters are to applied.
- **cosa :** Power factor used if rated power has been specified in hp (=745.7 W) or in kW.
- **Rated line-to-line voltage:** Rated line-to-line stator terminal voltage.
- **Frequency:** Rated frequency of voltage feeding the machine
- **Reference frame:** 3 types of reference frame are possible: Fixed to the rotor, stationary or synchronous. All related machine quantities are calculated according to this selection. This affects the numerical performance of the machine. Using "synchronous" will provide faster convergence and smoother waveforms in most cases.
- **Load-Flow solution device:** See explanations in the Load-Flow section below.
- **Initialization method:** The machine can start from no initial conditions (option none) or from a steady-state computations (option steady-state). If the steady-state option is chosen, the steady-state slip is required. EMTP automatically calculates the steady-state torque. This constant torque will be taken as the external torque as long the "Controlled torque start time" is not exceeded when a mechanical torque control signal is available.
- **Use full Thevenin in wound rotor network:** This option is available only when the Steady-state initialization method is selected and for the wound rotor type. The steady-state solution requires the computation of the Thevenin impedance seen by the rotor. It is used to account for machine slip. When this option is off, only the diagonal terms of the Thevenin impedance matrix are retained. It is provided for two reasons: backward compatibility and simplified initialization. In several cases where the rotor circuit is connected to controlled switching devices, the simplified initialization may provide better (faster) initialization. When the connected network topology is

fixed, then the more precise full Thevenin impedance matrix should perform best. A demonstration of this option is given in the design:

[thevenin_matrix.ecf](#)

- **Simulate saturation:** Piecewise characteristic of the magnetization curve of the machine. Only the positive part is entered. The origin is assumed if not explicitly entered. It can be determined from the no-load test curve of the machine. The common saturation effect can be taken into account with the "Total saturation" option. "Separate Saturation" simulates saturation on d-axis separately from q-axis.

2.2 Electrical data

- **Data type:** allows selecting the type of data. The "Basic" option provides access only to required "Circuit Parameters". If the option "Enable Name Plate Input Calculator" is selected, the user can enter nameplate data and request the calculation of "Circuit Parameters". By clicking on the button "Calculate circuit parameters" an auxiliary program calculates the electrical parameters. To load found data into the "Circuit Parameters" section click on the appearing link "Load this Data into Circuit parameters". The electrical parameters are generated in per unit. The auxiliary calculator also takes into account the leakage saturation and the skin effect (Deep bar factor). You can continue changing the "Circuit Parameters" after finding them automatically. Only the "Circuit Parameters" section is seen in EMTP.
- **Rotor type:** allows selecting the type of rotor.
- **Simulate saturation of the leakage inductances:** If this option is chosen, 50% of the stator and rotor leakage inductances are assumed to saturate as a function of the stator and rotor currents. Saturation is assumed to start when the current is greater than saturation current I_{sat} . I_{sat} must be specified in pu if the "Nameplate input calculator" is used.
- **Rs:** Resistance of each stator coil
- **Lls:** Stator leakage inductance
- **Lmd:** d-axis main inductance
- **Lmq:** q-axis main inductance
- **Deep bar factor:** Special factor for skin effect in deep bars. Only available for single-cage-rotor.
- **Rr1:** Resistance of the rotor windings from stator side.
- **Llr1:** Rotor leakage inductance from stator side.
- **Rr2:** Resistance of the second squirrel cage from stator side (only for double cage rotor).
- **Llr2:** Leakage inductance of the second squirrel cage from stator side (only for double cage rotor).

2.3 Mechanical data

- **Lock rotor shaft for negative speed:** This option allows locking the rotor shaft if the external torque tends to make the rotor speed negative.
- **Number of masses:** allows specifying the number of masses to model the mechanical shaft. The rotor mass is included in this number.
- **Index of rotor mass:** allows specifying the mass number of the generator or motor rotor within the interconnected mass-spring shaft system. This number must be positive and lower or equal to the number of masses.
- **Mechanical parameters for the shaft system:** parameters that describe the masses and connections between masses. See the above section "Mechanical equations" for more details on the damping coefficients. It is allowed to specify the fraction (%) of the total external mechanical torque

which is associated with the given mass. If the total is greater than 100% a scaling factor will be applied.

- **Use inertia constant H (s) instead of Moment of inertia:** If this option is unchecked the moment of inertia of the selected mass is specified in kgm^2 . Otherwise the moment of inertia of the mass is specified through the inertia constant in s. This constant is defined as the ratio of the kinetic energy of the rotating mass at base speed to the rated power : $H = \frac{J\omega_{bm}^2}{2S_b}$ (31)
- **Observe, scope and control selections:** allows selecting the mechanical variables that need to be observed by a control system, or need to be available under the machine scopes, or need to be controlled by an external control system.
 - The mechanical angle of each mass (in rad) can be selected for scope and observe: the stator phase a is the origin of the angles.
 - The mechanical speed (in rad/s) of each mass can be selected for scope and observe.
 - The torque (in Nm) between the different sections of the shaft can be selected for scope and observe.
 - The shaft torque $T_{m_i_j}$ is the torque on the shaft section connecting masses i and $j=i+1$.
 - The steady-state mechanical torque applied on mass i can only be observed. The external torque applied on mass i can be controlled.
- **Use pu for Scope variables units:** allows obtaining all the scope signals in pu.
- **Use pu for observe and control variables units:** allows obtaining and generating all observe and control signals in pu.

2.4 Control

- **Total mechanical torque:** If this option is chosen the total torque applied on the mechanical shaft is controlled. If this option is selected the independent mechanical torque applied on each mass of the shaft system (specified in the mechanical data form) is no more available. Positive torque is used for motor operation and negative torque is used for generator operation.
- **Speed:** If this option is select then the Mechanical data tab is deactivated in EMTP calculations. The rotor Speed must be calculated externally and connected to Speed control pin.
- **Use pu for Control variables units:** allows using control signals in pu.

2.5 Observe/Scopes

- If the Observe option is selected, the corresponding signal becomes automatically available in the observe signal bundle of the machine.
- If the Scope option is selected, the selected variable will become available under machine scopes.
- **Use pu for Scope variables units:** allows obtaining all the scope signals in pu.
- **Use pu for Observe variables units:** allows obtaining all the observe signals in pu.

2.6 Precision

- **Damping factor:** Ratio between built-in damping resistors and discretized inductive elements used in the machine model. Reduce this number when numerical stability problems are encountered.
- **Rotor speed tolerance:** Relative tolerance associated with the iterative solution of rotor speed at each solution time-point.
- **Voltage convergence tolerance:** Relative tolerance associated with the iterative solution of voltage at the machine terminals at each solution time-point. In most cases, when the connected network is not weak, a larger value of tolerance can be used.
- **Maximum number of iterations in rotor speed computation:** Maximum number of iterations allowed in the calculation of rotor speed at each solution time-point
- **Apply maximum precision:** when this option is checked, an iterative procedure is applied to achieve full convergence of machine equations with network equations. Selecting this option provides an increased precision, but reduced computational speed.

More details are available in Figure 1

3 Rules

Since the symbol of this device is automatically redrawn to account for user specified configurations, it is not allowed to change it using the symbol editor, to delete pins and change pin or signal attributes.

4 Netlist format

This device allows method-based scripting. The object data and methods are described in the script file referenced by the device Script.Open.Dev attribute.

Example of data for a wound rotor induction machine:

```
_ASM;ASM1a;21;13;s225a,s226a,s227a,s228a,s229,s216ia,s216ic,s216i0,s216ibr2,s216i0r,s216iQ2,s216Pe,s216Angle,
1,2,?m,5,
_ASM;ASM1b;21;13;s225b,s226b,s227b,s228b,s229,s216ia,s216ic,s216i0,s216ibr2,s216i0r,s216iQ2,s216Pe,s216Angle,
_ASM;ASM1c;21;13;s225c,s226c,s227c,s228c,s229,s216ia,s216ic,s216i0,s216ibr2,s216i0r,s216iQ2,s216Pe,s216Angle,
R=11000 hp 0.906 6.6,
f=60 4 1,
I=2,0.4271,4,
S=1 0 1 2 2,
1 1.2
10 1.5
;
1 1.3
10 1.7
;
Rs=.02453,1
Ls=.0009132,1
Lmd=.04413,1
Lmq=.04413,1
RT=2,0
Lsat=1,6,1A
Rr1=.10948,1
Lr1=.0009130,1
```



```

Rr2= 0,1
Lr2= 0,1
Ms=1 2 1,
0.9 1000 0 0 1E2 0
0.1 200 0 0 0 0
3 3 3 1 0
3 3 0 0 0
MSu=0 0 0,
CTRLu=1,
CTRL=1 0,
PR=100 1e-06 1e-3 30 1,
OBSu=0 1,
OBS=2 1 2 0 2 0 1 0 0 2 1 0 2 0 0 0 0 0 0 0 1 0 0 2 0 2 1 0 0 2,

```

Field	Description
ASM	Part name
ASM1a	Instance name for the phase a stator coil, any name.
21	Total number of pins
13	Number of pins given in this data section
s225a	Signal name connected to k-pin of the stator phase a coil, any name
s226a	Signal name connected to m-pin (Neutral) of the stator phase a coil, any name
s227a	Signal name connected to k-pin of the rotor phase a coil, any name
s228a	Signal name connected to m-pin (Neutral) of the rotor phase a coil, any name
s229	Signal name connected to the control pin for external torque
s216ia,s216ic,s216i0, s216ibr2,s216i0r,s216iQ2, s216Pe,s216Angle,	Signal names contained in the control bundle for Observe variables.
1	Armature winding connection: 0 for Wye grounded, 1 for Wye, 2 for Delta.
2	Rotor type: 1 for single cage, 2 for single cage with deep bar factor, 3 for wound rotor, 4 for double squirrel cage
?m	Request for scopes, sent to scope group Machine, optional
5	Number of selected scopes
ASM	Part name
ASM1b	Instance name for the phase b stator coil, any name.
21	Total number of pins
13	Number of pins given in this data section
s225b	Signal name connected to k-pin of the stator phase b coil, any name
s226b	Signal name connected to m-pin (Neutral) of the stator phase b coil, any name
s227b	Signal name connected to k-pin of the rotor phase b coil, any name
s228b	Signal name connected to m-pin (Neutral) of the rotor phase b coil, any name
s229	Signal name connected to the control pin for external torque
s216ia,s216ic,s216i0,	Signal names contained in the control bundle for Observe

s216ibr2,s216i0r,s216iQ2, s216Pe,s216Angle,	variables.
ASM	Part name
ASM1c	Instance name for the phase c stator coil, any name.
21	Total number of pins
13	Number of pins given in this data section
s225c	Signal name connected to k-pin of the stator phase c coil, any name
s226c	Signal name connected to m-pin (Neutral) of the stator phase c coil, any name
s227c	Signal name connected to k-pin of the rotor phase c coil, any name
s228c	Signal name connected to m-pin (Neutral) of the rotor phase c coil, any name
s229	Signal name connected to the control pin for external torque
s216ia,s216ic,s216i0, s216ibr2,s216i0r,s216iQ2, s216Pe,s216Angle,	Signal names contained in the control bundle for Observe variables.
R=	Start rated values section
11000	Rated power
hp	Unit of rated power : hp, kW, kVA, MW or MVA
0.906	Power factor
6.6	Rated line-to-line voltage in kV
f=	Start other parameters section
60	Operating frequency
4	Number of poles
1	Armature winding connection: 0 for Wye grounded, 1 for Wye, 2 for Delta.
I=	Start initialization type section
2	Steady-state initialization (0 for no initial conditions, 2 for steady state)
0.4271	Steady state slip
4	Control torque start time in seconds
S=	Start saturation values section
1	Simulate saturation (0 for no saturation, 1 for saturation)
0	Total saturation (0 for no total saturation, 1 for total saturation)
1	Independent saturation (0 for no independent saturation, 1 for independent saturation)
1 1.2 10 1.5	Magnetization characteristic on d-axis (or both axis)
1 1.3 10 1.7	Magnetization characteristic on q-axis
Rs=	Start stator resistance section
.02453	Stator resistance
1	Units for stator resistance: 1, 1k, 1M or 1pu
Ls=	Start stator leakage inductance section
.0009132	Stator leakage inductance
1	Units for stator leakage inductance: 1uH, 1mH, 1, 1Ohm or 1pu
Lmd=	Start d-axis stator linkage inductance section
.04413	D-axis stator linkage inductance
1	Units for d-axis stator leakage inductance
Lmq=	Start q-axis stator linkage inductance section
.04413	Q-axis stator linkage inductance
1	Units for q-axis stator leakage inductance

RT=	Start rotor type section
2	Rotor type
0	Deep bar factor
Lsat=	Start leakage saturation data
1	Model leakage saturation when 1
6	Isat value
1A	Isat units (1pu or 1A)
Rr1=	Start rotor resistance section
.10948	Rotor resistance
1	Units for rotor resistance
Lr1=	Start rotor leakage inductance section
.0009130	Rotor leakage inductance
1	Units for rotor leakage inductance
Rr2=	Start second cage rotor resistance section
.0	Second cage rotor resistance
1	Units for rotor resistance
Lr2=	Start second cage rotor leakage inductance section
.0	Rotor leakage inductance
1	Units for rotor leakage inductance
Ms=	Start mechanical parameters section
1 2 1	Lock rotor shaft for negative speed (1 for locking) Number of masses Index of rotor mass
0.9 1000 0 0 1E2 0 0.1 200 0 0 0 0	Mechanical parameters table (2 masses in this example)
3 3 3 1 0 3 3 0 0 0	Observable, scope and control table
MSu=	Start mechanical parameters units specification section
0	Use H instead of moment of inertia
0	Use “pu” for mechanical scope variable units
0	Use “pu” for mechanical observe and control variable units
CTRLu=1	Use “pu” for mechanical control variable units
CTRL=	Start total controlled torque section
1	Control total external torque
1	Control rotor speed
PR=	Start precision control data section
100	Damping factor
1e-6	Rotor speed tolerance
1e-3	Voltage convergence tolerance
30	Maximum number of iteration in rotor speed computation
1	Use iterative process when 1
OBSu=	Start Scope and Observe in “pu” section
0	Use “pu” for scope variable units when 1
1	Use “pu” for observe variable units when 1
OBS=	Start Scope and Observe requests
2 1 2 0 2 0 1 0.....	Scope and Observe requests: 0 for none, 1 for scope request, 2 for observe request, 3 for scope and observe request.

5 Load-flow model

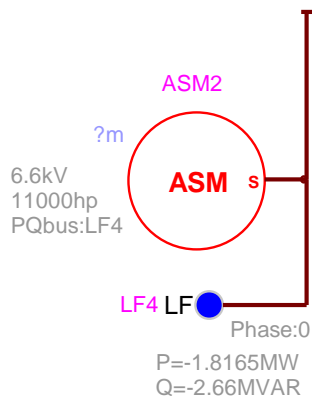
This device can refer to a “Load-Flow solution device”. Such a reference allows retrieving load-flow solution data for this machine from an LF (Load-Flow) device. A load-flow solution data file is automatically created by EMTP at the end of a load-flow solution.

If the “Load-Flow solution device” is blanked, then the machine participates into the Load-Flow solution if its “Steady-state slip” is specified and becomes disconnected otherwise. When the machine participates into the load-flow solution, its model is the same as the steady-state model presented below.

When the “Load-Flow solution device” (reference) is not blanked, the machine is disconnected in the load-flow solution and then at the end of the load-flow solution, the machine automatically calculates its sleep using its reference load-flow solution data. The calculated sleep becomes available through a separately and automatically saved data file (“Device load-flow data file”) and can be loaded into the machine data forms using the “Load now” button or *it is automatically retrieved by EMTP* for a subsequent simulation when “Start from Load-Flow solution” is turned on in the EMTP>Simulation Options. A subsequent simulation can be a Steady-state or a Time-domain simulation.

This option is not available for wound-rotor machines.

The “Load-Flow solution device” can be an LF device or “BUS:”. It establishes a link (a reference) for retrieving data from a load-flow solution. In this example (below) the machine ASM2 is disconnected in the load-flow solution and is referring to LF4 for its load-flow solution data.



If the selection is "BUS:" the connected stator signal name (bus) will be used to retrieve data. *You must enforce the signal name by making it visible.* This method is optional; it is suggested to use the LF device naming approach shown above.

The “Load now” button is displayed only when a load-flow solution file is available from a previous load-flow solution. It can be used to replace the entered steady-state slip value. This device is loading data using its own name as reference found in “Device load-flow data file”.

More help on the Load-Flow solution procedures can be found in the documentation section of the “Load-Flow” device.

6 Steady-state model

The steady-state equivalent circuit is shown in Figure 6.

The approach followed for the steady-state initialization of induction machines is to require the user to specify the desired rotor speed instead of the terminal voltage. The desired rotor speed is specified in terms of the slip (in %).

The steady-state initialization of the induction machine model is performed for only one frequency. Harmonic steady-state is not available in this release. The induction machine is disconnected from the rest of the network if the frequency of the sources is not equal to the rated frequency of the machine.

For wound rotor machines, the Thevenin equivalent circuit of the network connected to the rotor terminals is calculated. This network can be unbalanced. The steady-state initialization may give incorrect results if an external feedback between rotor and stator terminals exists. This version of EMTP replaces the Thevenin voltage by a short-circuit.

The slip is positive for motor operation and negative for generator operation.

The following steps are executed by the steady-state initialization procedure for the induction machine:

1. The induction machine device is replaced by positive sequence impedance for the steady-state solution. It is calculated from the specified slip.
2. From the steady-state solution and the given slip machine variables are found.
3. With the currents and voltages found in step 2, the electromagnetic torque is calculated. This torque will be taken as the total external torque as long as the "Controlled Torque Start Time" is not exceeded.

The above procedure does not require any iterations to find the machine variables.

With the steady-state initialization, a small transient can appear at the beginning of the simulation. This is related to the discretization method in time-domain equations. The user can decrease the simulation time-step to reduce the small transient at the beginning of the simulation. In some other situations, such as presence of a PWM circuit in the wound rotor circuit, the initialization method will use the initial state of the circuit and cannot account for the following firing process.

7 Initial conditions

Initial conditions are found from the steady-state solution and the given slip when the device is initialized in steady-state. State variables are automatically initialized for achieving quick steady-state in time-domain. The induction machine can also start with no initial conditions.

8 Frequency Scan model

The induction machine model with cage rotors can be used in frequency scan simulations. For each frequency it is replaced by a complex impedance calculated for the specified steady-state slip. The equivalent circuit presented in Figure 6 is used to calculate the complex impedance. The asynchronous machine with a wound rotor is disconnected from the rest of the network for a frequency scan solution.

9 Time-domain representation

The time-domain representation of the induction machine has been already explained in the previous sections.

In the time-domain solution this device is a nonlinear function. It is solved through the iterative procedures of EMTP until convergence according to the relative tolerance option for the given device.

EMTP uses an internal speed loop for each induction machine.

Two parameters controlling the speed loop and the voltage loop can be modified by the user. The Figure 9 shows the iterative process to solve the induction machine model.

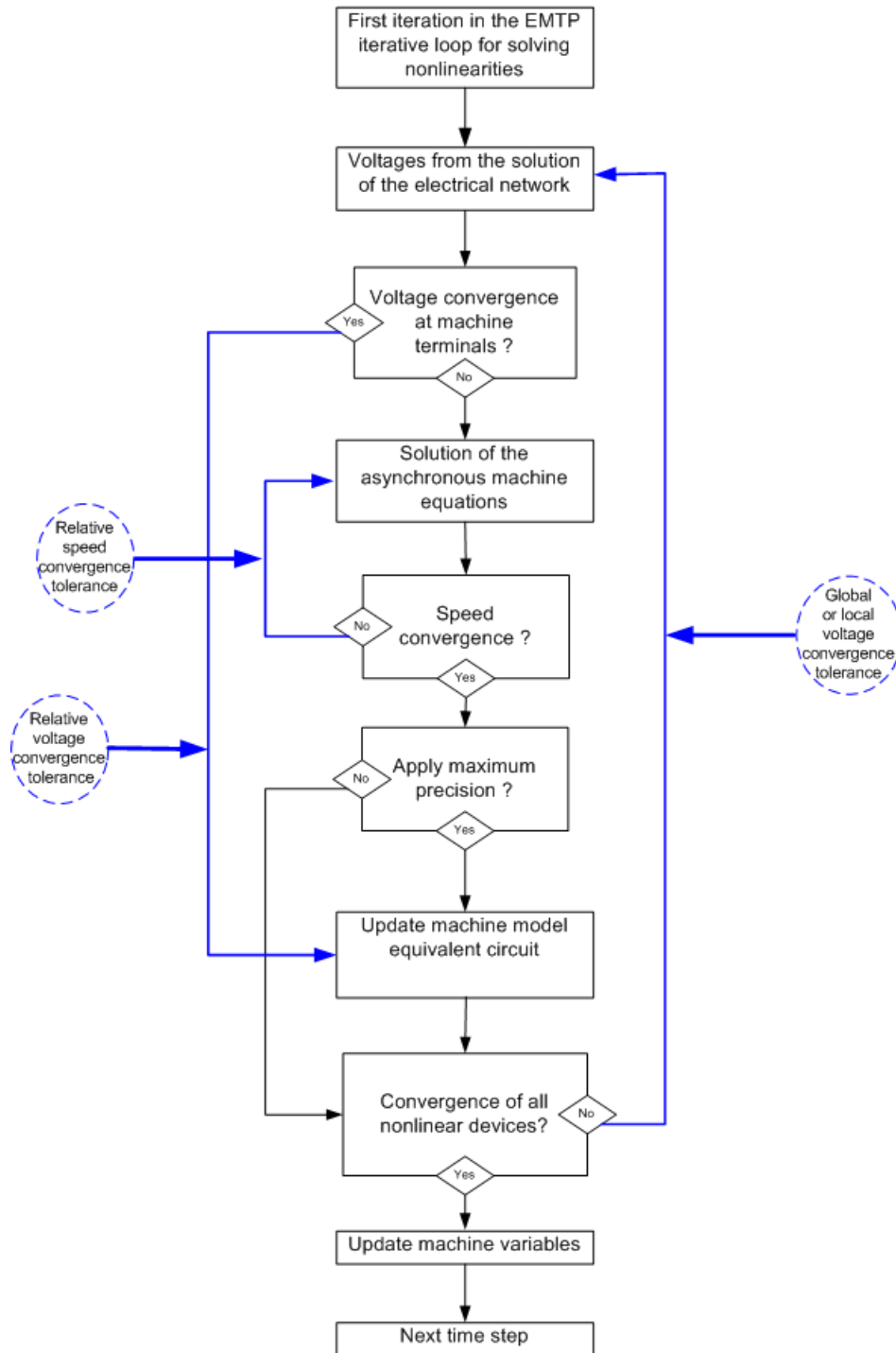


Figure 9 The iterative solution process: speed and voltage loops

The voltage convergence tolerance is an important simulation parameter for wound rotor machines (10^{-6} is recommended for better precision). This parameter is less important for the convergence of squirrel cage rotor machines (10^{-3} or less is sufficient). The user can change this parameter to increase the simulation speed. The voltage convergence is very quick when the connected network is not weak.

10 Example

This example is available in the Examples directory of EMTPWorks, under sync_and_async_machines\SM_ASM_EX.ecf. It is based on:

G. Rogers and D. Shirmohammadi, IEEE Transactions on Energy Conversion Vol. EC2, No.4, December 1987, pp. 622- 628.

Figure 10 shows the design.

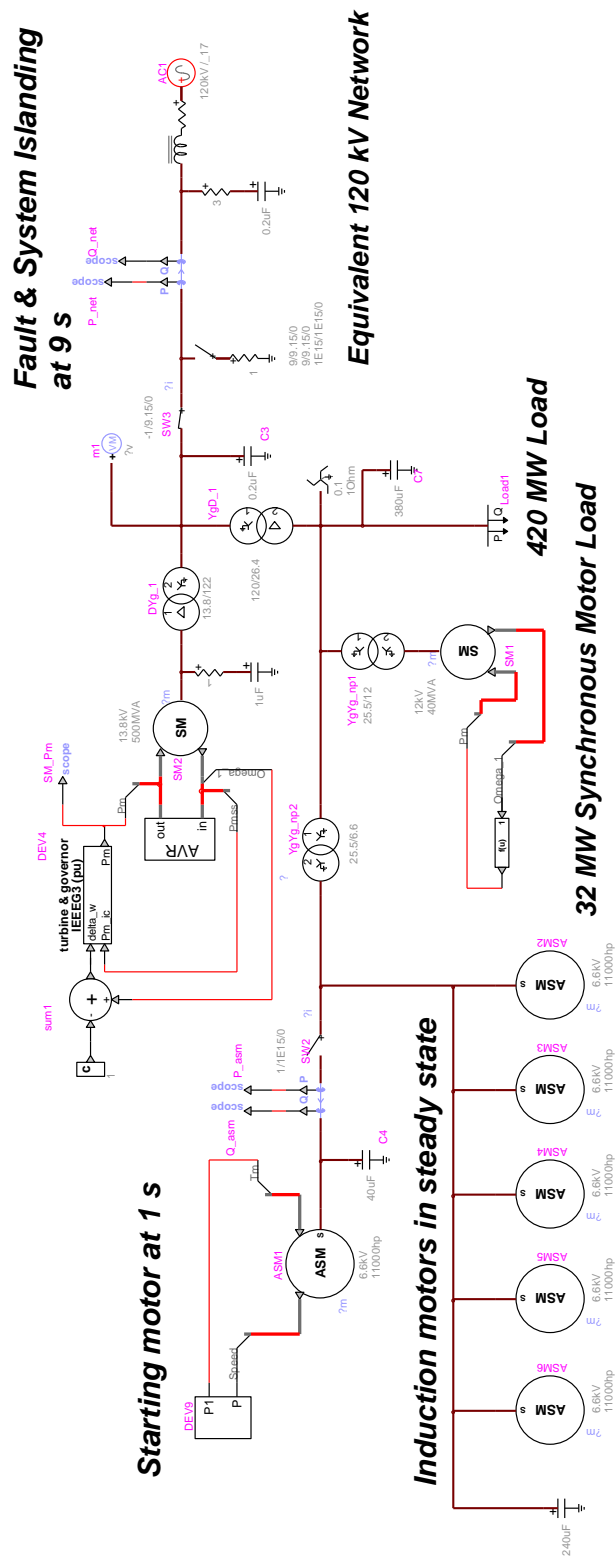


Figure 10 Example of induction machine and synchronous machine modeling (SM_ASM_EX.ecf)

There are 6 identical induction machines in this example. The characteristics of these machines are:

- ❑ Power : 11000 hp
- ❑ Nominal frequency : 60 Hz
- ❑ Terminal voltage : 6.6 kV
- ❑ Power factor : 0.906
- ❑ Nominal slip : 0.622 %
- ❑ Number of poles : 4
- ❑ Moment of inertia : 1200kgm²
- ❑ Stator winding connections : Wye grounded
- ❑ Equivalent circuit parameters :
 - $R_s = 0.02453\Omega$, $L_{ls} = 0.0009132H$, $L_{md} = 0.04413H$, $L_{mq} = 0.04413H$
 - $R_{r1} = 0.13218\Omega$, $R_{r2} = 0.04639\Omega$, $L_{lr2} = 0.00086H$

Five machines (ASM2 to ASM6) in this case are initialized in steady-state. Each machine is initialized with a user-defined steady-state slip. Their “Controlled Torque Start Time” has been set to a high value: the external torque is fixed to the electromagnetic torque calculated for the steady-state solution. That is why the input control pin for external torque is not used on these machines.

One induction machine (ASM1) is not initialized in steady-state, it starts at 1s from no initial conditions. The external torque on its rotor shaft is a function of speed:

$$T_{ext} = 0.0053 * \omega_r * 40000 + 4000$$

This type of torque represents a wind load. The “speed” observable signal is available in the observe bundle of the machine. A subcircuit has been made to calculate the external versus the rotor speed. The output of this subcircuit is directly connected to the control pin of the machine.

The different steps of this simulation are:

- ❑ Starting an 11000 hp motor at 1s with 5 induction machines already in steady-state.
- ❑ Line-Line to ground fault on the 120 kV bus with system islanding at 9s

Figure 11 shows the machine slips initialized in steady-state and Figure 12 shows the current in the stator of ASM1 during the line-line to ground fault.

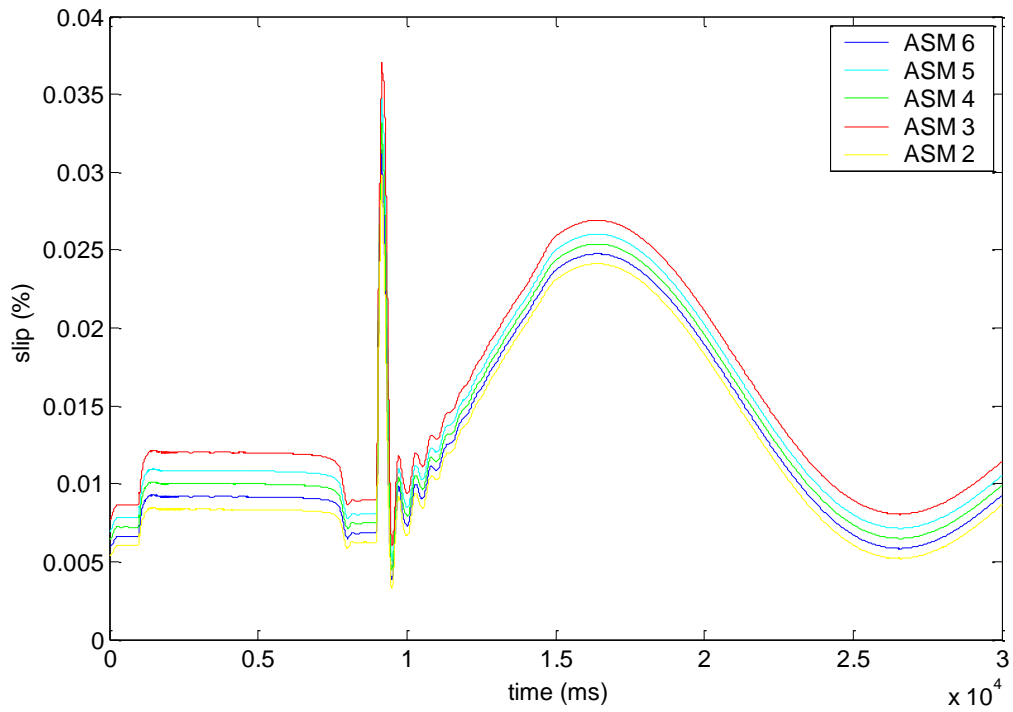


Figure 11 Machine slips initialized in steady-state

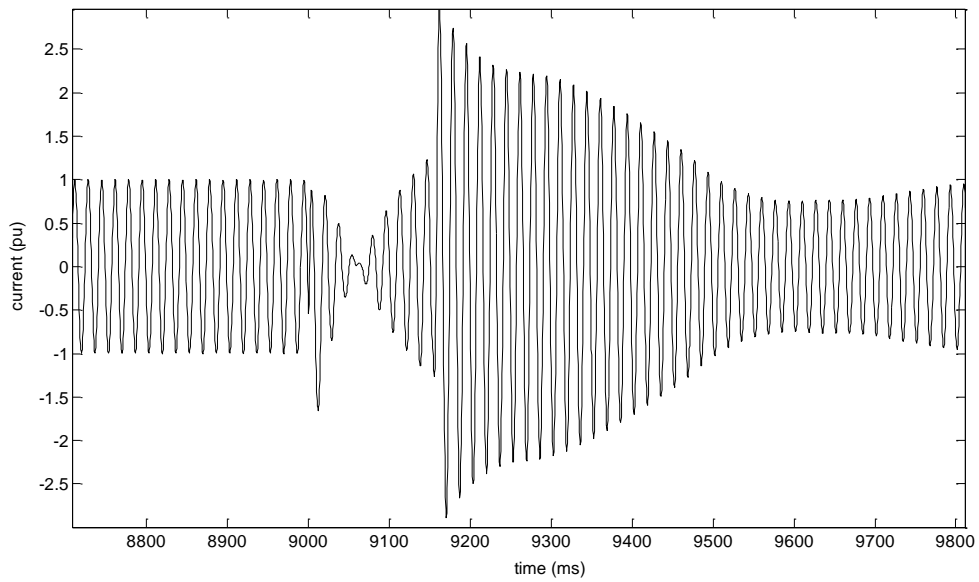


Figure 12 Phase a stator current in the induction machine ASM1 during the fault

11 References

- [1] G. J. Rogers, D. Shirmohammadi, "Induction machine modeling for electromagnetic transient program", IEEE Trans. On energy Conversion, Vol EC-2, No. 4, December 1987
- [2] Electromagnetic Transients Program (EMTP), EMTP-V3 Rule Book I, Development Coordination Group of EMTP, 1996.