Double phase induction machine device

DPIM2

0.25hp

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1 Description

This device is used to represent 2 types of double-phase induction machines: single-squirrel-cage or double-squirrel-cage.

1.1 The machine symbol

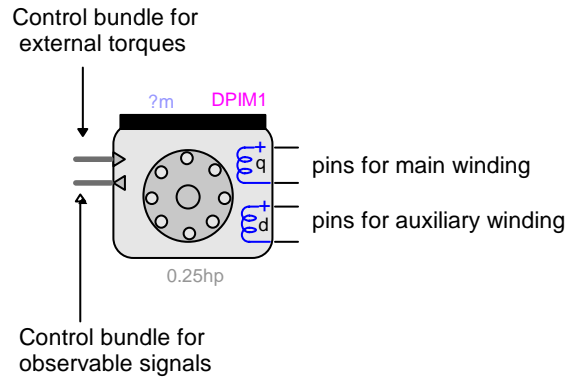The following figure presents the available device pins. All power pins are 1-phase. The control bundles are optional.

Figure 1 The double-phase induction machine

1.2 Theoretical summary

A 2-phase machine with identical rotor windings and nonsymmetrical stator windings is commonly considered as an unsymmetrical 2-phase induction machine. In the analysis of this type of machine, it is generally assumed that:

- Each stator winding is distributed to produce a sinusoidal mmf wave in space.
- The rotor coils or bars are arranged so that, for any fixed time, the rotor mmf waves can be considered as space sinusoids having the same number of poles as the corresponding stator mmf wave.
- The air gap is uniform.

In many applications these idealizing assumptions, which are usually made for symmetrical or unsymmetrical induction machines, offer a convenient and sufficiently accurate means of predicting the transients and steady-state characteristics of induction machines [1][2].

The equations which describe the transient and steady-state performance of an idealized unsymmetrical 2-phase machine can be established by considering the elementary 2-pole machine shown in Figure 2. Optional D2 and Q2 coils are used for representing double-squirrel-cage rotors.

Since it is assumed that each winding is distributed in such a way that it will produce a sinusoidal mmf wave, it is convenient to portray each winding as an equivalent single coil. The equivalent stator windings are in quadrature and are denoted as the d-winding and the q-winding. As the double-phase machine is commonly used for single-phase induction motors, the q-axis winding is named "main winding" and the d-axis winding is named "auxiliary winding".

The stator windings are unsymmetrical: the windings have an unequal resistance and an unequal number of turns. The rotor windings are also in quadrature.

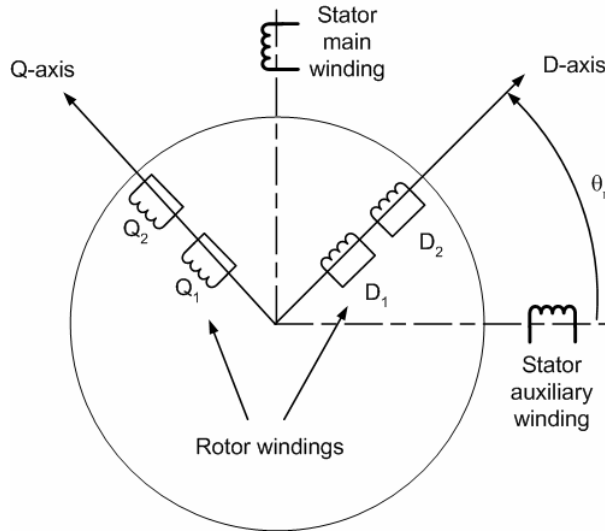This model has been based on the work presented in [3].

Figure 2 Unsymmetrical 2-phase induction machine

1.1.1 Variables used to define the induction machine model

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

Symbol	Description
P	Number of poles
ω_r	Electrical speed (rad/s)
θ_r	Electrical angle (rad/s)
ω_{rm}	Mechanical speed $\omega_{rm} = \left(\dfrac{2}{p}\right)\omega_r$
θ_{rm}	Mechanical angle $\theta_{rm} = \left(\dfrac{2}{p}\right)\theta_r$
ω_b	Base electrical speed (rad/s)
θ_b	Base electrical angle (rad/s)
ω_{bm}	Base mechanical speed $\omega_{bm} = \left(\dfrac{2}{p}\right)\omega_b$
θ_{bm}	Base mechanical angle $\theta_{bm} = \left(\dfrac{2}{p}\right)\theta_b$
s	Mechanical speed deviation (slip) $s = \dfrac{\omega_{bm} - \omega_{rm}}{\omega_{bm}}$
T_{eg}	Electromagnetic torque (Nm)

1.1.2 Main equations

The following equations will be written for a single-squirrel cage motor. Using the coupled-circuit approach and motor notation (currents entering into the windings), the voltage equations of the magnetically coupled stator and rotor circuits can be written as:

$$
\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} r_{qs} & 0 & 0 & 0 \\ 0 & r_{ds} & 0 & 0 \\ 0 & 0 & \hat{r}_{qr} & 0 \\ 0 & 0 & 0 & \hat{r}_{dr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} \dfrac{d\lambda_{qs}}{dt} \\ \dfrac{d\lambda_{ds}}{dt} \\ \dfrac{d\lambda_{qr}}{dt} \\ \dfrac{d\lambda_{dr}}{dt} \end{bmatrix}
\tag{1}
$$

The subscript s stands for stator and r for rotor.

The above equation is for a single-squirrel cage and λ is the flux linkage. The subscript s is used for quantities on the stator windings and the subscript r is used for rotor windings.

$$
\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{qr} \\ \lambda_{dr} \end{bmatrix} = \begin{bmatrix} L_{qs\ell} + L_{qsm} & 0 & L_{qsqr}\cos\theta_r & L_{qsdr}\sin\theta_r \\ 0 & L_{ds\ell} + L_{dsm} & -L_{dsqr}\sin\theta_r & L_{dsdr}\cos\theta_r \\ L_{qsqr}\cos\theta_r & -L_{dsqr}\sin\theta_r & \hat{L}_{qr\ell} + \hat{L}_{qrm} & 0 \\ L_{qsdr}\sin\theta_r & L_{dsdr}\sin\theta_r & 0 & \hat{L}_{dr\ell} + \hat{L}_{drm} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}
\tag{2}
$$

The hat symbol is used only for distinguishing from the final conversions given below. Inductances with the subscript ℓ represent leakage inductances and inductances with the subscript m are magnetization inductances.

Since the axes of the main and auxiliary stator windings are already orthogonal, the stationary qd axes may be aligned with the orthogonal axes of the physical windings. The cage rotor may be represented by a pair of equivalent qd symmetrical rotor windings. Choosing the qd reference frame on the asymmetrical stator, such that its q-axis is aligned with the axis of the qs winding and its d-axis with the ds winding, the rotor qd windings may be transformed to the chosen qd stationary reference frame using:

$$
\begin{bmatrix} f_{qr}^{S} \\ f_{dr}^{S} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} f_{qr}^{R} \\ f_{dr}^{R} \end{bmatrix}
\tag{3}
$$

where the variable f can represent the phase voltages, currents, or flux linkages of the qr and dr windings, and θ_r is electrical rotor angle between the axes of the qr (rotor) and qs (stator) windings. The superscript R means rotating and the superscript S means stationary.

Applying transformation to the previous equations we obtain the decoupled voltage equations on the stator side (same as in equation (1)):

$$
\begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} = \begin{bmatrix} r_{qs} & 0 \\ 0 & r_{ds} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} \dfrac{d\lambda_{qs}}{dt} \\ \dfrac{d\lambda_{ds}}{dt} \end{bmatrix}
\tag{4}
$$

For the rotor equations in the <u>stationary reference frame</u>:

$$
\begin{bmatrix} v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} r_r & 0 \\ 0 & r_r \end{bmatrix} \begin{bmatrix} i_{qr} \\ i_{dr} \end{bmatrix} + \omega_r \begin{bmatrix} -\lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + p \begin{bmatrix} \lambda_{qr} \\ \lambda_{dr} \end{bmatrix}
\tag{5}
$$

In this equation the <u>superscript S (for stationary) has been omitted</u> to simplify notation. Also it has been assumed that $r_r = \hat{r}_{qr} = \hat{r}_{dr}$. The differential of mechanical angle gives the electrical rotor frequency ω_r.

For the flux linkage relations in stationary reference frame:

$$\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{qr} \\ \lambda_{dr} \end{bmatrix} = \begin{bmatrix} L_{qs\ell} + L_{qsm} & 0 & L_{qsqr} & 0 \\ 0 & L_{ds\ell} + L_{dsm} & 0 & L_{dsdr} \\ L_{qsqr} & 0 & \hat{L}_{qr\ell} + \hat{L}_{qrm} & 0 \\ 0 & L_{dsdr} & 0 & \hat{L}_{dr\ell} + \hat{L}_{drm} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{6}$$

If is assumed that the permeance of the uniform gap is P_g then the winding inductance can be expressed in terms of their effective turns N_{qs}, N_{ds}, N_{qr} and N_{dr}. Normally $N_{qr} = N_{dr} = N_r$. The inductances are given by:

$$L_{qsm} = N_{qs}^2 P_g \tag{7}$$

$$L_{qsqr} = N_{qs} N_r P_g \tag{8}$$

$$L_{dsm} = N_{ds}^2 P_g \tag{9}$$

$$L_{dsdr} = N_{ds} N_r P_g \tag{10}$$

$$\hat{L}_{qrm} = N_r^2 P_g \tag{11}$$

$$\hat{L}_{drm} = N_r^2 P_g \tag{12}$$

$$\hat{L}_{qr\ell} = \hat{L}_{dr\ell} \tag{13}$$

$$\hat{L}_{qrm} = \hat{L}_{drm} \tag{14}$$

The rotor quantities are referred to the stator using transformation ratios:

$$v_{qr}' = \frac{N_{qs}}{N_r} v_{qr} \tag{15}$$

$$i_{qr}' = \frac{N_r}{N_{qs}} i_{qr} \tag{16}$$

$$v_{dr}' = \frac{N_{ds}}{N_r} v_{dr} \tag{17}$$

$$i_{dr}' = \frac{N_r}{N_{ds}} i_{dr} \tag{18}$$

If equations (15) to (18) are replaced into (5), the following set of equations is obtained:

$$v_{qr}' = r_{qr} i_{qr}' - \frac{N_{qs}}{N_{ds}} \omega_r \lambda_{dr}' + p\lambda_{qr}' \tag{19}$$

$$v_{dr}' = r_{dr} i_{dr}' + \frac{N_{ds}}{N_{qs}} \omega_r \lambda_{qr}' + p\lambda_{dr}' \tag{20}$$

with:

$$r_{qr} = \frac{N_{qs}^2}{N_r^2} r_r \tag{21}$$

$$r_{dr} = \frac{N_{ds}^2}{N_r^2} r_r \tag{22}$$

and:

$$r_{dr} = \left(\frac{N_{ds}}{N_{qs}} \right)^2 r_{qr} \tag{23}$$

In the case of equation (6) it is rewritten as:

$$\lambda_{qs} = L_{qs\ell} i_{qs} + L_{qsm} \left(i_{qs} + i_{qr}' \right) \tag{24}$$

$$\lambda_{ds} = L_{ds\ell}\, i_{ds} + L_{dsm}\left(i_{ds} + i'_{dr}\right) \tag{25}$$

$$\lambda'_{qr} = L_{qr\ell}\, i'_{qr} + L_{qsm}\left(i_{qs} + i'_{qr}\right) \tag{26}$$

$$\lambda'_{dr} = L_{dr\ell}\, i'_{dr} + L_{dsm}\left(i_{ds} + i'_{dr}\right) \tag{27}$$

with:

$$L_{qsm} = \left(\frac{N_{qs}}{N_r}\right)^2 \hat{L}_{qrm} = \frac{N_{qs}}{N_r} L_{qsqr} \tag{28}$$

$$L_{dsm} = \left(\frac{N_{ds}}{N_r}\right)^2 \hat{L}_{drm} = \frac{N_{ds}}{N_r} L_{dsdr} \tag{29}$$

$$L_{qr\ell} = \left(\frac{N_{qs}}{N_r}\right)^2 \hat{L}_{qr\ell} \tag{30}$$

$$L_{dr\ell} = \left(\frac{N_{ds}}{N_r}\right)^2 \hat{L}_{dr\ell} \tag{31}$$

thus:

$$L_{dr\ell} = \left(\frac{N_{ds}}{N_{qs}}\right)^2 L_{qr\ell} \tag{32}$$

$$L_{dsm} = \left(\frac{N_{ds}}{N_{qs}}\right)^2 L_{qsm} \tag{33}$$

1.1.3 Equivalent circuit

Previous equations are used to deduce the equivalent circuit for the single-squirrel cage rotor shown in Figure 3. The voltages v'_{qr} and v'_{dr} are zero. The leakage and magnetization inductances can be made saturable.

These equivalent circuits are assembled and solved in EMTP-RV. It is noticed that in some notations on the device data web the following equalities must be applied to match the actual variables used in the equations above and in the equivalent circuits:

$N_{ds} = N_d$

$N_{qs} = N_q$

$v_d = v_{ds}$

$i_d = i_{ds}$

$i_{D1} = i'_{dr}$

$v_q = v_{qs}$

$i_q = i_{qs}$

$i_{Q1} = i'_{qr}$

$L_{qs\ell} = L_{qsl} = L_{sq}$

$L_{qr\ell} = L_{qrl}$

$$L_{ds\ell} = L_{dsl} = L_{sd}$$
$$L_{dr\ell} = L_{drl}$$
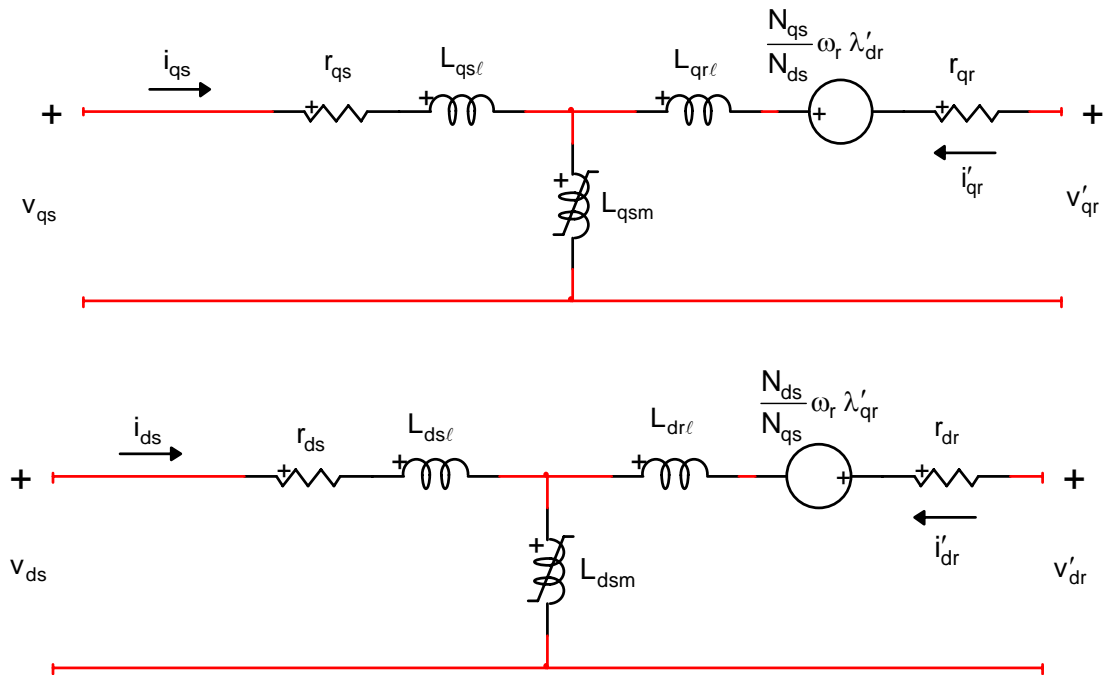
Figure 3 Equivalent circuits of a double-phase induction machine (single-squirrel cage)

1.1.4 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:

$$J\frac{d\omega_{rm}}{dt} + D\,\omega_{rm} = T_e - T_{turbine} \tag{34}$$

where:
- ❑   J is the moment of inertia of rotating turbine 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 motor

Modeling the mechanical part of an induction machine with a single mass representation is not sufficiently accurate in some situations.

The mechanical part of the double-phase induction machine model in EMTP 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 4 shows a typical 3-mass model.

Figure 4 Mechanical part 3-mass model

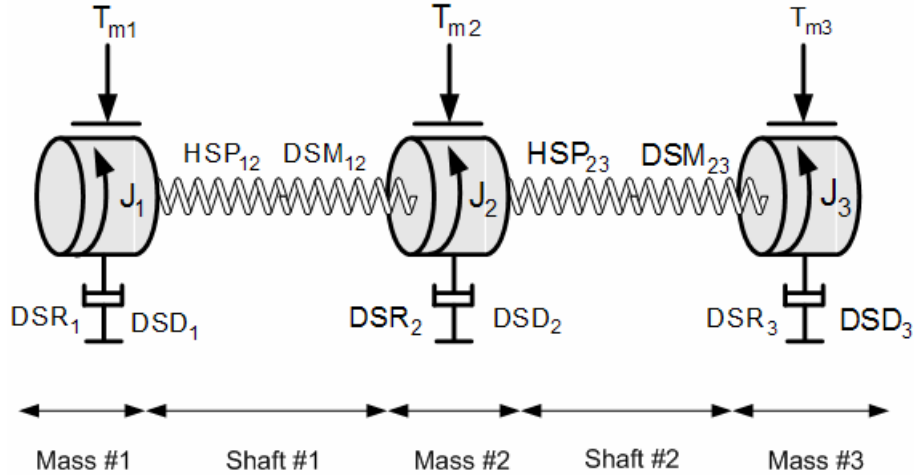The shaft/rotor system is assumed to be linear, which is reasonable for the small amplitudes of torsional vibrations. The n-spring-connected rotating masses are then described by the rotational form of Newton's second law:

$$\mathbf{J}\frac{d\boldsymbol{\omega}_{rm}}{dt}+\mathbf{D}\,\boldsymbol{\omega}_{rm}+\mathbf{HSP}\,\boldsymbol{\theta}_{rm}=\mathbf{T}_e-\mathbf{T}_{turbine} \tag{35}$$

where:

$\mathbf{J}$ is the diagonal matrix of moments of inertia (J_1, J_2 and J_3 in Figure 4)

$\boldsymbol{\omega}_{rm}$ 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 ($\mathbf{T}_{m1}$, $\mathbf{T}_{m2}$ and $\mathbf{T}_{m3}$ in Figure 4)

$\mathbf{T}_e$ 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 $\theta_{rm\,i}-\theta_{rm\,i+1}$. The proportionality factor is the stiffness coefficient or spring constant $HSP_{i\,i+1}$. This spring action torque acts in opposite directions on masses i-1 and i:

$$T_{spring\,i-1}=-T_{spring\,i}=HSP_{i-1\,i}\left(\theta_{rm\,i-1}-\theta_{rm\,i}\right) \tag{36}$$

From equation (36) it can be seen that the **HSP** matrix has the following form (3 masses):

$$\mathbf{HSP}=\begin{bmatrix} HSP_{12} & -HSP_{12} & 0 \\ -HSP_{12} & HSP_{12}+HSP_{23} & -HSP_{23} \\ 0 & -HSP_{23} & HSP_{23} \end{bmatrix} \tag{37}$$

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

$$T_{damping\,i}=DSD_i\,\omega_{rm\,i}+DSM_{i-1\,i}\left(\omega_{rm\,i}-\omega_{rm\,i-1}\right)+DSM_{i\,i+1}\left(\omega_{rm\,i}-\omega_{rm\,i+1}\right) \tag{38}$$

From equation (38) it can be seen that **D** has the same structure as **HSP** except that the diagonal element is now $DSD_i+DSM_{i-1\,i}+DSM_{i\,i+1}$:

$$\mathbf{D} = \begin{bmatrix} DSD_1 + DSM_{12} & -DSM_{12} & 0 \\ -DSM_{12} & DSD_2 + DSM_{12} + DSM_{23} & -DSM_{23} \\ 0 & -DSM_{23} & DSD_3 + DSM_{23} \end{bmatrix} \tag{39}$$

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

$$T_i = DSR_i \left(\omega_{m\,i} - \omega_{bm} \right) \tag{40}$$

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.

1.1.5 Saturation

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

❑ **Saturation of the magnetizing inductances**

The saturation is in principle dependent on the electrical current in every circuit. That is why the double phase 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:

$$\Psi_m = \sqrt{\Psi_{md}^2 + \Psi_{mq}^2} \tag{41}$$

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 saturation of the leakage reactances is chosen in EMTP, 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 the specified saturation current (I_{sat}). The saturable portion of the leakage reactance reduces as the current increases in the manner of the describing function for saturation nonlinearity. This saturation model was shown to be suitable in [1]. Contrary to the asynchronous 3-phase machine, saturation is not balanced on d and q axis: each leakage inductance is calculated from the current flowing in its corresponding winding.

The saturation describing function is the ratio of the amplitude of the fundamental component of a sinusoid clipped at the saturation level to the full amplitude of the sinusoid exceeds more and more the saturation level. That is :

$$\begin{aligned} DF(y) &= \frac{2}{\pi}\left(\arcsin y + y\sqrt{1-y^2} \right) \qquad y \le 1 \\ DF(y) &= 1 \qquad\qquad\qquad\qquad\qquad y > 1 \end{aligned} \tag{42}$$

For a saturable reactance $y = \left| \dfrac{I_{sat}}{I} \right|$

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.

1.3 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 (connected) 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 the "Controlled torque start time" is not exceeded.

1.4 Base quantities

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

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

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 rated power of the machine. Used in the definition of base values upon which pu machine parameters are to applied.
- **cosα** : Power factor used if rated power has been specified in hp (=745.7 W) or in W, kW, MW.
- **Rated voltage**: Rated stator terminal voltage.
- **Frequency**: Rated frequency of voltage feeding the machine
- **Winding turn ratio**: winding turn ratio $\frac{N_d}{N_q} = \frac{N_{ds}}{N_{qs}}$ between main and auxiliary windings.
- **Initialization method**: The machine can start from no initial conditions (option none) or from a steady-state computation (option steady-state) of initial conditions. 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. The machine can be initialized without its auxiliary winding if the checkbox "Disable auxiliary winding" is checked. The auxiliary winding will remain connected in the Time-domain solution.
- **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. 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

- **Rotor type**: allows selecting the type of rotor. User can choose single squirrel cage or double-squirrel-cage.
- r_{qs} : Resistance of main stator coil
- $L_{qs\ell}$: Stator leakage inductance, main winding
- L_{qsm} : q-axis magnetizing inductance
- r_{qr} : First cage rotor resistance, main axis
- $L_{qr\ell}$: First cage rotor leakage inductance, main axis.
- r_{Qr} : Second cage rotor resistance, main axis (If double cage is chosen)
- $L_{Qr\ell}$: Second cage rotor leakage inductance, main axis (If double cage is chosen)
- r_{ds} : Resistance of auxiliary stator coil
- $L_{ds\ell}$: Stator leakage inductance, auxiliary winding
- L_{dsm} : d-axis magnetizing inductance (must respect equation (33))
- r_{dr} : First cage rotor resistance, auxiliary axis (must respect equation (23))
- $L_{dr\ell}$: First cage rotor leakage inductance, auxiliary axis (must respect equation (32))
- r_{Dr} : Second cage rotor resistance, auxiliary axis (If double cage is chosen, related to r_{Qr} as r_{dr} to r_{qr})

- $L_{Dr\ell}$: Second cage rotor leakage inductance, auxiliary axis (If double cage is chosen, related to $L_{Qr\ell}$ as $L_{dr\ell}$ to $L_{qr\ell}$)
- **Saturation of 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 a saturation current (I_{sat}) specified by the user.

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 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 : $H = \dfrac{J\omega_{bm}^2}{2S_b}$ (43)
- **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 Tm_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.

- **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.

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.
- **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 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.

More details are available in Figure 5.

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 single-squirrel cage rotor induction machine:

```
_DPIM;DPIM1;6;6;qk,qm,dk,dm,s7Tm,s8vd,
1,0.25hp,110,60,1.18,4,0,28,1e15,0,1,2.02,2.79Ohm,66.8Ohm,7.14,3.22Ohm,9
2.9Ohm,4.12,2.12Ohm,4.12,
2.12Ohm,4.12,2.12Ohm,5.74,2.95Ohm,0,12A,
S=0 1 0 0 1,
1 1
;
MS=1 1 1,
1 1.46e-2 0 0 0 0
```

```
0 0 0 0 0
MSu=0 0 0,
PR=100 1e-06 1e-6 30 1,
CTRLu=0,
CTRL=1,
OBSu=0 0,
OBS=2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0,
```

Field	Description
DPIM	Part name
DPIM1	Instance name any name.
6	Total number of pins
6	Number of pins given in this data section
qk	Signal name connected to k-pin of the stator main coil, any name
qm	Signal name connected to m-pin of the stator main coil, any name
dk	Signal name connected to k-pin of the stator auxiliary coil, any name
dm	Signal name connected to m-pin of the stator auxiliary coil, any name
s7Tm	Signal names contained in the control bundle for Control variables.
s8vd	Signal names contained in the control bundle for Observe variables.
1	Rated power unit (1 for hp)
0.25hp	Rated power
110	Rated voltage
60	Rated frequency
1.18	Winding turn ratio
4	Number of poles
0	Initialization method (0 for none, 2 for steady-state)
28	Steady-state slip
0	Disable auxiliary winding when 1
1	Rotor type (1 for single cage, 3 for double cage)
2.02	Stator resistance main winding
2.79Ohm	Stator leakage inductance, main winding
66.8Ohm	Magnetization inductance, main axis
7.14	Stator resistance auxiliary winding
3.22Ohm	Stator leakage inductance, auxiliary winding
92.9Ohm	Magnetization inductance, auxiliary axis
4.12	First cage rotor resistance, main axis
2.12Ohm	First cage rotor leakage inductance, main axis
4.12	First cage rotor resistance, auxiliary axis
2.12Ohm	First cage rotor leakage inductance, auxiliary axis
4.12	Second cage rotor resistance, main axis
2.12Ohm	Second cage rotor leakage inductance, main axis
5.74	Second cage rotor resistance, auxiliary axis
2.95Ohm	Second cage rotor leakage inductance, auxiliary axis
0	Leakage inductance saturation when 1
12A	Saturation current Isat
?m	Request for scopes, scope group machine
22	Number of scope outputs
S=	Start saturation values section

1	Simulate saturation (0 for no saturation, 1 for saturation)
0	Total saturation (1 for total saturation)
1	Independent saturation (1 for independent saturation)
2	Number of points on d-axis characteristic
2	Number of points on q-axis characteristic
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
Ms=	Start mechanical parameters section
1 1 1	Lock rotor shaft for negative speed (1 for locking, 0 for don't lock) Number of masses Index of rotor mass
1 1.46e-2 0 0 0 0	Mechanical parameters table (1 mass in this example)
0 0 0 0 0	Observe, scope and control table data
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	Controlled external torque when 1
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
1	Use "pu" for scope variable units when 1
1	Use "pu" for observe variable units when 1
OBS=	Start Scopes and Observes requests
2 0 0 0 0 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 machine is connected in the Load-Flow solution only when its stead-state slip is specified.

6 Steady-state model

The steady-state equivalent circuits are the frequency domain versions of the circuits shown in Figure 3.
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.

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 and negative 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 and taken as the total external torque as long as the "Controlled torque start time" is not exceeded.

The above procedure does not require any iteration 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.
The machine can be initialized without its auxiliary winding if the checkbox "Disable auxiliary winding" is checked. The auxiliary winding is always connected in Time-domain. If auxiliary winding is disabled a "floating network" warning can be avoided in time-domain solution by connecting high resistances to ground as shown from d-winding pins.

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 rotor can be used in frequency scan simulations. For each frequency it is replaced by complex impedance calculated for the specified steady-state slip. The equivalent circuit presented in **Error! Reference source not found.** is used to calculate the complex impedance. The steady-state slip must be specified.

9 Time-domain representation

The time-domain representation of the double phase 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 5 shows the iterative process to solve the double-phase induction machine model.
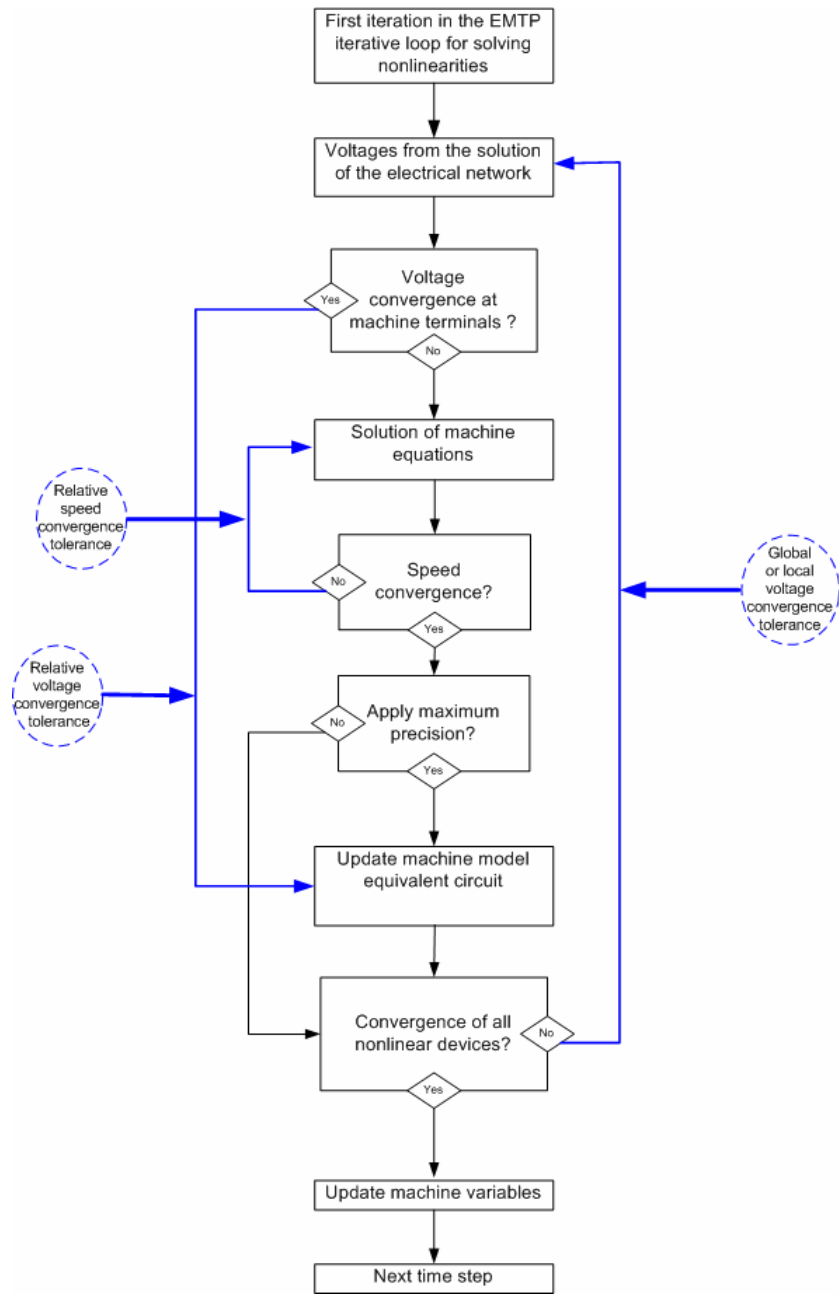
Figure 5 The iterative solution process: speed and voltage loops

10 References

[1]   D. C. White and H. H. Woodson, "Electromechanical Energy Conversion", New York, Wiley, 1959.

[2]   C. G. Veinott, "Theory and Design of Small Induction Motors. New York", McGraw-Hill, 1959.

[3]   Chee-Mun Ong, "Dynamic simulation of electric machinery using Matlab® / Simulink, Prentice-Hall Ptr, 1998.