Synchronous machine

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1   Description

This device is used to represent the usual design of a synchronous machine with 3-phase ac armature windings on the stator. Up to 3 windings may be modeled on rotor d-axis (a field winding and two dampers). Three more windings can be modeled on the rotor q-axis.
The model represents both generator and motor behavior.

1.1 The synchronous machine symbol

The 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.
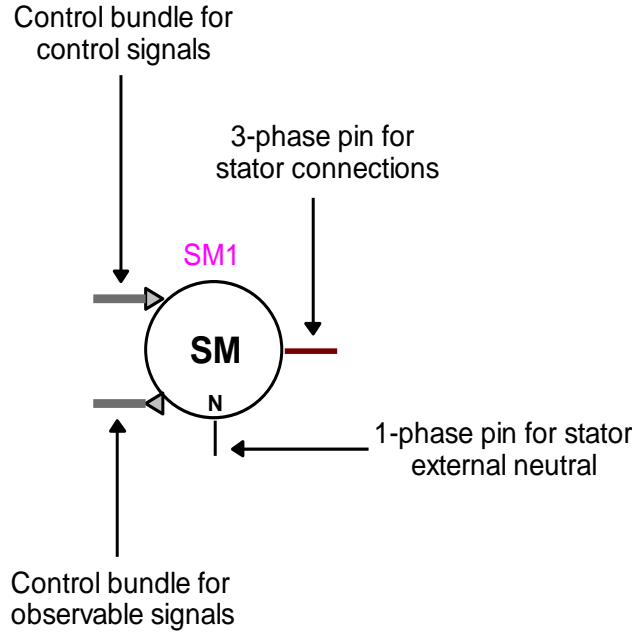
Figure 1 The synchronous machine symbol

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 has several improvements and new calculation methods. Some details can be also found in [2]. The complete new approach presented in [2] will be available in 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_f , $v_{D1} = v_{D2} = v_{Q1} = v_{Q2} = v_{Q3} = 0$	Field voltage v_f . All other rotor voltages equal zero.
i_d , i_q , i_0	Stator currents in dq0 domain
i_{D1} , i_{Q1} , i_{D2} , i_{Q2} , i_{Q3} , i_f	Rotor currents on d and q axis
p	Number of poles
ω_{el}	Electrical speed (rad/s)
ω	Mechanical speed $\omega = \left(\dfrac{2}{p} \right) \omega_{el}$
ω_b	Base electrical speed (rad/s)
ω_{bm}	Base mechanical speed $\omega_{bm} = \left(\dfrac{2}{p} \right) \omega_b$

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 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, which is the direct axis, there are the excitation winding f and a maximum of 2 damper windings denoted by D1 and D2. 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.
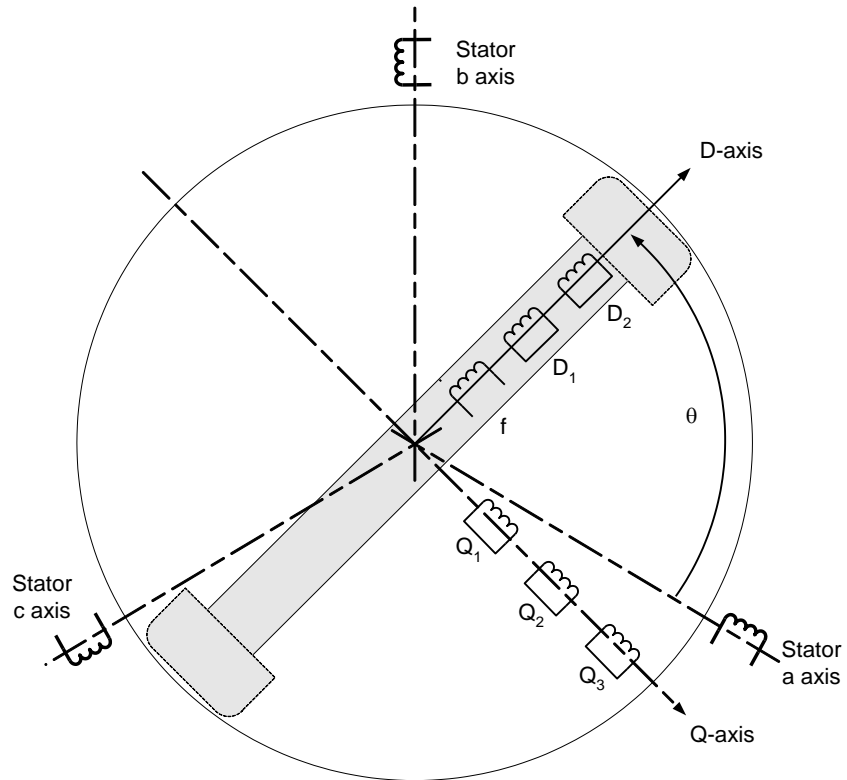
Figure 2 Schematic representation of the machine in DQ

The Park's transformation matrix is defined by:

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

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:

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

(2)

The schematic representation of the machine is now given by the diagram of Figure 3.
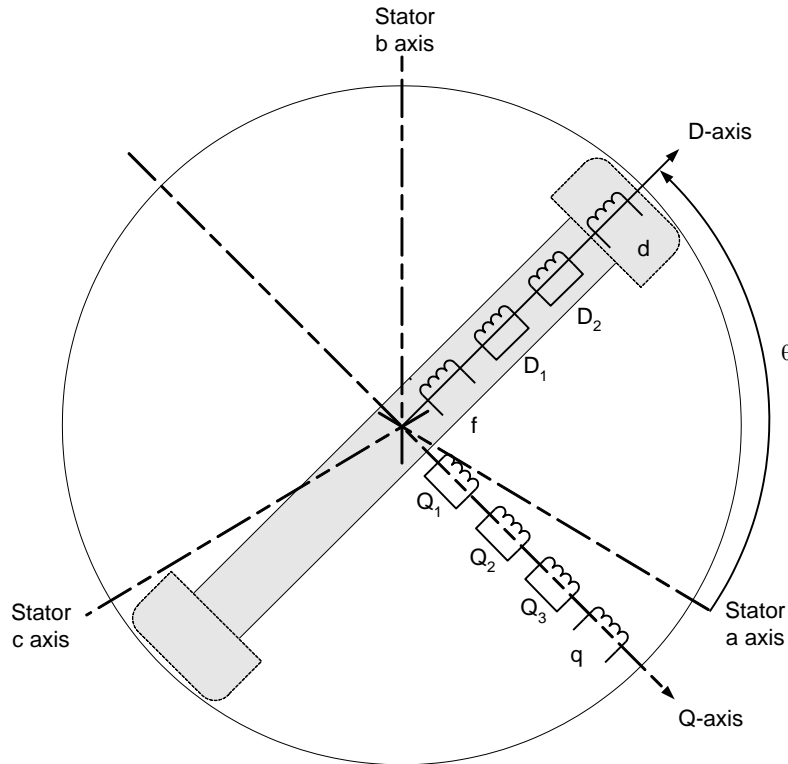
Figure 3 Schematic representation of the machine after Park's transformation

1.3 Flux equations

The circuit consists of a maximum 9 coupled windings. 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:

$$
\begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_0 \\ \Psi_f \\ \Psi_{D1} \\ \Psi_{D2} \\ \Psi_{Q1} \\ \Psi_{Q2} \\ \Psi_{Q3} \end{bmatrix} =
\begin{bmatrix}
L_d & 0 & 0 & M_{df} & M_{dD1} & M_{dD2} & 0 & 0 & 0 \\
0 & L_q & 0 & 0 & 0 & 0 & M_{qQ1} & M_{qQ2} & M_{qQ3} \\
0 & 0 & L_0 & 0 & 0 & 0 & 0 & 0 & 0 \\
M_{df} & 0 & 0 & L_{ff} & M_{fD1} & M_{fD2} & 0 & 0 & 0 \\
M_{dD1} & 0 & 0 & M_{fD1} & L_{D1} & M_{D1D2} & 0 & 0 & 0 \\
M_{dD2} & 0 & 0 & M_{fD2} & M_{D1D2} & L_{D2} & 0 & 0 & 0 \\
0 & M_{qQ1} & 0 & 0 & 0 & 0 & L_{Q1} & M_{Q1Q2} & M_{Q1Q3} \\
0 & M_{qQ2} & 0 & 0 & 0 & 0 & M_{Q1Q2} & L_{Q2} & M_{Q2Q3} \\
0 & M_{qQ3} & 0 & 0 & 0 & 0 & M_{Q1Q3} & M_{Q2Q3} & L_{Q3}
\end{bmatrix}
\begin{bmatrix} i_d \\ i_q \\ i_0 \\ i_f \\ i_{D1} \\ i_{D2} \\ i_{Q1} \\ i_{Q2} \\ i_{Q3} \end{bmatrix}
$$

(3)

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

1.4 Voltage equations

The rotor consists of 6 windings, the excitation winding f producing the flux in the machine, and 5 short-circuited damper windings D1, D2, 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:

$$r_a = r_b = r_c = R_a \tag{4}$$

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:

$$
\begin{bmatrix} v_d \\ v_q \\ v_0 \\ -v_f \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = - \begin{bmatrix} R_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_a & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & r_f & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_{D1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & r_{D2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & r_{Q1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_{Q2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_{Q3} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \\ i_f \\ i_{D1} \\ i_{D2} \\ i_{Q1} \\ i_{Q2} \\ i_{Q3} \end{bmatrix} - \frac{d}{dt} \begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_0 \\ \Psi_f \\ \Psi_{D1} \\ \Psi_{D2} \\ \Psi_{Q1} \\ \Psi_{Q2} \\ \Psi_{Q3} \end{bmatrix} + \begin{bmatrix} -\omega_{el}\Psi_q \\ \omega_{el}\Psi_d \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{5}
$$

where r gives the resistance of the winding.

1.5 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:

$$
\begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_0 \\ \Psi_f \\ \Psi_{D1} \\ \Psi_{D2} \\ \Psi_{Q1} \\ \Psi_{Q2} \\ \Psi_{Q3} \end{bmatrix} = \begin{bmatrix} \Psi_{ld} \\ \Psi_{lq} \\ \Psi_0 \\ \Psi_{lf} \\ \Psi_{lD1} \\ \Psi_{lD2} \\ \Psi_{lQ1} \\ \Psi_{lQ2} \\ \Psi_{lQ3} \end{bmatrix} + \begin{bmatrix} \Psi_{md} \\ \Psi_{mq} \\ 0 \\ \left(\dfrac{n_f}{n_d}\right)\Psi_{md} \\ \left(\dfrac{n_{D1}}{n_d}\right)\Psi_{md} \\ \left(\dfrac{n_{D2}}{n_d}\right)\Psi_{md} \\ \left(\dfrac{n_{Q1}}{n_q}\right)\Psi_{mq} \\ \left(\dfrac{n_{Q2}}{n_q}\right)\Psi_{mq} \\ \left(\dfrac{n_{Q3}}{n_q}\right)\Psi_{mq} \end{bmatrix} \tag{6}
$$

Here Ψ_{ld} is the leakage flux and Ψ_{md} is the flux linking all d-axis windings (total flux minus leakage flux).

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 4). This model disregards the cross flux.
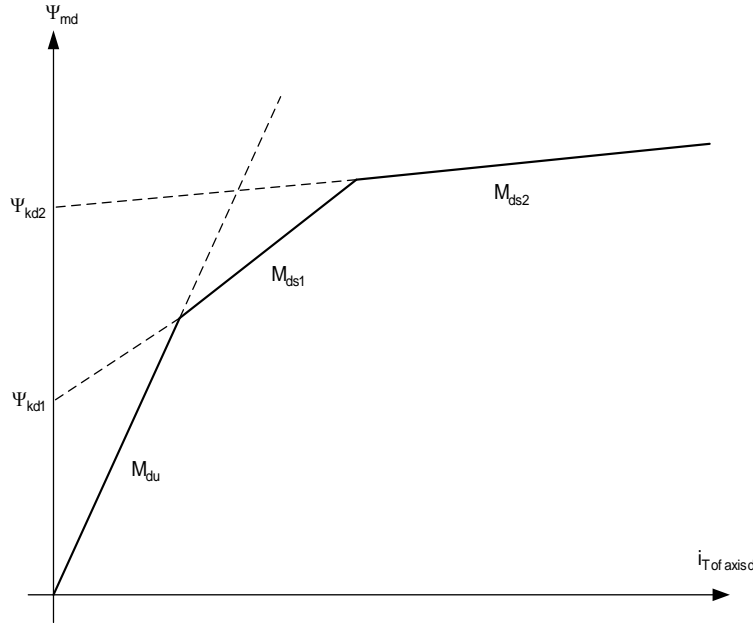
Figure 4 Saturation model for the d-axis

The current i_{T_d} represents the sum of the currents of the windings d, f, D_1 and D_2 referred back to the excitation coil f. 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 (3) after subtracting the leakage flux:
$$\Psi_{md_u} = M_{du} i_{T_d} = \left(L_d - L_{ld}\right)i_d + M_{df}i_f + M_{dD1}i_{D1} + M_{dD2}i_{D2} \tag{7}$$
where u means unsaturated.
For the saturated case the equation of a line segment in Figure 4 can be combined with the current i_{T_d} relation taken from the above equation:

$$\Psi_{md_s} = M_{ds\,i} i_{T_d} + \Psi_{kd\,i} = \frac{M_{ds\,i}}{M_{du}}\left[\left(L_d - L_{ld}\right)i_d + M_{df}i_f + M_{dD1}i_{D1} + M_{dD2}i_{D2}\right] + \Psi_{kd\,i} \tag{8}$$

It is not necessary to know the number of turns in each winding. Only their ratios need to be known. EMTP calculates them using the assumption of the existence of a single common air gap flux. For the first ratio, for example, it finds:
$$\frac{n_f}{n_d} = \frac{M_{df}}{L_d - L_{ld}} \tag{9}$$
Equation (6) can be replaced into equation (5) 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 4, 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:

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

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

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

By comparing the above two relations:

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

$$M_{ds_i} = M_{s_i} \tag{13}$$

with:

$$i_T = \sqrt{i_{T_d}^2 + i_{T_q}^2} \tag{14}$$

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

1.6   Steady-state initialization

The steady-state positive sequence (hat) equations can be written from equations (5) and (3) respectively:

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

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

$$-\hat{v}_f = -r_f \hat{i}_f \tag{17}$$

$$\hat{\Psi}_d = L_d \hat{i}_d + M_{df} \hat{i}_f \tag{18}$$

$$\hat{\Psi}_q = L_q \hat{i}_q \tag{19}$$

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.

1.7 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 5 shows a typical 6-mass model representing a turbine/alternator assembly.
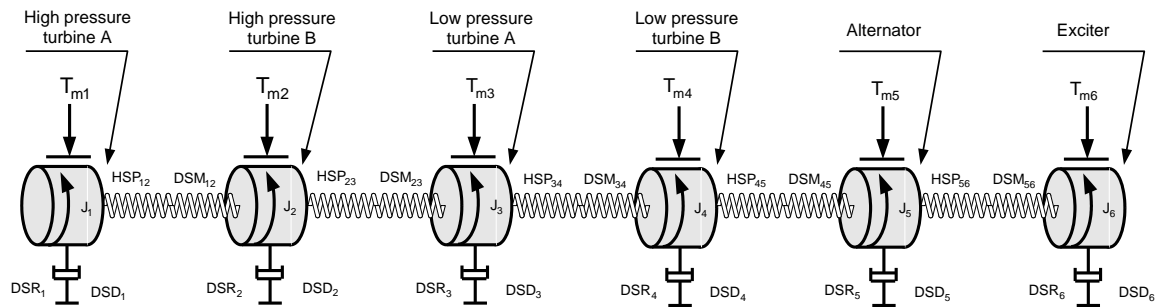
Figure 5 Diagram of the turbine/alternator assembly of the mechanical part

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

$$\mathbf{J}\frac{d\boldsymbol{\omega}_{rm}}{dt} + \mathbf{D}\boldsymbol{\omega}_{rm} + \mathbf{HSP}\boldsymbol{\theta}_{rm} = \mathbf{T_{turbine}} - \mathbf{T_{gen/exc}} \tag{20}$$

where:

$\mathbf{J}$ is the diagonal matrix of moments of inertia (J_1 to J_6 in Figure 5)

$\boldsymbol{\omega}_{rm}$ 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 torques applied to the turbine stages (see T_{m1} to T_{m4} in Figure 5)

$\mathbf{T_{gen/exc}}$ is the vector of electromagnetic torques of generator and exciter (see T_{m5} and T_{m6} in Figure 5)

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 :

$$T_{spring\ i-1} = -T_{spring\ i} = HSP_{i-1\ i}\left(\theta_{rm\ i-1} - \theta_{rm\ i}\right) \tag{21}$$

From equation (21) it can be seen that the **HSP** matrix has the following form (3 masses case):

$$\mathbf{HSP} = \begin{bmatrix} HSP_{12} & -HSP_{12} & 0 \\ -HSP_{12} & HSP_{12} + HSP_{23} & -HSP_{23} \\ 0 & -HSP_{23} & HSP_{23} \end{bmatrix} \tag{22}$$

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:

$$T_{damping\,i} = DSD_i\,\omega_{rm\,i} + DSM_{i-1\,i}\left(\omega_{rm\,i} - \omega_{rm\,i-1}\right) + DSM_{i\,i+1}\left(\omega_{rm\,i} - \omega_{rm\,i+1}\right) \tag{23}$$

From equation (23) 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:

$$\mathbf{D} = \begin{bmatrix} DSD_1 + DSM_{12} & -DSM_{12} & 0 \\ -DSM_{12} & DSD_2 + DSM_{12} + DSM_{23} & -DSM_{23} \\ 0 & -DSM_{23} & DSD_3 + DSM_{23} \end{bmatrix} \tag{24}$$

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

$$T_i = DSR_i\left(\omega_{m\,i} - \omega_{bm}\right) \tag{25}$$

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:

$$T_{turbine\,i} = \frac{P_{turbine\,i}}{\omega_{rm\,i}} \tag{26}$$

$$T_{generator} = \frac{p}{2}\left(\Psi_d i_q - \Psi_q i_d\right) \tag{27}$$

The torque on the exciter is

$$T_{exciter} = \frac{v_f i_f}{\omega_{exciter}} \tag{28}$$

where $\omega_{exciter}$ is the mechanical speed of the exciter.

1.8 Electrical parameters

Before starting the simulation, it is necessary to determine the parameters used in the equations of the machine. These may be given by the constructor. In this case, the user provides data in pu and EMTP will internally convert them into SI units.

There is another method of characterizing the machine. It involves measurements obtained via three-phase short-circuit tests or via frequency response tests defined by IEEE or IEC standards. In this second case, EMTP must employ a parameter fitting method to calculate the self inductances, mutual inductances and resistances of the machine.

The details of the calculations will be made available in a future release of EMTP. The material that was used in coding the data conversion was based on the references [3]-[10]

It is noticed that this version has more options for data input and allows entering an extra damper winding on each axis. The calculated machine data is available for each simulation in a separate HTML file for machines.

It is recalled that according to IEEE and IEC the known quantities are:

    o R_a : armature resistance

    o X_l : armature leakage reactance

- X_0 : zero sequence reactance
- $X_d^{'}$, $X_q^{'}$: transient reactances
- $X_d^{''}$, $X_q^{''}$: subtransient reactances
- $X_d^{'''}$, $X_q^{'''}$: sub-subtransient reactances
- $T_d^{'}$, $T_q^{'}$: transient short-circuit time constants
- $T_d^{''}$, $T_q^{''}$: subtransient short-circuit time constants
- $T_d^{'''}$, $T_q^{'''}$: sub-subtransient short-circuit time constants
- $T_{d0}^{'}$, $T_{q0}^{'}$: transient time constants in open-circuit
- $T_{d0}^{''}$, $T_{q0}^{''}$: sub-transient time constants in open-circuit
- $T_{d0}^{'''}$, $T_{q0}^{'''}$: sub-subtransient time constants in open-circuit

The Canay reactance X_c (L_c) is used to model the machine more accurately along the direct axis. It takes into account a linkage air gap flux for the windings f and D1 in addition to the real air gap flux common to the three windings d, f and D1. Figure 6 shows the equivalent with the extra damper winding D2 circuit.
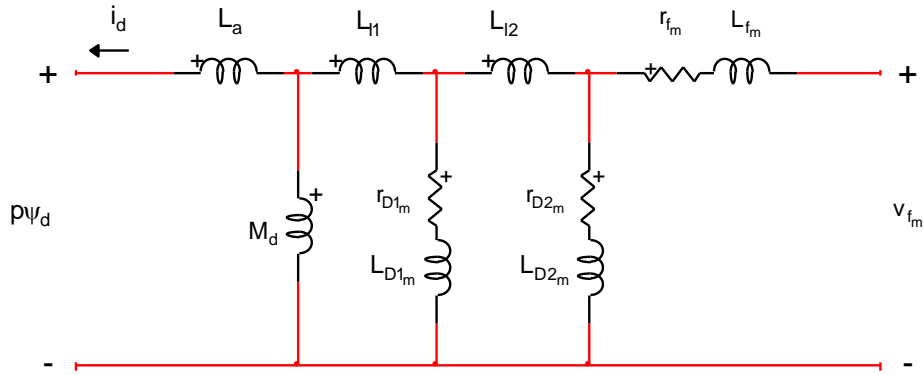
Figure 6 Equivalent network on d-axis solved in EMTP

This circuit is constructed after rescaling the field structure quantities. The subscript m stands for modified. It is noticed that:

$$M_d = L_d - L_a \tag{29}$$

The inductance L_a is the armature leakage reactance.

The damper winding circuit inductances must also account for M_d in addition to rescaling. It can be shown that:

$$\frac{1}{L_c - L_a} = \frac{1}{M_d} + \frac{1}{L_{l1}} \tag{30}$$

Another option is available through the $G(p)$ (p is the differential operator in Laplace domain) function. It allows defining extra time-constants and calculating L_{l1} and L_{l2}. It can be given by:

$$G(p) = \frac{\Delta \Psi_d(p)}{\Delta v_f(p)} = \frac{M_d}{r_{fm}} \frac{(1 + T_1 p)}{(1 + T_{d0}^{'} p)(1 + T_{d0}^{''} p)} \tag{31}$$

for the presence of only one damper and by:

$$G(p) = \frac{\Delta\Psi_d(p)}{\Delta v_f(p)} = \frac{M_d}{r_{fm}} \frac{(1+T_1p)(1+T_2p)}{(1+T'_{d0}p)(1+T''_{d0}p)(1+T'''_{d0}p)} \qquad (32)$$

for the presence of two damper windings on d-axis.

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.

- **Steady-state voltage and angle** θ: represents steady-state phasors at the terminals of the machine. This data can be entered manually or taken directly and automatically from the EMTP Load-Flow solution. When the Load-Flow solution device is selected, these phasors are automatically overwritten.
- **Load-Flow solution device**: see Load-Flow section below.
- **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.
- **Armature winding connection** type can be Wye (Y), Wye grounded (internal ground) or Delta.
- **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.
- **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.
- **Field current for 1 pu armature voltage** is the value of field current which will produce rated armature (1 pu) voltage on the air gap line. This quantity is also called i_{agline}.

- **Several machines on the same bus**: if this option is chosen the user has to define the P and Q power splits: proportionality factors which are used only to split the power among the machines during initialization. If, for example, this is a dual machine, if P_A is specified for this half of the dual, and P_B for the other half, then the fraction $\dfrac{P_A}{P_A + P_B}$ will be assigned to this half of the dual machine initialization.
- **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.
    - 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. Several data input options are available and tooltips provide identification for all variables. Some details on the data conversion methods are provided in the above theoretical section of this document.

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.

For each simulation involving synchronous machines, EMTP produces an HTML page showing the calculated parameters for each machine. The page is available from the main Output HTML file from the menu "EMTP>View Output Files".

2.3 Mechanical data tab

- ❑ **Share mechanical shaft** option can be chosen if the mechanical shaft of the machine is shared with another machine in the current circuit (or subcircuit). When this option is selected the Mass Data of this machine is automatically made equal to the Mass Data of the shared machine.
- ❑ **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.
- ❑ **Index of exciter mass** allows specifying the mass number of the exciter mass on the shaft system. If no exciter mass exists, use 0.
- ❑ **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 MNm) 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

- ❑ **Field voltage (on d-axis)**: if this option is selected, the field voltage on d-axis E_f is controlled in V or pu. See the section 2.7 for more explanations on this variable.
- ❑ **Field voltage**: if this voltage is selected then the controlled voltage is v_f in V or pu (see section 2.7). The symbol V_f is used in this tab instead of v_f.
- ❑ **Total mechanical torque**: if this option is chosen the total torque (in MNm or pu) 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 generator operation and negative torque is used for motor operation.
- ❑ **Total mechanical power**: If this option is chosen the total power (in MW or pu) 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_SMX
  is the signal name that becomes available for the machine named SMX 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 stator current $i_{bs} = \dfrac{S_b}{\sqrt{3}V_b}$

- Base rotor current $i_{br} = I_{agline}$

- Base stator impedance $Z_{bs} = \dfrac{V_b^2}{S_b}$

- Base torque $T_b = \left(\dfrac{p}{2}\right)\dfrac{S_b}{\omega_b}$

- Base flux $\Psi_b = \dfrac{V_b}{\omega_b}$

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>.

It is noticed that when the machine is operating in open-circuit mode, equations (15) to (19) can be used to write:

$$M_{df} = \frac{v_q}{\omega_{el}i_f} \tag{33}$$

which is also equivalent to:

$$M_{df} = \frac{V_b}{\omega_{el}i_{agline}} \tag{34}$$

The field voltage E_f is calculated as follows:

$$E_f = \omega_{el}M_{df}i_f = \omega_{el}M_{df}\frac{v_f}{r_f} \tag{35}$$

The quantities E_f and v_f are identical when pu values are used assuming nominal frequency conditions.

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.

For the synchronous machine to initialize and operate properly it is mandatory to have steady-state conditions established by other energy source types.

3 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:

```
_SM;SM1a;4;2;s114a,s116,
?m,10,
_SM;SM1b;4;2;s114b,s116,
_SM;SM1c;4;2;s114c,s116,
V=22 22 22,1kVRMSLL,
P=0 -120 120,1,
f=60 2 1,
R=22 600 1200,
S=0 1 1 1 1 0 2 0,
1322 1.0
2200 1.2
;
Ra=.0045 .14 0.12
ds=0 2 1.65
Xdp=0.25 0.20 0.2273
Td0p=4.5 0.04 0.00215
Noex=1 0 0.0019 0.000075
Xc=0
qs=0 2 1.59
Xqp=0.46 0.20 0.244
Tq0p=0.55 0.09 0.0085
MS=0  4 2 1,
0 58.27 46.51 0 5.953E06 0
0 7423.5 5926.96 0 132.85E06 0
0.5 13091.06 10451.96 0 67.96E06 0
0.5 2102.8 1678.89 0 0 0
0 2 2 0 0
0 2 2 0 0
0 2 2 0 0
0 2 0 0 0
MSu=0 1 0,
PR=100 1e-06 300 0 1e-06,
CTRL=0 0 0 0,
OBSu=0 0,
OBS=0 0 0 1 1 1 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
_SM	Part name
SM1a	Instance name for the phase a stator coil, any name.
4	Total number of pins
2	Number of pins given in this data section
S114a	Signal name connected to k-pin of the stator phase a coil, any name
S116	Signal name connected to m-pin (Neutral) of the stator phase a coil, any name
?m	Request for scopes, sent to scope group Machine, optional
10	Number of scope outputs

|	
SM	Part name
SM1b	Instance name for the phase b stator coil, any name.
4	Total number of pins
2	Number of pins given in this data section
S114b	Signal name connected to k-pin of the stator phase b coil, any name
S116	Signal name connected to m-pin (Neutral) of the stator phase b coil, any name
ASM	Part name
ASM1c	Instance name for the phase c stator coil, any name.
4	Total number of pins
2	Number of pins given in this data section
S114c	Signal name connected to k-pin of the stator phase c coil, any name
S116	Signal name connected to m-pin (Neutral) of the stator phase c coil, any name
V=	Start steady state values section
22	Steady state voltage phase a
22	Steady state voltage phase b
22	Steady state voltage phase c
1kVRMSLL	Units of steady state voltage: V, kV, MV, kVRMS, kVRRMSLL
P=	Start Steady state phasor angle section
0	Steady state phasor angle at the terminals of the machine, phase a
-120	Steady state phasor angle at the terminals of the machine, phase b
120	Steady state phasor angle at the terminals of the machine, phase c
1	Units for steady state angle: degrees (1) or radians (1rad)
f=	Start steady state operating frequency section and dummy parameters
60	Steady state operating frequency
2	Number of poles
1	Armature winding connections: 0 for Wye grounded, 1 for Wye, 2 for Delta.
R=	Start rated values section
22	Rated line to line voltage (kVRMS)
600	Rated power (MVA)
1200	Field current for 1 pu armature voltage
S=	Start saturation values section
0	Several machines on the same bus
1	P power split
1	Q power split
1	Simulate saturation (0 for no saturation, 1 for saturation)
1	Total saturation (0 for no total saturation, 1 for total saturation)
0	Independent saturation (0 for no independent saturation, 1 for independent saturation)
2	Number of points in the d-axis characteristic
2	Number of points in the q-axis characteristic
1322 1.0 2200 1.2	Magnetization characteristic on d-axis (or both axis)
Ra=	Start stator windings parameters section
.0045	Armature resistance
.14	Armature leakage reactance
.12	Zero-sequence reactance
ds=	Start d-axis data type section
0	0 for Open Circuit or 1 for Short Circuit or 2 for FREQ or 3 for PU

1	Number of dampers on the rotor
1.65	Self reactance for the d-axis of the armature
Xdp=	Start reactance specifications section
0.25	d-axis transient reactance
0.20	d-axis subtransient reactance
0.2273	d-axis sub-subtransient reactance
Td0p=	Start time constant specifications section
4.5	d-axis open-circuit transient time constant
0.04	d-axis open-circuit subtransient time constant
0.00215	d-axis open-circuit sub-subtransient time constant
Noex=	Start extra data section
1	No extra data (1) or extra data (0)
0.0019	First constant for G(p) definition
0.000075	Second constant for G(p) definition
Xc=0	Canay reactance
2	Rotor type : 1 for single cage, 2 for wound, 3 for double cage.
qs=	Start q-axis data type section
0	0 for Open Circuit or 1 for Short Circuit or 2 for FREQ or 3 for PU
2	Number of dampers on the rotor q-axis
1.59	Self reactance for the q-axis of the armature
Xdq=	Start reactances specifications section
0.46	q-axis transient reactance
0.20	q-axis subtransient reactance
0.244	q-axis sub-subtransient reactance
Tq0p=	Start time constant specifications section
0.55	q-axis open-circuit transient time constant
0.09	q-axis open-circuit subtransient time constant
0.0085	q-axis open-circuit sub-subtransient time constant
Ms=	Start mechanical parameters section
0	Share mechanical; shaft (1 for yes)
4	Number of masses
2	Index of rotor mass
1	Index of exciter mass
Table of data	Mechanical parameters table (4 masses in this example)
0 2 2 0 0 2 2 0 0 2 2 0 0 2 2 0	Observable, scope and control table
MSu=	Start mechanical parameters units specification section
0	Use H instead of moment of inertia
1	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 when 1
1e-6	Voltage convergence tolerance
CTRL=	Start Control section, 0 means 0ff and 1 means On
0	Control on field voltage (d-axis)
0	Control on external torque
0	Control on external power
0	Control on field voltage
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: 0 for none, 1 for scope request, 2 for observe request, 3 for scope and observe request.

4 Load-Flow model

This machine does not participate (open-circuit) into the Load-Flow solution directly, but it can provide its Thevenin circuit equivalent to the requesting Load-Flow (LF) solution device. It can also reference a Load-Flow solution device (see "Load-Flow solution device" on the first data tab) for automatically retrieving its steady-state voltage phasors from the Load-Flow solution file when acting in the Steady-State solution.

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 SM1 is disconnected in the load-flow solution and is referring to LF3 for its load-flow solution data automatically retrieved by EMTP from the "Load-Flow solution data file" during the subsequent Steady-state solution when "Start from Load-Flow solution" is turned on in the EMTP>Simulation Options. Note also that LF3 is referring back to SM1 for obtaining the Thevenin impedance of LF3 in the Load-Flow solution.
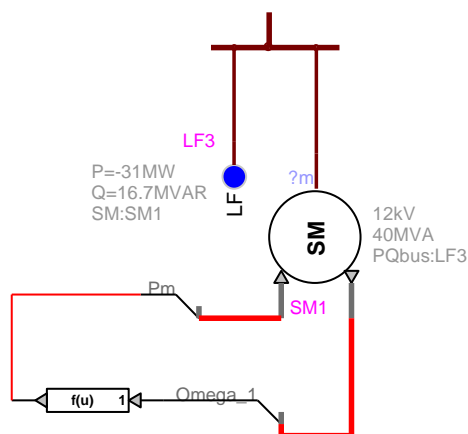
If the selection is "BUS:" the connected stator signal name (bus) will be used to retrieve data. *You must enforce the signal name by making it visible.*

A load function ("Load now" button) option is also available on the first data tab to manually load the steady-state voltage phasors for visualization purposes. It can be also optionally used to eliminate the reference to the Load-Flow solution device in the Steady-state initialization process.

5 Steady-state model

A steady-state solution is always 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. 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.

6   Initial conditions

Initial conditions are calculated from the steady-state solution as explained in "1.6Steady-state initialization". The synchronous machine can not start from no initial conditions, it needs a steady-state solution before starting the time-domain solution.

7   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.

8   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.
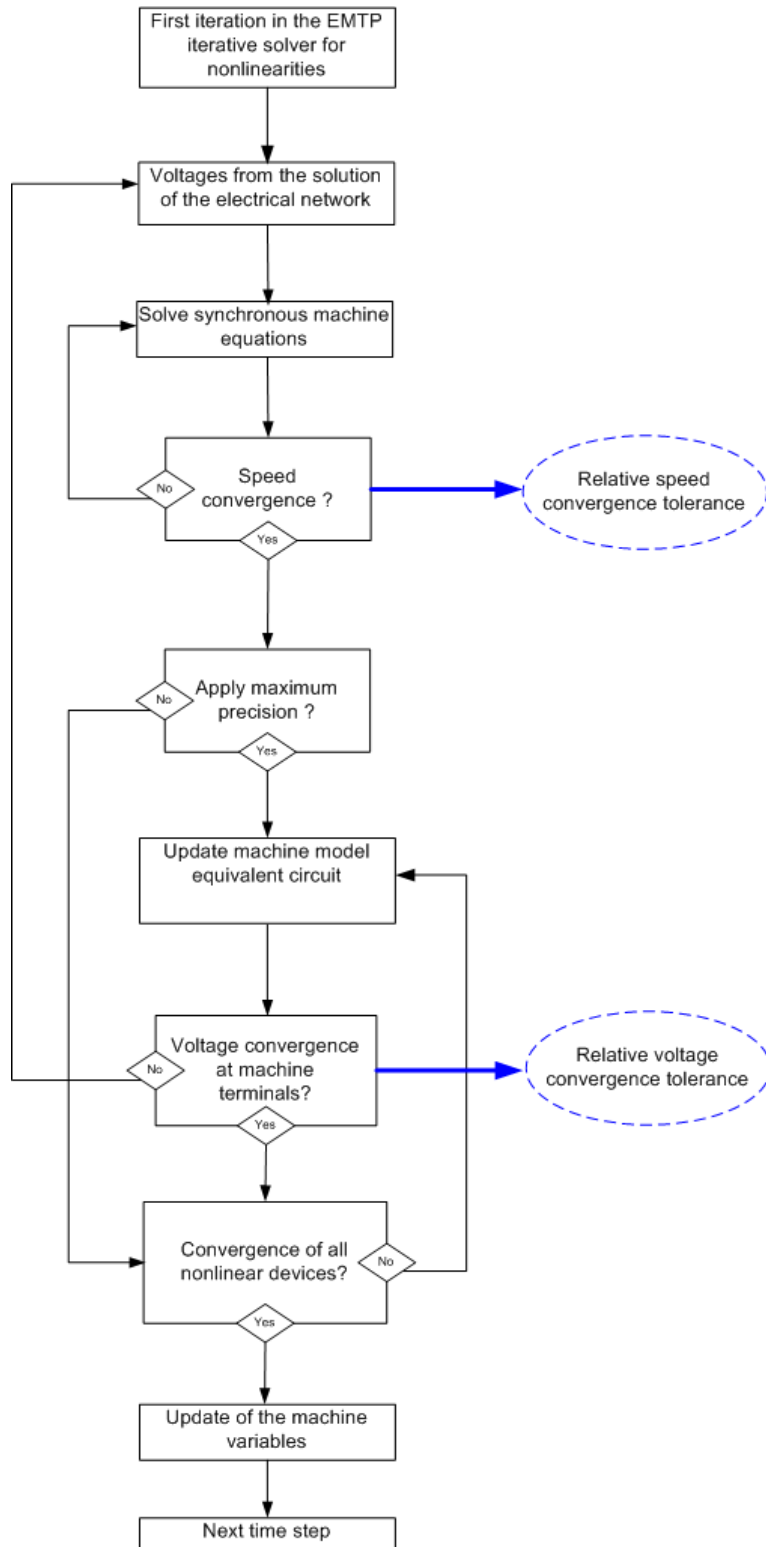
Figure 7 The iterative solution process: speed and voltage loops

9 References

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