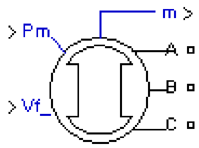
Synchronous Machine

Model the dynamics of three-phase round-rotor or salient-pole synchronous machine

Library

Machines

Description

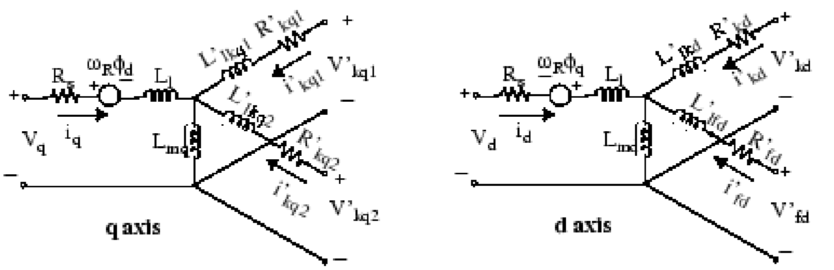


The Synchronous Machine block operates in generator or motor modes. The operating mode is dictated by the sign of the mechanical power (positive for generator mode, negative for motor mode). The electrical part of the machine is represented by a sixth-order state-space model and the mechanical part is the same as in the Simplified Synchronous Machine block.

The model takes into account the dynamics of the stator, field, and damper windings. The equivalent circuit of the model is represented in the rotor reference frame (qd frame). All rotor parameters and electrical quantities are viewed from the stator. They are identified by primed variables. The subscripts used are defined as follows:

- *d,q*: d and q axis quantity
- *R,s*: Rotor and stator quantity
- *l,m*: Leakage and magnetizing inductance
- *f,k*: Field and damper winding quantity

The electrical model of the machine is



with the following equations.

$$V_d = R_s i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q$$

$$V_q = R_s i_q + \frac{d}{dt}\varphi_q + \omega_R \varphi_d$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\varphi'_{fd}$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\varphi'_{kd}$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1}$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2}$$

$$\varphi_d = L_d i_d + L_{md}(i'_{fd} + i'_{kd})$$

$$\varphi_q = L_q i_q + L_{mq} i'_{kq}$$

$$\varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd})$$

$$\varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i_d + i'_{fd})$$

$$\varphi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q$$

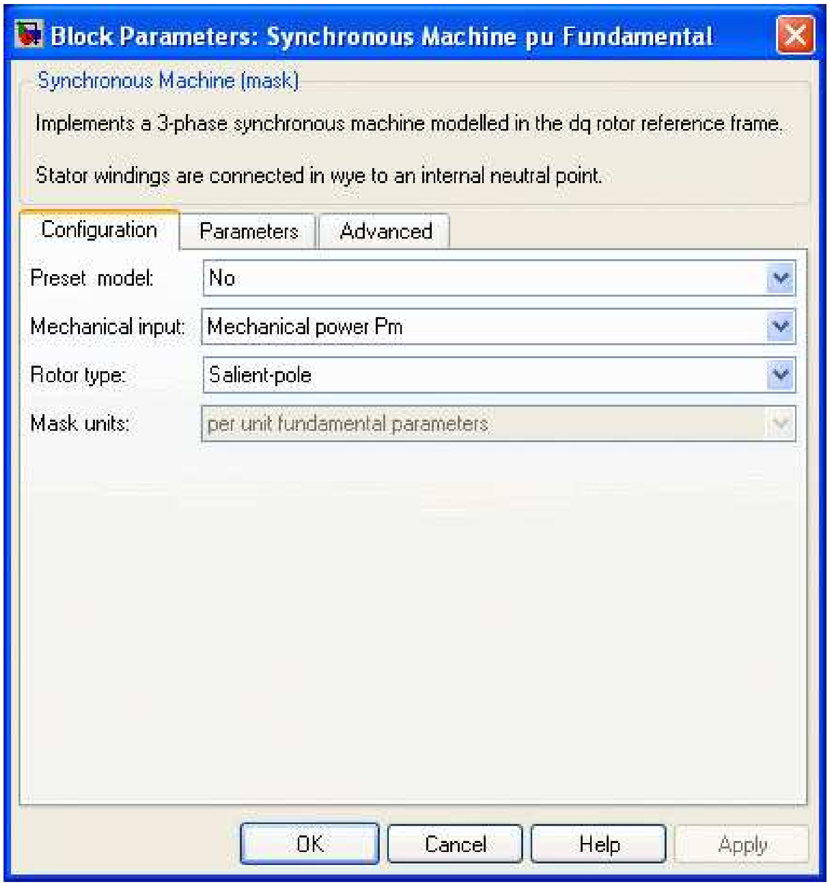
$$\varphi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q$$

Note that this model assumes currents flowing into the stator windings. The measured stator currents returned by the Synchronous Machine block (Ia, Ib, Ic, Id, Iq) are the currents flowing out of the machine.

Dialog Box and Parameters

In the **powerlib** library you can choose between three Synchronous Machine blocks to specify the parameters of the model. They simulate exactly the same synchronous machine model; the only difference is the way of entering the parameter units in the **Parameters** tab.

Configuration Tab



Preset model

Provides a set of predetermined electrical and mechanical parameters for various synchronous machine ratings of power (kVA), phase-to-phase voltage (V), frequency (Hz), and rated speed (rpm).

Select one of the preset models to load the corresponding electrical and mechanical parameters in the entries of the dialog box. Select `No` if you do not want to use a preset model, or if you want to modify some of the parameters of a preset model, as described below.

When you select a preset model, the electrical and mechanical parameters in the **Parameters** tab of the dialog box become unmodifiable (grayed out). To start from a given preset model and then modify machine parameters, you have to do the following:

1. Select the desired preset model to initialize the parameters.
2. Change the **Preset model** parameter value to `No`. This will not change the machine parameters. By doing so, you just break the connection with the particular preset model.
3. Modify the machine parameters as you wish, then click **Apply**.

Mechanical input

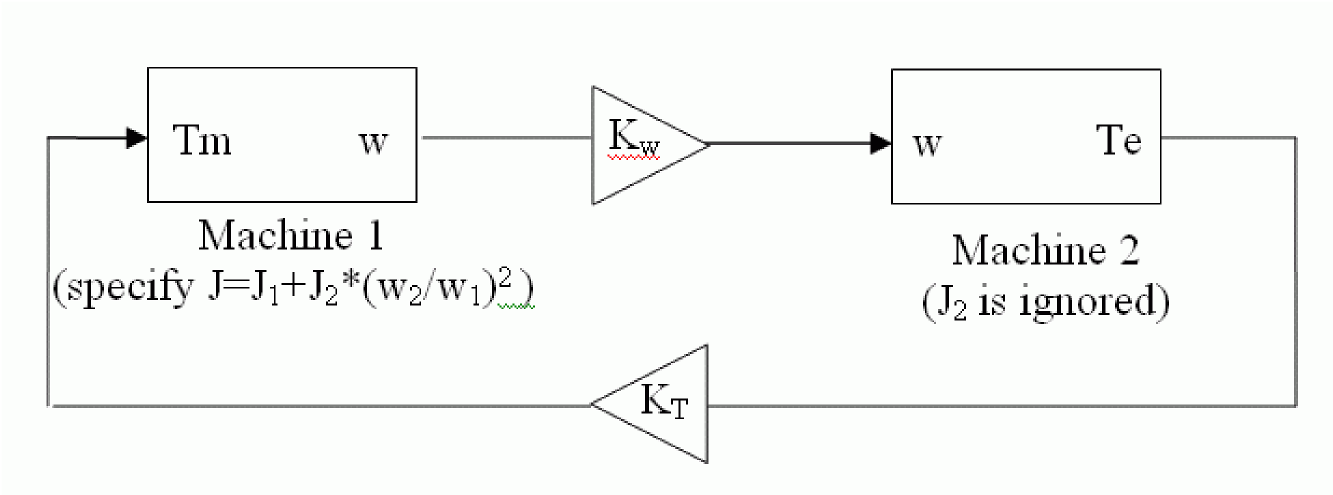
Allows you to select either the torque applied to the shaft or the rotor speed as the Simulink signal applied to the block's input.

Select **Mechanical power Pm** to specify a mechanical power input, in W or in pu, and change labeling of the block's input to `Pm`. The machine speed is determined by the machine Inertia J (or inertia constant H for the pu machine) and by the difference between the mechanical torque Tm, resulting from the the applied mechanical power Pm, and the internal electromagnetic torque Te. The sign convention for the mechanical power is the following: when the speed is positive, a positive mechanical power signal indicates generator mode and a negative signal indicates motor mode.

Select **Speed w** to specify a speed input, in rad/s or in pu, and change labeling of the block's input to `w`. The machine speed is imposed and the mechanical part of the model (inertia constant H) is ignored. Using the speed as the mechanical input allows modeling a mechanical coupling between two machines and interfacing with SimMechanics and SimDriveline models.

The next figure indicates how to model a stiff shaft interconnection in a motor-generator set, where both machines are synchronous machines.

The speed output of machine 1 (motor) is connected to the speed input of machine 2 (generator). In this figure friction torque is ignored in machine 2. Therefore, its electromagnetic torque output Te corresponds to the mechanical torque Tm applied to the shaft of machine 1. The corresponding mechanical input power of machine 1 is computed as Pm = Tm*w.The Kw factor takes into account speed units of both machines (pu or rad/s) and gear box ratio w2/w1. The KT factor takes into account torque units of both machines (pu or N.m) and machine ratings. Also, as the inertia J2 is ignored in machine 2, J2 referred to machine 1 speed must be added to machine 1 inertia J1.



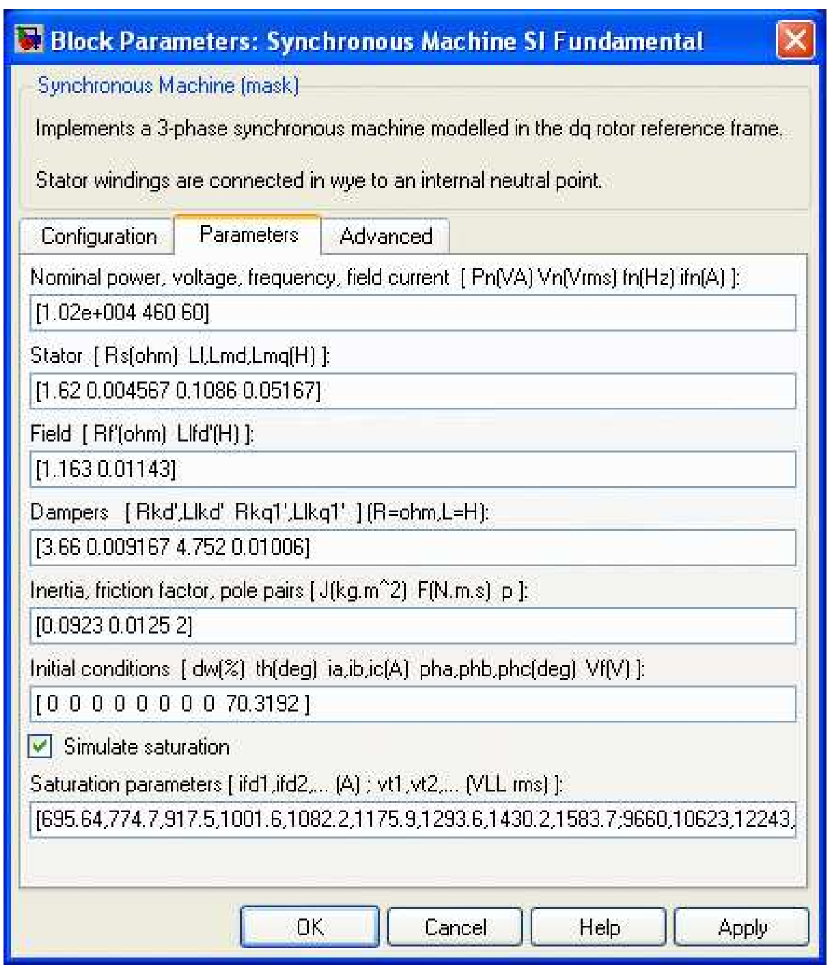
Rotor type

Specify rotor type: `Salient-pole` or `Round` (cylindrical). This choice affects the number of rotor circuits in the q-axis (damper windings).

Mask units

Specifies the units of the electrical and mechanical parameters of the model. This parameter is not modifiable; it is provided for information purposes only.

Parameters Tab for Synchronous Machine SI Fundamental



Nominal power, voltage, frequency, field current

The total three-phase apparent power Pn (VA), RMS line-to-line voltage Vn (V), frequency fn (Hz), and field current ifn (A).

The nominal field current is the current that produces nominal terminal voltage under no-load conditions. This model was developed with all quantities viewed from the stator. The nominal field current makes it possible to compute the transformation ratio of the machine, which allows you to apply the field voltage viewed from the rotor, as in real life. This also allows the field current, which is a variable in the output vector of the model, to be viewed from the rotor. If the value of the nominal field current is not known, you must enter 0 or leave it blank. Since the transformation ratio cannot be determined in this case, you have to apply the field voltage as viewed from the stator and the field current in the output vector is also viewed from the stator.

Stator

The resistance Rs (Ω), leakage inductance Lls (H), and d-axis and q-axis magnetizing inductances Lmd (H) and Lmq (H).

Field

The field resistance Rf' (Ω) and leakage inductance Llfd' (H), both referred to the stator.

Dampers

The d-axis resistance Rkd' (Ω) and leakage inductance Llkd' (H), the q-axis resistance Rkq1' (Ω) and leakage inductance Llkq1' (H), and (only if round rotor) the q-axis resistance Rkq2' (Ω) and leakage inductance Llkq2' (H). All these values are referred to the stator.

Inertia, friction factor, pole pairs

The inertia coefficient J ($kg.m^2$), friction factor F (N.m.s), and number of pole pairs p. The friction torque Tf is proportional to the rotor speed ω (Tf = F.ω, where Tf is expressed in N.m, F in N.m.s, and ω in rad/s).

Initial conditions

The initial speed deviation Δω (% of nominal speed), electrical angle of the rotor Θe (degrees), line current magnitudes ia, ib, ic (A) and phase angles pha, phb, phc (degrees), and the initial field voltage Vf (V).

You can specify the initial field voltage in one of two ways. If you know the nominal field current (first line, last parameter), enter in the dialog box the initial field voltage in volts DC referred to the rotor. Otherwise, enter a zero as nominal field current, as explained earlier, and specify the initial field voltage in volts DC referred to the stator. You can determine the nominal field voltage viewed from the stator by selecting the **Display Vfd which produces a nominal Vt** check box at the bottom of the dialog box.

Simulate saturation

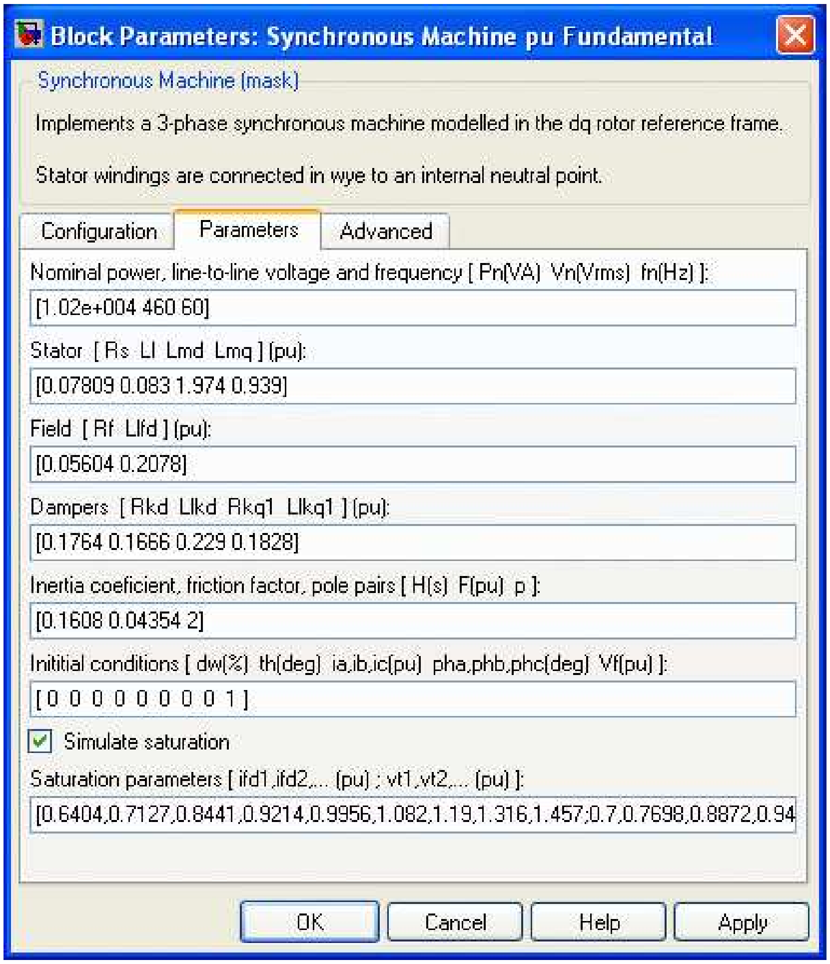
Specifies whether magnetic saturation of rotor and stator iron is to be simulated or not.

Saturation parameters

The no-load saturation curve parameters. Magnetic saturation of stator and rotor iron is modeled by a nonlinear function (in this case a polynomial) using points on the no-load saturation curve. You must enter a 2-by-n matrix, where n is the number of points taken from the saturation curve. The first row of this matrix contains the values of field currents, while the second row contains values of corresponding terminal voltages. The first point (first column of the matrix) must correspond to the point where the effect of saturation begins.

You must select the **Simulate saturation** check box to simulate saturation. This check box allows you to enter the matrix of parameters for simulating the saturation. If you do not want to model saturation in your simulation, do not select the **Simulate saturation** check box. In this case the relationship between ifd and Vt obtained is linear (no saturation).

Parameters Tab for Synchronous Machine pu Fundamental



Nominal power, line-to-line voltage, and frequency

Total three-phase apparent power (VA), RMS line-to-line voltage (V), frequency (Hz), and field current (A).

This line is identical to the first line of the fundamental parameters in SI dialog box, except that you do not specify a nominal field current. This value is not required here because we do not need the transformation ratio. Since rotor quantities are viewed from the stator, they are converted to pu using the stator base quantities derived from the preceding three nominal parameters.

Stator; Field; Dampers

Contain exactly the same parameters as in the previous dialog box, but they are expressed here in pu instead of SI units.

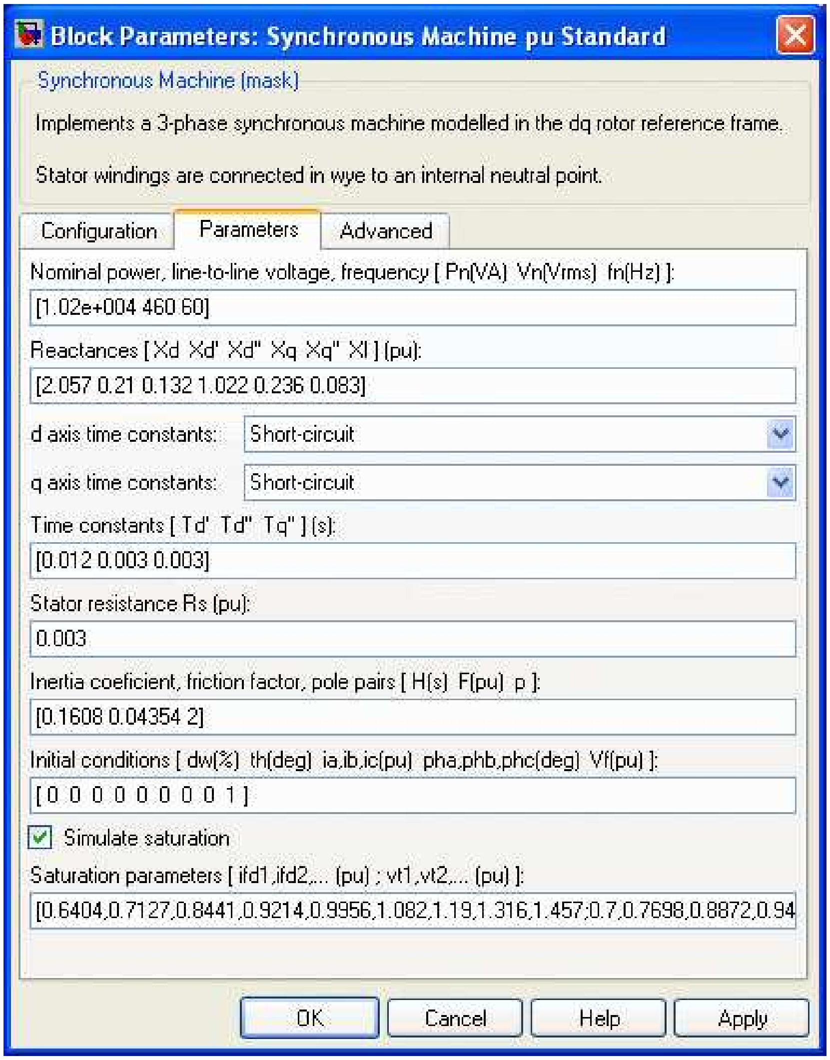
Inertia coefficient, friction factor, pole pairs

The inertia constant H (s), where H is the ratio of energy stored in the rotor at nominal speed over the nominal power of the machine, the friction factor F (pu torque/pu speed), and the number of pole pairs p. The friction torque Tf is proportional to the rotor speed ω (Tf=F.ω, where all quantities are expressed in pu).

Initial conditions; Simulate saturation; Saturation parameters

The same initial conditions and saturation parameters as in the SI units dialog box, but all values are expressed in pu instead of SI units. For saturation, the nominal field current multiplied by the d-axis magnetizing inductance and nominal RMS line-to-line voltage are the base values for the field current and terminal voltage, respectively.

Parameters Tab for Synchronous Machine pu Standard



Nominal power, line-to-line voltage, and frequency

The same parameters as in the pu Fundamental dialog box.

Reactances

The d-axis synchronous reactance Xd, transient reactance Xd', and subtransient reactance Xd'', the q-axis synchronous reactance Xq, transient reactance Xq' (only if round rotor), and subtransient reactance Xq'', and finally the leakage reactance Xl (all in pu).

d-axis time constants; q-axis time constant(s)

Specify the time constants you supply for each axis: either open-circuit or short-circuit.

Time constants

The d-axis and q-axis time constants (all in s). These values must be consistent with choices made on the two previous lines: d-axis transient open-circuit (Tdo') or short-circuit (Td') time constant, d-axis subtransient open-circuit (Tdo'') or short-circuit (Td'') time constant, q-axis transient open-circuit (Tqo') or short-circuit (Tq') time constant (only if round rotor), q-axis subtransient open-circuit (Tqo'') or short-circuit (Tq'') time constant.

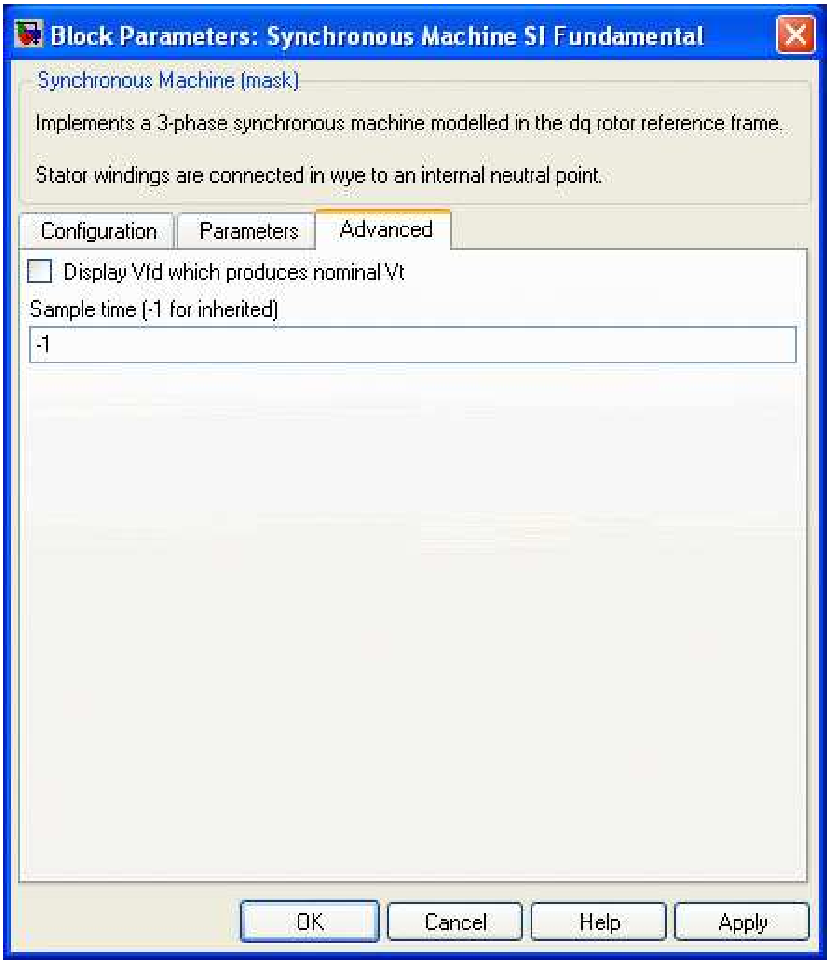
Stator resistance

The stator resistance Rs (pu).

Inertia coefficient, friction factor, pole pairs; Initial conditions; Simulate saturation; Saturation parameters

The same parameters as in the pu Fundamental dialog box.

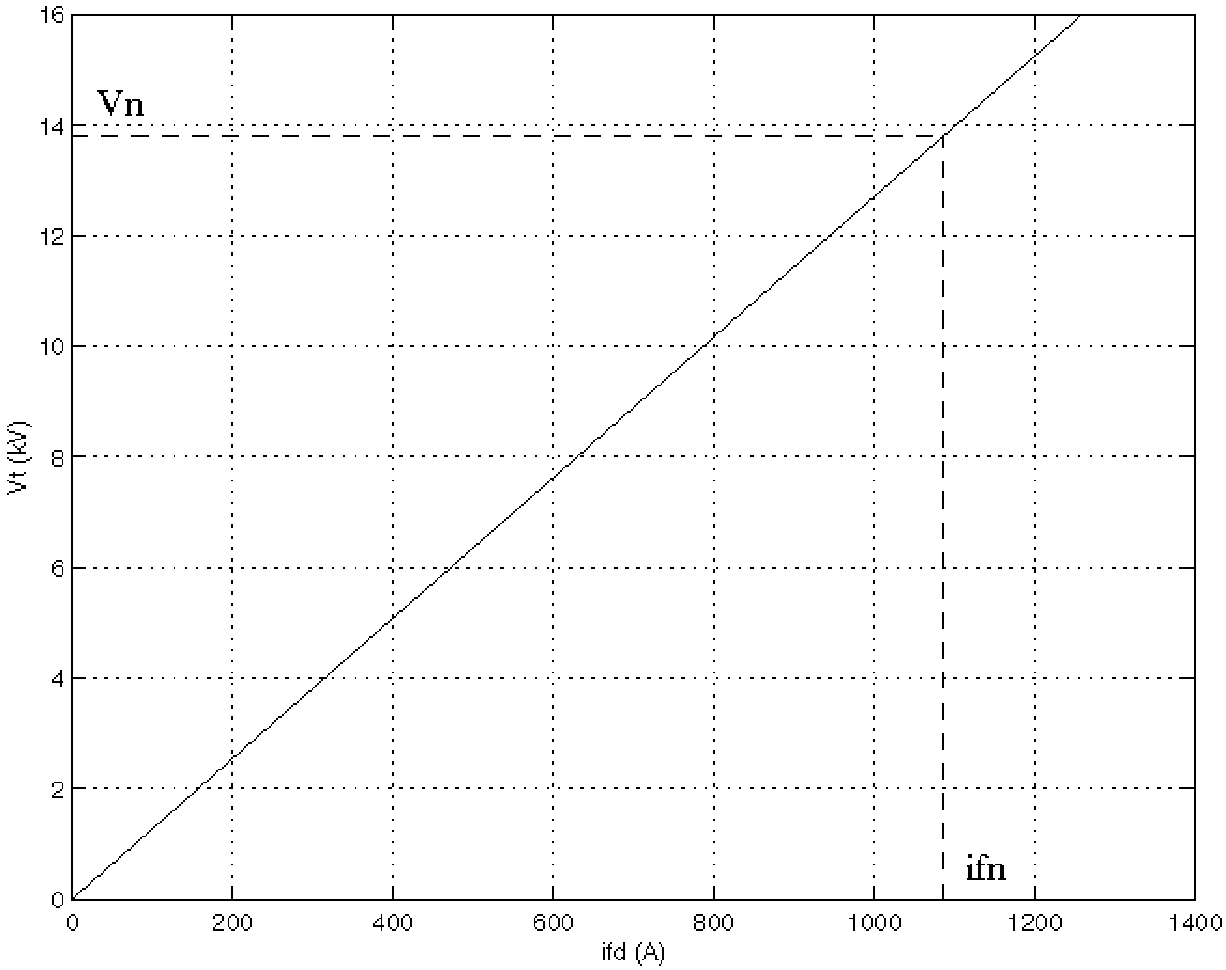
Advanced Tab



Display Vfd which produces a nominal Vt

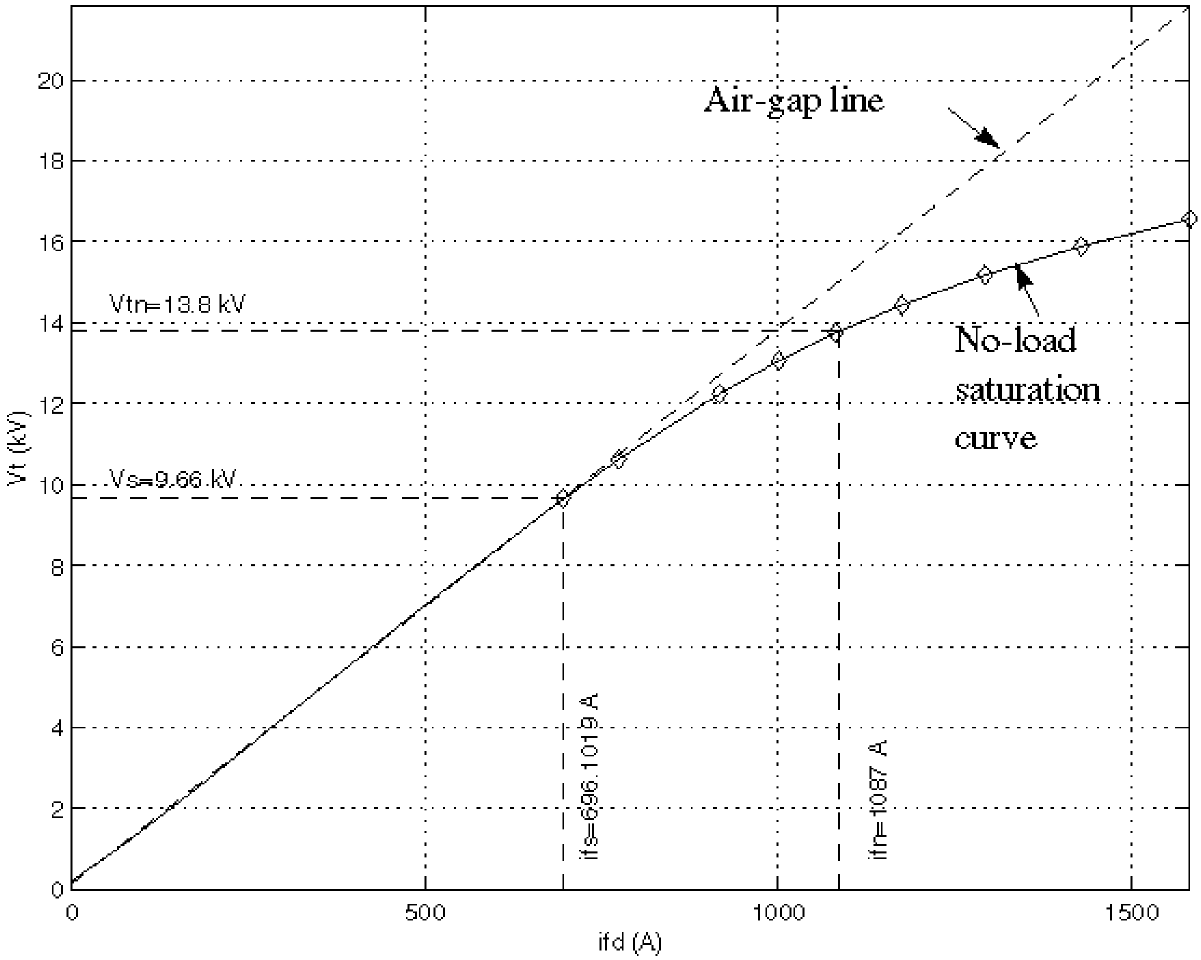
Select to determine the nominal field voltage viewed from the stator. This parameter is visible only for the Synchronous Machine SI Fundamental block.

As an example, without saturation, a typical curve might be as shown below. Here ifn is 1087 A and Vn is 13800 V RMS line-to-line, which is also 11268 V peak line-to-neutral.



Saturation is modeled by fitting a polynomial to the curve corresponding to the matrix of points you enter. The more points you enter, the better the fit to the original curve.

The next figure illustrates the good fit graphically (the diamonds are the actual points entered in the dialog box).



In this particular case, the following values were used:

ifn	1087 A
ifd	[695.64, 774.7, 917.5, 1001.6, 1082.2, 1175.9, 1293.6, 1430.2, 1583.7] A
Vt	[9660, 10623, 12243, 13063, 13757, 14437, 15180, 15890, 16567] V

Sample time (-1 for inherited)

Specifies the sample time used by the block. To inherit the sample time specified in the Powergui block, set this parameter to `-1`.

Inputs and Outputs

The units of inputs and outputs vary according to which dialog box was used to enter the block parameters. If the fundamental parameters in SI units is used, the inputs and outputs are in SI units (except for dw in the vector of internal variables, which is always in pu, and angle Θ, which is always in rad). Otherwise, the inputs and outputs are in pu.

`Pm`

The first Simulink input is the mechanical power at the machine's shaft. In generating mode, this input can be a positive constant or function or the output of a prime mover block (see the Hydraulic Turbine and Governor or Steam Turbine and Governor blocks). In motoring mode, this input is usually a negative constant or function.

`w`

The alternative block input instead of `Pm` (depending on the value of the **Mechanical input** parameter) is the machine speed, in rad/s.

`Vf`

The second Simulink input of the block is the field voltage. This voltage can be supplied by a voltage regulator in generator mode (see the Excitation System block). It is usually a constant in motor mode.

If you use the model in SI fundamental units, the field voltage Vf should be entered in volts DC if nominal field current Ifn is specified or in volts referred to stator if Ifn is not specified. To obtain the Vfd producing nominal voltage, select the last check box of the dialog box. If you use the model in pu Standard or in pu Fundamental units, Vf should be entered in pu (1 pu of field voltage producing 1 pu of terminal voltage at no load).

m

The Simulink output of the block is a vector containing 22 signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library.

Signal	Definition	Units
1	Stator current is_a	A or pu
2	Stator current is_b	A or pu
3	Stator current is_c	A or pu
4	Stator current is_q	A or pu
5	Stator current is_d	A or pu
6	Field current ifd	A or pu
7	Damper winding current ikq1	A or pu
8	Damper winding current ikq2	A or pu
9	Damper winding current ikd	A or pu
10	Mutual flux phimq	V.s or pu
11	Mutual flux phimd	V.s or pu
12	Stator voltage vq	V or pu
13	Stator voltage vd	V or pu
14	Rotor angle deviation d_theta	rad
15	Rotor speed wm	rad/s.
16	Electrical power Pe	VA or pu
17	Rotor speed deviation dw	rad/s
18	Rotor mechanical angle theta	rad
19	Electromagnetic torque Te	N.m or pu
20	Load angle delta	N.m or pu
21	Output active power Peo	rad

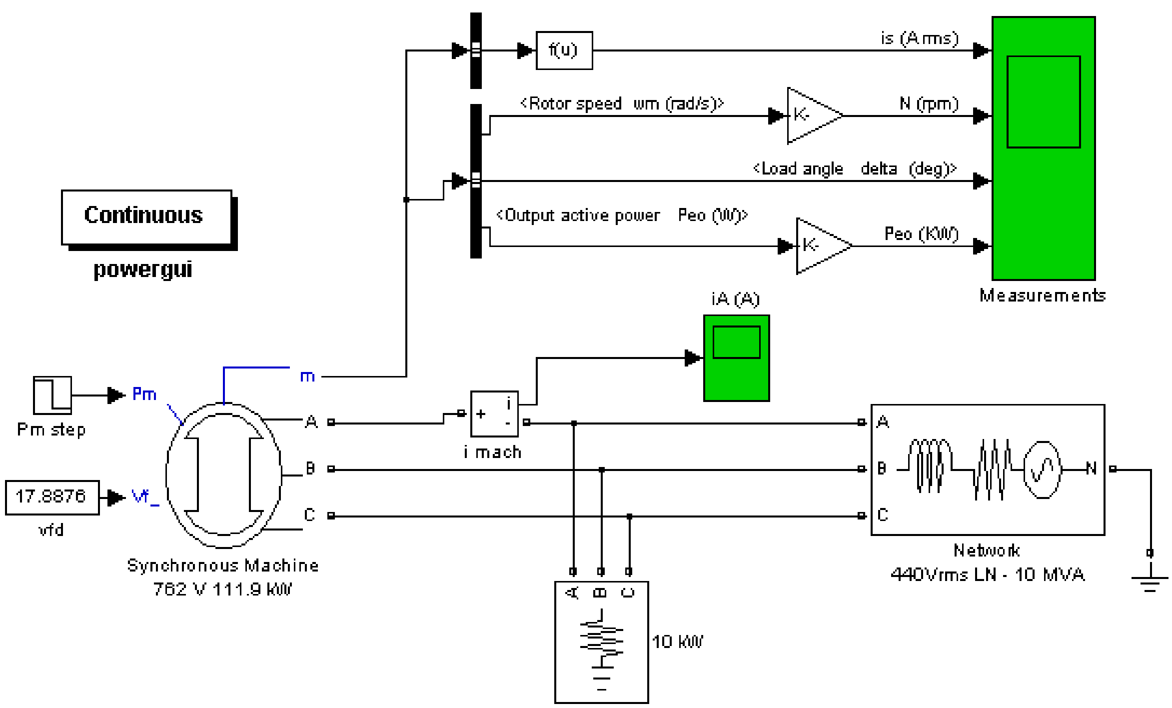
Signal	Definition	Units
22	Output reactive power Qeo	rad

Limitations

When you use Synchronous Machine blocks in discrete systems, you might have to use a small parasitic resistive load, connected at the machine terminals, in order to avoid numerical oscillations. Large sample times require larger loads. The minimum resistive load is proportional to the sample time. As a rule of thumb, remember that with a 25 μs time step on a 60 Hz system, the minimum load is approximately 2.5% of the machine nominal power. For example, a 200 MVA synchronous machine in a power system discretized with a 50 μs sample time requires approximately 5% of resistive load or 10 MW. If the sample time is reduced to 20 μs, a resistive load of 4 MW should be sufficient.

Example

The `power_syncmachine` demo illustrates the use of the Synchronous Machine block in motor mode. The simulated system consists of an industrial grade synchronous motor (150 HP (112 kVA), 762 V) connected to a network with a 10 MVA short-circuit level. In order to start simulation in steady state, the machine is initialized using the **Load Flow and Machine Initialization** option of the Powergui. The machine is initialized for an output electrical power of -50 kW (negative value for motor mode), corresponding to a mechanical power of -48.9 kW. The corresponding values of mechanical power and field voltage have been automatically entered by the **Load Flow** analysis into the Pm Step block and in the Vf Constant block. The Pm Step block has been programmed in order to apply a sudden increase of mechanical power from -48.9 kW to -60 kW at time t = 0.1 s.



Run the simulation and observe the RMS current, RMS voltage, speed, load angle δ, and output electrical power of the motor.

Since this is a four-pole machine, the nominal speed is 1800 rpm. The initial speed is 1800 rpm as prescribed. After the load has increased from 48.9 kW to 100 kW at t = 0.1 s, the machine speed oscillates before stabilizing to 1800 rpm. The load angle (angle between terminal voltage and internal voltage) increases from -21 degrees to -53 degrees.

References

[1] Krause, P.C., *Analysis of Electric Machinery*, McGraw-Hill, 1986, Section 12.5.

[2] Kamwa, I., et al., "Experience with Computer-Aided Graphical Analysis of Sudden-Short-Circuit Oscillograms of Large Synchronous Machines," *IEEE Transactions on Energy Conversion*, Vol. 10, No. 3, September 1995.

See Also

Excitation System, Hydraulic Turbine and Governor, Powergui, Simplified Synchronous Machine, Steam Turbine and Governor

Was this topic helpful? Yes No