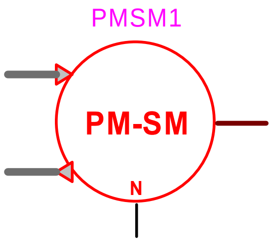
Permanent Magnet Synchronous Machine device



1 Description

This device is used to represent the usual design of a permanent magnet synchronous machine with 3-phase ac armature windings on the stator. Up to 3 windings may be modeled on rotor d-q axis.
The model represents both generator and motor behavior.

1.1 The permanent magnet synchronous machine symbol

The permanent magnet synchronous machine device is a 3-phase device. Its symbol is automatically updated according to internal winding configuration. The following figure presents available device pins.

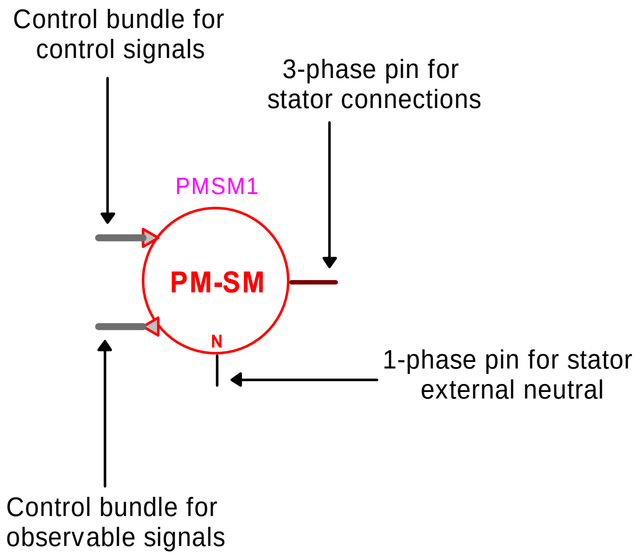


Figure 1 The permanent magnet synchronous machine symbol

1.2 Theoretical summary

A detailed background to the machine modeling method can be found in [1] which is also referring to previously available EMTP models. The model developed for this version of EMTP is based on the synchronous machine model. Details on the new techniques will become available in documents attached to a future release of EMTP.
The aim of this section is to provide some background notions that can help understanding the modeling approach and the data requirements.
The following table presents a listing of the main variables used in the formulation of the machine equations.

Symbol	Description
v_d, v_q, v_0	Stator voltages in dq0 domain
$v_{D1} = v_{D2} = v_{D3} = v_{Q1} = v_{Q2} = v_{Q3} = 0$	All rotor voltages equal zero.
i_d, i_q, i_0	Stator currents in dq0 domain
$i_{D1}, i_{D2}, i_{D3}, i_{Q1}, i_{Q2}, i_{Q3}$	Rotor currents on d and q axis
p	Number of poles
ω_{el}	Electrical speed (rad/s)
ω	Mechanical speed $\omega = \left(\frac{2}{p}\right)\omega_{el}$
ω_b	Base electrical speed (rad/s)

ω_{bm}	Base mechanical speed $\omega_{bm} = \left(\frac{2}{p}\right)\omega_b$

The Park's transformation is initially used with saturation neglected so as to obtain linear relations and apply superposition.
It is assumed that the resistance of each winding is constant.

The magnetic circuits of the rotor windings are assumed to be symmetric with respect to the direct axis, which is the axis of the field created by the rotor. The quadrature axis is located 90 degrees behind the direct axis.

The self and mutual inductances of the armature windings are a constant plus a second harmonic sinusoidal function of the rotor position. The mutual inductances between any winding of the field structure and any armature winding is a sinusoidal function of the rotor position.

A current in any winding produces a magnetic field in the air gap with sinusoidal distribution. It can be decomposed along the direct and quadrature axes. With this assumption, the effect of harmonics in field distribution is negligible for a correctly dimensioned machine.

The hysteresis effects are neglected.

Eddy currents are negligible, except in the case of a solid rotor (cylindrical rotor) machine where they can be represented by a q-axis winding.

In this version of EMTP, the permanent magnet synchronous machine consists of 9 windings :

- ☐ 3 for the stator, one for each phase. They are denoted with the indices a, b, c, respectively.
- ☐ 6 for the rotor. On the axis of the rotor field created by the permanent magnet, which is the direct axis, there are a maximum of 3 damper windings denoted by D_1, D2 and D3. On the quadrature axis, there are a maximum of 3 damper windings denoted Q1, Q2 and Q3.

The machine is represented by the diagram of Figure 2.

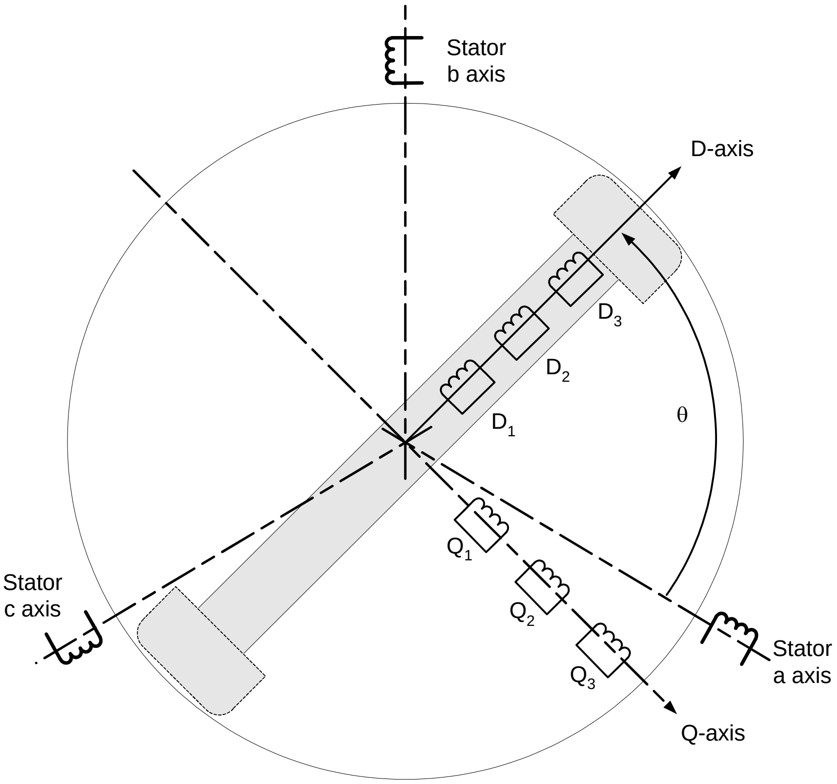


Figure 2 Schematic representation of the machine in DQ

The Park's transformation matrix is defined by:

$$\mathbf{P} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) & 0 & 0 & 0 & 0 & 0 & 0 \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sqrt{\frac{3}{2}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sqrt{\frac{3}{2}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sqrt{\frac{3}{2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sqrt{\frac{3}{2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sqrt{\frac{3}{2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sqrt{\frac{3}{2}} \end{bmatrix} \qquad (1)$$

This transformation is power invariant. Physically, the three coils of the stator are replaced by three windings 0, d, q revolving at the speed of the rotor and giving the same field and the same induced voltage. The speed of the reference frame is:

$$\omega_{el} = \frac{d\theta}{dt} \tag{2}$$

The schematic representation of the machine is now given by the diagram of Figure 3.

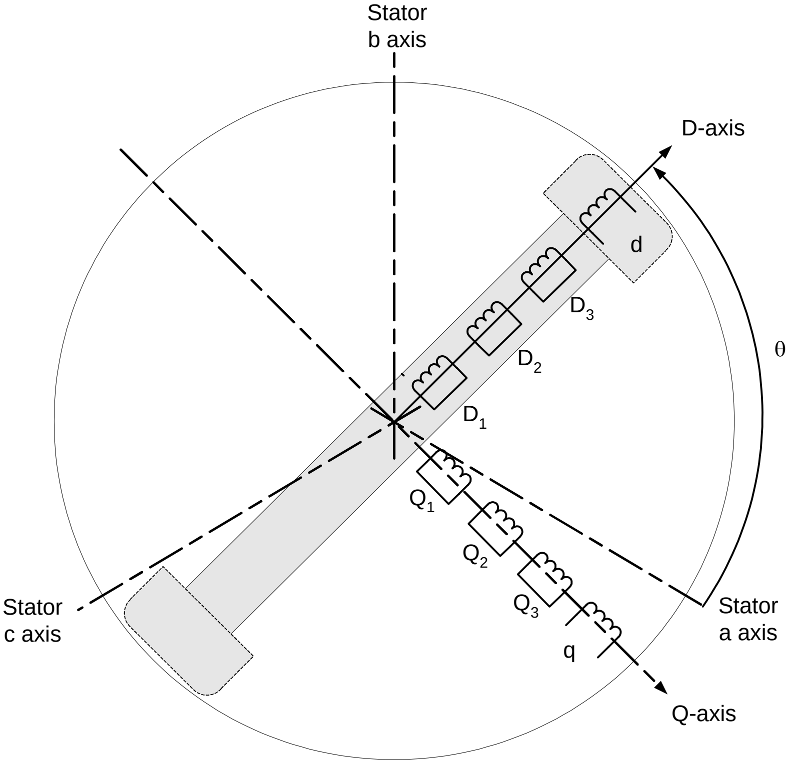


Figure 3 Schematic representation of the machine after Park's transformation

1.2.1 Flux equations

The permanent magnet generates a constant d-axis flux Ψ_m. It is represented by an inductance in parallel with a constant current source. By definition:

$$\Psi_m = L_m I_m \tag{3}$$

Figure 4 shows the d-axis equivalent circuit of a permanent magnet synchronous machine with 1 damper.

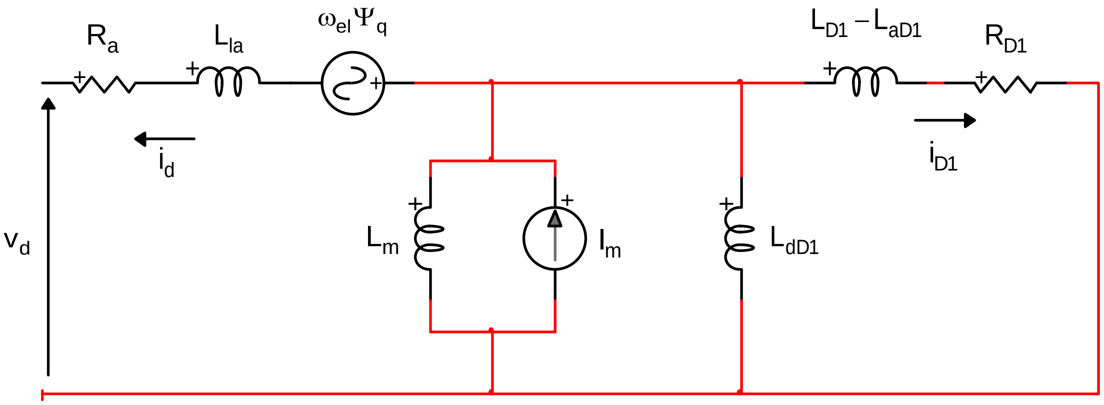


Figure 4 Equivalent d-axis circuit of a permanent magnet synchronous machine with 1 damper

The circuit consists of a maximum 9 coupled windings and a permanent magnet. By knowing the expression of each winding inductance as a function of θ, writing the relation between fluxes and currents in phase-domain and applying the Park's transformation of (1) results into:

$$\begin{bmatrix}\Psi_d\\ \Psi_q\\ \Psi_0\\ \Psi_{D1}\\ \Psi_{D2}\\ \Psi_{D3}\\ \Psi_{Q1}\\ \Psi_{Q2}\\ \Psi_{Q3}\end{bmatrix} = \begin{bmatrix} L_d & 0 & 0 & M_{dD1} & M_{dD2} & M_{dD3} & 0 & 0 & 0\\ 0 & L_q & 0 & 0 & 0 & 0 & M_{qQ1} & M_{qQ2} & M_{qQ3}\\ 0 & 0 & L_0 & 0 & 0 & 0 & 0 & 0 & 0\\ M_{dD1} & 0 & 0 & L_{D1} & M_{D1D2} & M_{D1D3} & 0 & 0 & 0\\ M_{dD2} & 0 & 0 & M_{D1D2} & L_{D2} & M_{D2D3} & 0 & 0 & 0\\ M_{dD3} & 0 & 0 & M_{D1D3} & M_{D2D3} & L_{D3} & 0 & 0 & 0\\ 0 & M_{qQ1} & 0 & 0 & 0 & 0 & L_{Q1} & M_{Q1Q2} & M_{Q1Q3}\\ 0 & M_{qQ2} & 0 & 0 & 0 & 0 & M_{Q1Q2} & L_{Q2} & M_{Q2Q3}\\ 0 & M_{qQ3} & 0 & 0 & 0 & 0 & M_{Q1Q3} & M_{Q2Q3} & L_{Q3}\end{bmatrix} \begin{bmatrix} i_d\\ i_q\\ i_0\\ i_{D1}\\ i_{D2}\\ i_{D3}\\ i_{Q1}\\ i_{Q2}\\ i_{Q3}\end{bmatrix} + \begin{bmatrix}\Psi_m\\ 0\\ 0\\ \Psi_m\\ \Psi_m\\ \Psi_m\\ 0\\ 0\\ 0\end{bmatrix} \qquad (4)$$

where M_{ij} gives the mutual inductance between coils i and j.

1.2.2 Voltage equations

The rotor consists of 6 windings : 6 short-circuited damper windings D1, D2, D3, Q1, Q2 and Q3. For the stator, there are two possible setups: Wye (Y) or Delta-connection of the windings. Owing to the symmetry of the stator circuit the resistances of the windings of the stator are equal and constant:

$$r_a = r_b = r_c = R_a \qquad (5)$$

Taking the Y connection circuit and establishing the Kirchoff's law for each phase, results into a relation that can be again rewritten through Park's transformation:

$$\begin{bmatrix} v_d\\ v_q\\ v_0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\end{bmatrix} = -\begin{bmatrix} R_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & R_a & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & R_a & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & r_{D1} & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & r_{D2} & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & r_{D3} & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & r_{Q1} & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_{Q2} & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_{Q3}\end{bmatrix} \begin{bmatrix} i_d\\ i_q\\ i_0\\ i_{D1}\\ i_{D2}\\ i_{D3}\\ i_{Q1}\\ i_{Q2}\\ i_{Q3}\end{bmatrix} - \frac{d}{dt}\begin{bmatrix}\Psi_d\\ \Psi_q\\ \Psi_0\\ \Psi_{D1}\\ \Psi_{D2}\\ \Psi_{D3}\\ \Psi_{Q1}\\ \Psi_{Q2}\\ \Psi_{Q3}\end{bmatrix} + \begin{bmatrix} -\omega_{el}\Psi_q\\ \omega_{el}\Psi_d\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\end{bmatrix} \qquad (6)$$

where r gives the resistance of the winding.

1.2.3 Modeling saturation

To increase the accuracy of this model it is necessary to introduce saturation. The relation giving the flux with respect to the currents is no longer linear; it is not represented by a single straight line. It is difficult to model saturation very accurately. The data requirements can also become problematic. The following approximations have been made in EMTP:

- ☐ EMTP decomposes each flux into a leakage flux and an air gap flux for each of the windings. The leakage flux Ψ_{li} is a flux passing only through the relevant winding i. It does not affect the other coils. Its path lies mainly in air. Thus, for the software this flux is not saturable. On the other hand the air-gap flux Ψ_{mi} is considered to cross all the windings for each of the axes. EMTP does not consider any flux crossing two windings without passing through the third (for saturation calculations only). Its path lies mainly in iron. It will consequently be subject to saturation.
- ☐ The homopolar flux Ψ_0 is not saturable.

The following equation separates the leakage flux from the mutual flux:

$$\begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_0 \\ \Psi_{D1} \\ \Psi_{D2} \\ \Psi_{D3} \\ \Psi_{Q1} \\ \Psi_{Q2} \\ \Psi_{Q3} \end{bmatrix} = \begin{bmatrix} \Psi_{ld} \\ \Psi_{lq} \\ \Psi_0 \\ \Psi_{lD1} \\ \Psi_{lD2} \\ \Psi_{lD3} \\ \Psi_{lQ1} \\ \Psi_{lQ2} \\ \Psi_{lQ3} \end{bmatrix} + \begin{bmatrix} \Psi_{md} \\ \Psi_{mq} \\ 0 \\ \Psi_{md} \\ \Psi_{md} \\ \Psi_{md} \\ \Psi_{mq} \\ \Psi_{mq} \\ \Psi_{mq} \end{bmatrix} \qquad (7)$$

Here Ψ_{ld} is the leakage flux and Ψ_{md} is the flux linking all d-axis windings (total flux minus leakage flux). The permanent flux created by the permanent magnet is included in Ψ_{md}.
There are two options for modeling saturation: independent and total saturation.

The choice of independent saturation is suitable in the case of a salient pole machine since the magnetic structure differs between the direct and the quadrature axes. For each of the total air gap fluxes Ψ_{md} and Ψ_{mq}, EMTP uses a simplified saturation curve, represented by several straight line segments (see Figure 5). This model disregards the cross flux.

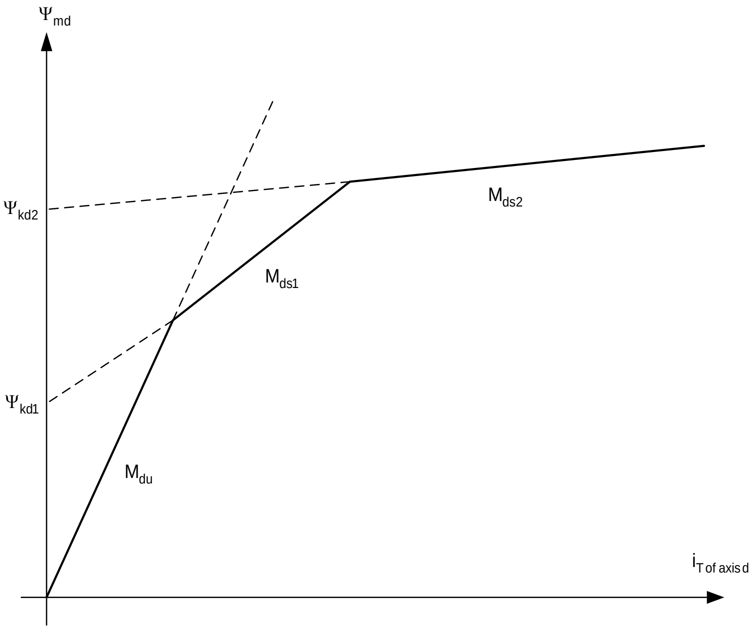


Figure 5 Saturation model for the d-axis

The current i_{T_d} represents the sum of the currents of the windings d, D_1, D_2 and D_3 referred back to the coil d. The current i_{T_q} represents the sum of the currents of the windings q, Q_1, Q_2 and Q_3 referred back to the coil q.

The unsaturated equation is taken from equation (4) after subtracting the leakage flux:

$$\Psi_{md_u} = M_{du}\, i_{T_d} = \left(L_d - L_{ld}\right) i_d + M_{dD1} i_{D1} + M_{dD2} i_{D2} + M_{dD3} i_{D3} + L_m I_m \qquad (8)$$

where u means unsaturated.

For the saturated case the equation of a line segment in Figure 5 can be combined with the current i_{T_d} relation taken from the above equation:

$$\Psi_{md_s} = M_{ds\,i}\, i_{T_d} + \Psi_{kd\,i} = \frac{M_{ds\,i}}{M_{du}} \left[\left(L_d - L_{ld}\right) i_d + M_{dD1} i_{D1} + M_{dD2} i_{D2} + M_{dD3} i_{D3} + L_m I_m\right] + \Psi_{kd\,i} \qquad (9)$$

It is not necessary to know the number of turns in each winding. All the variables referred to the stator side.

Equation (7) can be replaced into equation (6) to account for saturation. The same approach is used for q-axis.

The total saturation model is suitable for solid-rotor machines (round rotor). In this case, saturation is taken into account only with regard to the total air gap flux which is the result of the vector sum of the common total fluxes for the axes d and q. A single saturation curve is sufficient to characterize the phenomenon. In EMTP, it is represented by several straight line segments as shown in Figure 5, only now the d subscript is replaced by the T subscript for total.

To simplify the problem, EMTP decomposes this case into 2 independent saturations for the direct and the quadrature axes. This allows the expressions established in the first case to be used again. Since the machine has smooth poles (solid rotor), it is assumed that the magnetic structure is independent of the position of the rotor. In other words, for the 2 axes d and q, the saturation curves are the same as that given by the total air gap flux. Thus, the slopes M_{du} and M_{qu} are the same and equal to a common slope M_u.

For the d-axis, the mutual flux can be written again as:

$$\Psi_{md} = \Psi_{kd\,i} + M_{ds\,i}\; i_{T_d} \qquad (10)$$

If it is expressed as a function of the total mutual flux $\Psi_m = \sqrt{\Psi_{md}^2 + \Psi_{mq}^2}$, it becomes:

$$\Psi_{md} = \frac{\Psi_m}{\Psi_{m_u}} \Psi_{md_u} = \frac{\Psi_{kT\,i} + M_{s\,i}\; i_T}{M_u\, i_T} M_{d_u}\; i_{T_d} \qquad (11)$$

By comparing the above two relations:

$$\Psi_{kd\,i} = \Psi_{kT\,i}\; \frac{i_{T_d}}{i_T} \qquad (12)$$

$$M_{ds_i} = M_{s_i} \qquad (13)$$

with:

$$i_T = \sqrt{i_{T_d}^2 + i_{T_q}^2} \qquad (14)$$

Thus, it is possible to reuse the equations established in the case of two independent saturations.

1.3 Steady-state initialization

The steady-state positive sequence (hat) equations can be written from equations (6) and (4) respectively: $\hat{\Psi}_d = L_d \hat{i}_d + L_m I_m$

$$\hat{v}_d = -R_a \hat{i}_d - \omega_{el} \hat{\Psi}_q \qquad (15)$$

$$\hat{v}_q = -R_a \hat{i}_q + \omega_{el} \hat{\Psi}_d \qquad (16)$$

$$\hat{\Psi}_d = L_d \hat{i}_d + L_m I_m \qquad (17)$$

$$\hat{\Psi}_q = L_q \hat{i}_q \qquad (18)$$

The currents in the damper windings are zero.

EMTP performs steady-state initialization of the machine by replacing the machine with 3 ideal positive sequence voltage sources. The current flowing into the voltage sources is taken from the network solution and the Fortescue transformation is applied to extract the sequence currents flowing into the machine. The sequence currents are used to calculate the d and q axis currents and to obtain all the steady-state phasors of the machine. Initialization for both positive and negative sequence currents is performed. This is an approximation for the unbalanced case since the machine impedance is not represented.
The electromagnetic torque is also initialized from the steady-state solution.

In this version of EMTP, the machine impedance matrix is not represented for the steady-state initialization. It will be included when the 3-phase load-flow option becomes available.
The computations to account for saturation in the steady-state model are based on an iterative process for finding the operating segment in the saturation characteristic in steady-state. The iterations are only internal to the machine model since the terminal voltages and thus currents do not change due to the previous assumptions for steady-state.

1.4 Equations for mechanical part

A single mass representation is usually adequate for hydro units, since the generator and the turbine are close to each other on the same shaft. It is not correct for thermal units, specially when subsynchronous resonance or similar problems related to torsional vibrations are being studied.

The model used by the software is a mass-spring system. It gives good results compared to finite element models in the bandwidth of EMTP applications. It makes it possible to model the subsynchronous resonances with good accuracy, and since this model is linear, it gives relations which are simple to implement. However it remains valid for small angles between two masses.

Unlimited number of masses can be specified to define the rotor shaft. 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 6 shows a typical 6-mass model representing a turbine/alternator assembly.

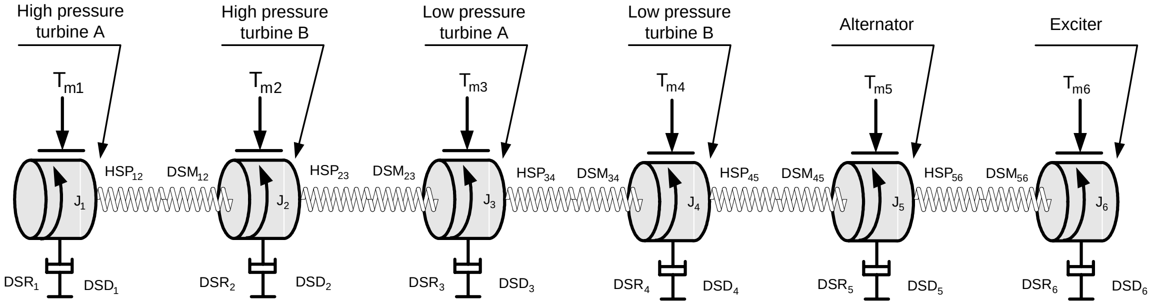


Figure 6 Diagram of the turbine/alternator assembly of the mechanical part

The n-spring-connected rotating masses are then described by the rotational form of Newton's second law:

$$\mathbf{J}\frac{d\boldsymbol{\omega}_{\mathbf{rm}}}{dt}+\mathbf{D}\,\boldsymbol{\omega}_{\mathrm{rm}}+\mathbf{HSP}\boldsymbol{\theta}_{\mathrm{rm}}=\mathbf{T}_{\mathbf{gen/exc}}-\mathbf{T}_{\mathbf{turbine}} \tag{19}$$

where:

$\mathbf{J}$ is the diagonal matrix of moments of inertia (J_1 to J_6 in Figure 6)

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

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

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

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

$\mathbf{T}_{\mathbf{turbine}}$ is the vector of torques applied to the turbine stages (see T_{m1} to T_{m4} in Figure 6)

$\mathbf{T}_{\mathbf{gen/exc}}$ is the vector of electromagnetic torques of generator and exciter (see T_{m5} and T_{m6} in Figure 6)

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 $\theta_{\mathrm{rm}\ i}-\theta_{\mathrm{rm}\ i+1}$. 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 :

$$T_{\mathrm{spring}\ i-1}=-T_{\mathrm{spring}\ i}=HSP_{i-1\ i}\left(\theta_{\mathrm{rm}\ i-1}-\theta_{\mathrm{rm}\ i}\right) \tag{20}$$

From equation (20) it can be seen that the $\mathbf{HSP}$ matrix has the following form (3 masses case):

$$\mathbf{HSP}=\begin{bmatrix} HSP_{12} & -HSP_{12} & 0 \\ -HSP_{12} & HSP_{12}+HSP_{23} & -HSP_{23} \\ 0 & -HSP_{23} & HSP_{23} \end{bmatrix} \tag{21}$$

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:

$$T_{\mathrm{damping}\ i}=DSD_i\ \omega_{\mathrm{rm}\ i}+DSM_{i-1\ i}\left(\omega_{\mathrm{rm}\ i}-\omega_{\mathrm{rm}\ i-1}\right)+DSM_{i\,i+1}\left(\omega_{\mathrm{rm}\ i}-\omega_{\mathrm{rm}\ i+1}\right) \tag{22}$$

From equation (22) it can be seen that **D** has the same structure as **HSP** except that the diagonal element is now $DSD_i + DSM_{i-1\,i} + DSM_{i\,i+1}$, as shown in this 3 masses example:

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

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

$$T_i = DSR_i \left(\omega_{m\,i} - \omega_{bm}\right) \tag{24}$$

where ω_{bm} is the base mechanical (synchronous) speed.

It is very difficult to obtain realistic values for these damping coefficients. Fortunately, they have very little influence on the peak torque value during transient disturbances.

The torques are known through the following relations:

$$T_{turbine\ i} = \frac{P_{turbine\ i}}{\omega_{rm\ i}} \tag{25}$$

$$T_{generator} = \frac{p}{2}\left(\Psi_d i_q - \Psi_q i_d\right) \tag{26}$$

1.5 Electrical parameters

In this current release of EMTP the user must provides data in pu or SI units. Parameters such as transient, subtransient reactances and time constants are not supported in this version. The data conversion will be available in a future release of EMTP.

2 Parameters and Rules

2.1 Main data tab

The first tab “Main Data” allows selecting initialization options, entering the general data of the machine and the magnetization characteristics if needed.

- ☐ **Rated line-to-line voltage** is the Rated line-to-line stator terminal voltage used in the definition of base values upon which pu machine parameters are assumed to apply.
- ☐ **Armature winding connection** type can be Wye (Y), Wye grounded (internal ground) or Delta.
- ☐ **Rated power** is the total 3-phase volt-ampere rating of the machine. Used in the definition of base values upon which pu machine parameters are assumed to apply.
- ☐ **Frequency** (f) is the steady-state operating (synchronous) frequency of the machine.
- ☐ **Number of poles** is the number of poles (p) which characterizes the machine rotor.
- ☐ **Permanent magnet specifications:** specify the permanent magnet. 3 choices are available :
  1. Define permanent magnet current: the user specifies the equivalent current of the magnet. In this case the equivalent flux Ψ_m is equal to $I_m L_{aD1}$ and the user must specify at least 1 damper on rotor d-axis.
  2. Define permanent magnet flux: the user specifies the equivalent flux Ψ_m of the magnets in Wb.
  3. Define permanent magnet inductance and current: the user defines parameters I_m and L_m. EMTP automatically calculates $\Psi_m = L_m I_m$

- **Steady-state voltage and angle θ:** represents steady-state phasors at the terminals of the machine. This data is generally available from a load-flow solution with given constraints on the machine and PQ loads. In this version it can be taken from a separate load-flow program. The next EMTP version will provide a load-flow feature that allows to fix these values automatically. 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 start from zero initial conditions if at least one rotor damper has been defined.
- **Simulate saturation** allows entering the piecewise characteristic of the magnetization curve of the machine. It can be determined from the no-load test curve of the machine. Only the positive part is entered. The origin is assumed if not explicitly entered.
    4. 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. The modeling methods are presented in the theoretical section above.

2.2 Electrical data tab

The second data tab allows entering the data for making the electrical circuit of the machine on each axis. In the current version of EMTP only basic data input option is available
It is noticed that for the q-axis parameters, when winding parameters are unavailable, the user can choose the option "Undefined". In this case $X_{aQ1}=X_{aQ2}=X_{aQ3}=0$, $X_{Q1}=X_{Q2}=X_{Q3}=0$ and $R_{Q1}=R_{Q2}=R_{Q3}=\infty$ for all types of q-axis data.

2.3 Mechanical data tab

- **Number of masses** is used to enter the total number of masses to model the mechanical shaft.
- **Index of rotor mass**: allows specifying the mass number of the generator rotor within the interconnected mass-spring shaft system. This number must be positive and lower or equal to the number of masses.
- **Mass data: mechanical parameters for the shaft system** gives the parameters that describe the masses and connections between masses. See the above section "2.3 Equations for mechanical part" 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 in seconds (s) instead of the Moment of inertia** allows using H instead of the Moment of inertia. This constant is defined as the ratio of the kinetic energy of the rotating mass at base mechanical speed to the rated power:

  $$H=\frac{J\omega_{bm}^2}{2S_b}$$

  The user can click on the hyperlink title of this data grid to get more information on entered data.
- **Mass data: 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 user can click on the hyperlink title of this data grid to get more information on entered data. The selected scopes become available under the machine scopes in the plot processing package. Observe and control selections become available in the Observe and Control bundles respectively.

- The mechanical angle of each mass (in rad) can be selected for observe: the stator phase-a is the origin of the angles. The difference between the mechanical angle and the synchronous angle of each mass (in deg) can be selected for scope.
- The mechanical speed (in rad/s or in pu) 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 is the torque on the shaft section connecting masses i and i+1.
- The steady-state mechanical power applied on mass i can only be observed.
- The external mechanical power applied on mass i can be controlled. If this control option is chosen, the total power or total torque control can not be used.
- **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 calculating all the observe and control signals in pu.

2.4 Precision data tab

- **Damping factor** is the ratio between built-in damping resistors and discretized inductive elements used in the machine model. Reduce this number when numerical stability problems are encountered. The selected default data is suitable for most cases.
- **Rotor speed tolerance**: Relative tolerance associated with the iterative solution of rotor speed at each solution time-point.
- **Maximum number of iterations in rotor speed computation** is the 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.
- **Relative tolerance**: Relative tolerance associated with the iterative solution of voltage (if the maximum precision option is checked) at the machine terminals at each solution time-point.

More details are available in Figure 7.

2.5 Control tab

- **Total mechanical torque**: if this option is chosen the total torque (in Nm) applied on the mechanical shaft is controlled. If this option is selected the mechanical power control of the previous data tab on any mass is no more available. Positive torque is used for motor operation and negative torque is used for generator operation.
- **Total mechanical power**: If this option is chosen the total power (in W) applied on the mechanical shaft is controlled. If this option is selected the mechanical power control of the previous tab on any mass is no more available.
- **Use "pu" for Control variables units**: all control signals are entered in pu.

2.6 Observe/Scopes tab

The selections on this tab are self-explanatory.

- 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. It will be identified by the corresponding signal name followed by the machine name.

Example:
id_PMSMX
is the signal name that becomes available for the machine named PMSMX and the variable i_d.

- ☐ 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.

2.7 Base quantities

The base quantities with rms value of a p-pole, three phase machine with rated line-to-line rms voltage V_{rated}, rated value of angular frequency ω_b (ω_{bm} for mechanical), and rated volt-ampere S_{rated}, are as follows (all entered data is first converted to fundamental units, no multiplicative factors):

- Base rotor and stator voltages, rms line-to-line: $V_b = V_{rated}$
- Base volt-ampere $S_b = S_{rated}$
- RMS base current $i_b = \frac{S_b}{\sqrt{3}V_b}$
- Base impedance $Z_b = \frac{V_b^2}{S_b}$
- Base torque $T_b = \left(\frac{p}{2}\right)\frac{S_b}{\omega_b}$
- Base flux $\Psi_b = \frac{V_b}{\omega_b}$

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

2.8 Rules

A number of tests in the internal EMTP code are designed to signal data errors and solution problems. It is however impossible to intercept all errors and some conditions may conduct to catastrophic error messages. The data forms can not intercept errors when undetermined (named parameters) values are entered in data fields.
Since the symbol of this device is automatically redrawn through scripts, it is not allowed to modify it through the symbol editor. It is not allowed to delete any pins or to modify pin attributes.

3 Netlist format

Example of data for a 3 phases synchronous machine :

```
_PMSM;PMSM1a;10;8;s3a,s4,s1Tm,s2Rated_kV,
0.0173pu,0.0652pu,0.0652pu,3,2,0.543pu,0.054pu,0.6078pu,0.4778pu,0,0,0,0
,0,0,0,0,0,3,1,1.086pu,
0.1080pu,1.1508pu,1.0208pu,0,0,0,0,0,0,0,0,0,?m,24,
_PMSM;PMSM1b;10;8;s3b,s4,s1Tm,s2Rated_kV,
_PMSM;PMSM1c;10;8;s3c,s4,s1Tm,s2Rated_kV,
GD=0.230 1 0.002875MVA 60 2,
PM=1 4 0 0.093316 0 0.023329 4,
SSiniV=1 221.49 221.49 221.49, 1,
SSiniA=8.3 -111.7 128.3, 1,
CTst=0.5,
S=0 1 0 2 0,
1 1
1 2
;
MS=1 1 1,
1 0.3 0 0 0 0
2 2 0 0 0
MSu=1 0 0,
PR=100 1e-06 300 1 1e-06,
CTRL=1 0,
OBSu=0 0,
OBS=2 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 1 1 2 1 1 1,
```

Field	Description
_PMSM	Part name
PMSM1a	Instance name for the phase a stator coil, any name.
10	Total number of pins
8	Number of pins given in this data section
s3a	Signal name connected to k-pin of the stator phase a coil, any name
s4	Signal name connected to m-pin (Neutral) of the stator phase a coil, any name
s1Tm	Signal name connected to control bundle
s2Rated_kV	Signal name connected to observable bundle
0.0173pu	Ra with units
0.0652pu	Xl with units
0.0652pu	X0 with units
3	Type of data on d-axis, blocked to 3
2	Number of dampers +1 on d-axis
0.543pu,.054pu,…	d-axis data: comma separated resistance and inductances with units. Same order as on the data web.
3	Type of data on q-axis, blocked to 3
1	Number of dampers on q-axis
1.086pu,…	q-axis data: comma separated resistance and inductances with units. Same order as on the data web.
?m	Request for scopes, sent to scope group Machine, optional
24	Number of scope outputs
PMSM	Part name
PMSM1b	Instance name for the phase b stator coil, any name.

10	Total number of pins
8	Number of pins given in this data section
S3b	Signal name connected to k-pin of the stator phase b coil, any name
S4	Signal name connected to m-pin (Neutral) of the stator phase b coil, any name
s1Tm	Signal name connected to control bundle
s2Rated_kV	Signal name connected to observable bundle
PMSM	Part name
PMSM1c	Instance name for the phase c stator coil, any name.
10	Total number of pins
8	Number of pins given in this data section
S3c	Signal name connected to k-pin of the stator phase c coil, any name
S4	Signal name connected to m-pin (Neutral) of the stator phase c coil, any name
s1Tm	Signal name connected to control bundle
s2Rated_kV	Signal name connected to observable bundle
GD=	Start general data section
0.230	Rated voltage
1	Stator connection type
0.002875MVA	Rated power
60	Rated frequency
2	Number of poles
PM=	Start permanent magnet definition section
1	Definition with current when 1
4	Equivalent current
0	Definition with flux when 1
0.093316	Equivalent flux
0	Equivalent inductance and current when 1
0.023329	Equivalent inductance
4	Equivalent current
SSiniV=	Start steady state voltage section
1	1 when initialization is turned on
221.49	Steady state voltage phase a
221.49	Steady state voltage phase b
221.49	Steady state voltage phase c
1	Unit of steady state voltage : 1, 1kV, 1MV, 1kVRMS, 1kVRMSLL
SSiniA=	Start steady state angle section
8.3,	Steady state phasor angle at the terminals of the machine, phase a
-111.7	Steady state phasor angle at the terminals of the machine, phase b
128.3	Steady state phasor angle at the terminals of the machine, phase c
1	Units for steady state angle : degrees (1) or radians (1rad)
CTst=	Start control torque start time section
0.5	control torque start time
Ms=	Start mechanical parameters section
1	Lock rotor for negative speed?
1	Number of masses
1	Index of rotor mass
1 0.3 0 0 0 0	Mechanical parameters table (1 masse in this example)
2 2 0 0 0	Observable, scope and control table
MSu=	Start mechanical parameters units specification section
1	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
PR=	Start precision control data section
100	Damping factor
1e-6	Rotor speed tolerance
300	Maximum number of iteration in rotor speed computation
0	Apply maximum of precision ?
1e-6	Voltage convergence tolerance
CTRL=	Start Control section
0	Control on external torque
0	Control on external power
OBSu=	Start Scope and Observe in “pu” section
0	Use “pu” for scope variable units
1	Use “pu” for observe variable units
OBS=	Start Scope and Observe requests
2 1 2 0 2 0 1 0…….	Scope and Observe requests in appearance order: 0 for none, 1 for scope request, 2 for observe request, 3 for scope and observe request.

4 Steady-state model

A steady state solution can be computed by EMTP at the fundamental frequency of each synchronous machine. At fundamental frequency the machine is replaced by 3 voltage sources. The voltage of this source is specified by the user. All the machine parameters are initialized at this step.

At non fundamental frequency steady-state solution the machine is represented by a harmonic impedance matrix using techniques similar to [10]. The steady-state solution obtained with this impedance is superimposed with the steady-state solution at fundamental frequency. A non fundamental frequency steady-state solution can occur in some cases when EMTP must perform a harmonic steady-state solution.

A steady state torque is calculated by EMTP during the steady state solution and is applied on the rotor shaft as long as the “Controlled Torque Start Time” is not exceeded.

5 Initial conditions

Initial conditions are calculated from the steady-state solution as explained in “1.3 Steady-state initialization”. The permanent magnet synchronous machine can also start from no initial condition; it needs rotor dampers to start.

6 Frequency Scan model

For a frequency scan study the synchronous machine is modeled by a harmonic impedance matrix as in the steady-state case. No ideal voltage source is inserted during this calculation, even for the fundamental frequency of the machine.

7 Time-domain representation

The time-domain representation of the synchronous machine has already been explained in the above sections. In the time-domain solution this device is a nonlinear function. If the option “Apply maximum precision” is chosen, it is solved through the iterative procedure of EMTP with all nonlinear devices until convergence according to the relative tolerance option for each machine.

EMTP uses an internal speed loop for each synchronous machine.

Two parameters controlling the speed loop and the voltage loop can be modified by the user. The Figure 7 shows the iterative process for solving the synchronous machine model.

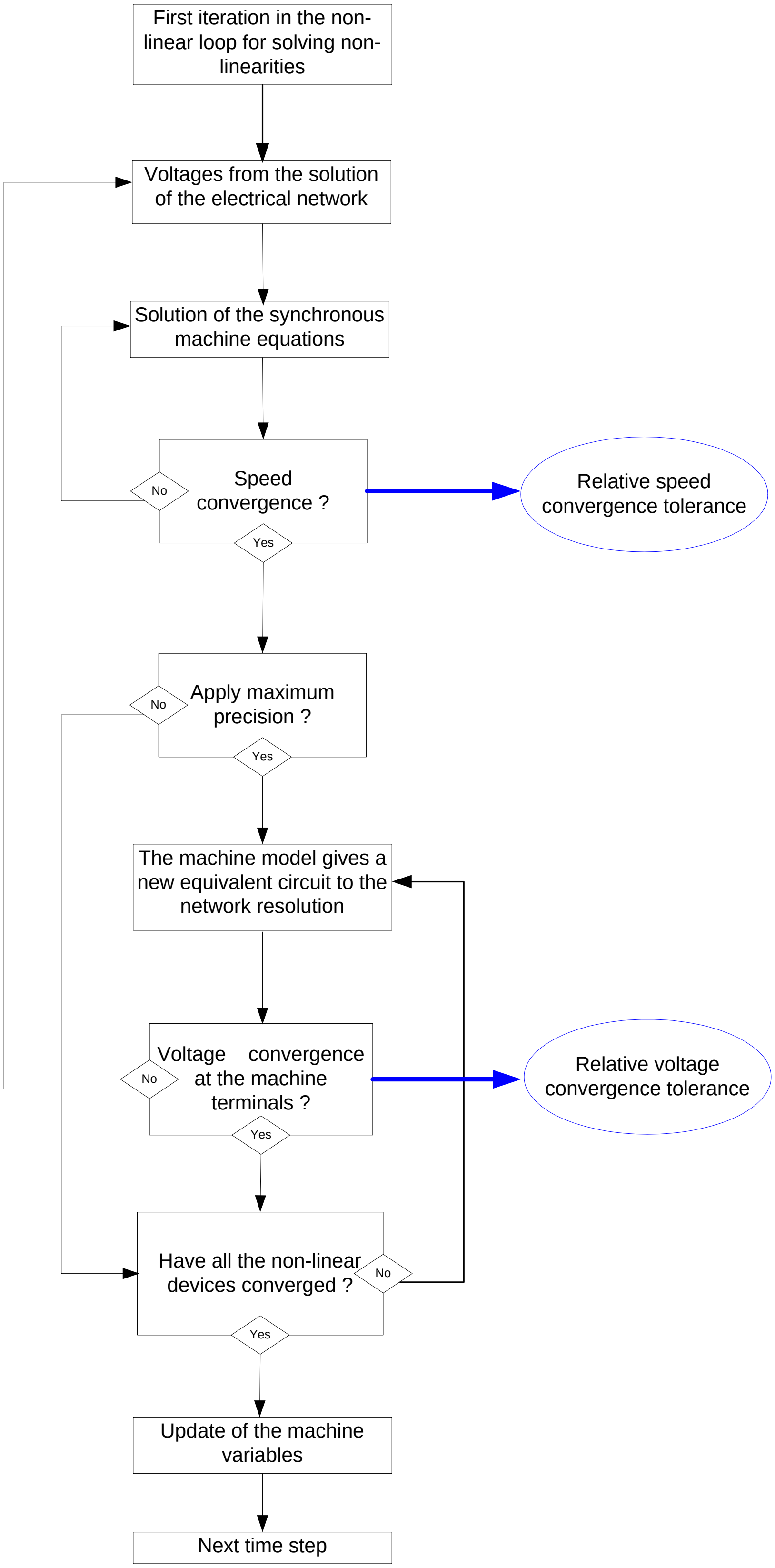


Figure 7 The iterative solution process: speed and voltage loops

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