About

Provide general information regarding the described model.

Model name	SynchronousMachine
Author / organization	Andrés Felipe Cortés Borray / TECNALIA
Short description	A model of a small three-phase synchronous machine in generator mode with constant mechanical power and the excitation system control.
Present use / development status	The model is part of TECNALIA's repository in Simulink for electric power components and is usable for simulation in combination with other electric network models. This model was defined for low voltage network applications.

Classification

Describe the context of the model regarding application (modelling domain, intended use) and technical details (modelling approach, model dynamics, model of computation, functional representation).

Domain	☐ electrical storage ☐ thermal storage ☐ energy conversion device ☒ other, please specify: Rotary electrical machine
Intended application (including scale and resolution)	It is intended to be used to simulate a three-phase synchronous machine for an European low voltage network. By combining it with linear and nonlinear elements such as transformers, lines, loads, breakers, etc., it can be used to simulate electromechanical transients in an electrical network. The temporal resolution is milliseconds to a few seconds. The model can be used directly in a low voltage network or through an MV/LV transformer for higher voltage levels.
Modelling of spatial aspects *Explain the approach of how this model describes the spatial distribution of the system.*	☐ lumped (single device) ☒ discretized (single device) ☐ averaged (multiple devices) ☐ other, please specify: The model represents a three-phase synchronous generator to be coupled to a low voltage network.
Model dynamics *Explain how the model captures the dynamic behaviour of the system.*	☐ quasi-static ☒ dynamic ☐ other, please specify:

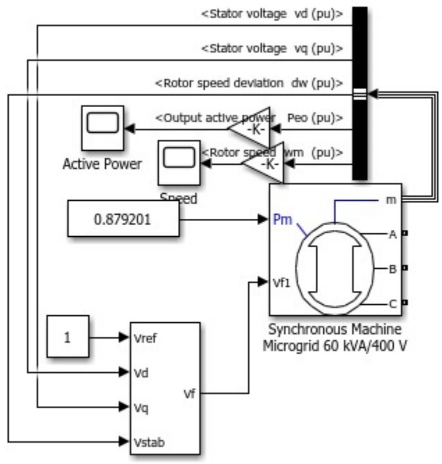
	The synchronous machine is modelled using standard parameters in p.u. The operating mode is dictated by the sign of the mechanical power (positive for generator mode or negative for motor mode). The electrical part of the machine is represented by a sixth-order state-space model and the mechanical part is represented by the following equations. $$\Delta\omega = \frac{1}{2H}\int_0^1 (Tm - Te) - Kd\, \Delta\omega\,(t)dt$$ $$\omega(t) = \Delta\omega(t) + \omega_0$$ where Δω = Speed variation with respect to speed of operation H = constant of inertia Tm = mechanical torque Te = electromagnetic torque Kd = damping factor representing the effect of damper windings ω(t) = mechanical speed of the rotor ω_0 = speed of operation (1 p.u.) See Simulink documentation of the "Simplified Synchronous Machine" for additional mechanical equations. 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 (*dq* frame). Stator windings are connected in wye to an internal neutral point. All rotor parameters and electrical quantities are viewed from the stator.
Model of computation *Explain how the model captures the system's evolution with respect to time and/or external stimuli.*	☒ time-continuous ☒ discrete-event ☐ state machine ☐ other, please specify:
	By combining the model with linear and nonlinear elements such as transformers, lines, loads, breakers, etc., it can be used to simulate electromechanical transients in an electrical network. The simulation type can be set through the "powergui" interface in Simulink, depending on the surrounding elements of the network.
Functional representation	☒ explicit ☐ implicit ☐ other, please specify:

Are the model functions explicit, i.e., of type y = f(x), or implicit, i.e., of type g(x,y) = 0?	

Mathematical Model

This section provides information about the actual mathematical model by specifying variables, parameters and equations. Variables and parameters should be specified with type (Real, Integer, Boolean, String) and (physical) unit. In case the equations are too complex to be reproduced here, also a reference to a book or any other publication can be given.

Input variables (name, type, unit, description)	**Pm**, Real, [p.u.], mechanical power at the machine's shaft, specified as a scalar. In generator mode, this input can be a positive constant or function or the output of a prime mover block. **w**, Real, [rad/s], machine speed. **Vf**, Real, [p.u.], field voltage. This voltage can be supplied by a voltage regulator in generator mode.
Output variables (name, type, unit, description)	The main output variables are listed below. See Simulink model documentation for the remaining variables. **theta**, Real, [degree], rotor mechanical angle **delta**, Real, [degree], load angle **Te**, Real, [p.u.], electromagnetic torque **w**, Real, [p.u.], rotor speed **Pe**, Real, [p.u.], electrical power **Pe0**, Real, [p.u.], output active power **Qe0**, Real, [p.u.], output reactive power
Parameters (name, type, unit, description)	See Simulink documentation of the “Synchronous Machine pu Standard” for the list of parameters.
Internal variables (name, type, unit, description)	**w**, Real, [p.u.], rotor speed
Internal constants (name, type, unit, description)	
Model equations *Formulate or provide references to the model’s governing equations (describing the system state) and the constitutive equations (describing material properties)*	Governing equations See Simulink documentation of the “Synchronous Machine pu Standard” and “Simplified Synchronous Machine”. Constitutive equations
Initial conditions	Bus Type: Swing bus Uan phase: 0.00° Uab: 400 Vrms [1 p.u.] 30.00°

	Ubc: 400 Vrms [1 p.u.] -90.00° Uca: 400 Vrms [1 p.u.] 150.00° Ia: 72.088 Arms [0.8324 p.u.] 0.00° Ib: 72.088 Arms [0.8324 p.u.] -120.00° Ic: 72.088 Arms [0.8324 p.u.] 120.00° P: 49944 W [0.8324 p.u.] Q: 0 var [0 p.u.] Pmec: 52752 W [0.8792 p.u.] Torque: 335.83 N.m [0.8792 p.u.] Vf: 1.9814 p.u.
Boundary conditions	-
Optional: graphical representation (schematic diagram, state transition diagram, etc.)	 *Simulink model diagram*

Testing

Please provide a (simple) test design for the purpose of component model validation. This test should enable three different kinds of comparisons:

- ***model validation**: compare the behaviour of an implementation of the exact same model based on time-series data*
- ***model harmonization**: compare the behaviour of an implementation of a (supposedly) similar model with the same or comparable intrinsic time resolution based on the comparison of key performance indicators*
- ***model upscaling**: compare the behaviour of an implementation of a (supposedly) similar model with a lower intrinsic time resolution based on the comparison of aggregated key performance indicators*

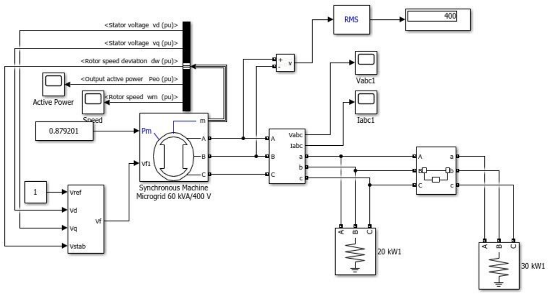
Model Validation *Provide the description of a test setup (i.e., simulation) that enables others to validate their implementation of the same model. The results should be provided as time series.*	
Narrative *Provide a simple description of the test specification.*	A three-phase generator rated 60 kVA, 400 V, 1500 rpm feeds two constant loads rated 10 kW and 30 kW, respectively, which are separated by a three-phase breaker. The breaker remains close during the simulation. The initial

<table>
<tr><td></td><td>parameters of the generator are presented in the "Initial conditions" section.</td></tr>
<tr><td>Test system configuration

Describe the test setup, including:

How long does the simulation run?

Are there any other models required for this setup? If yes, provide a link to their description.

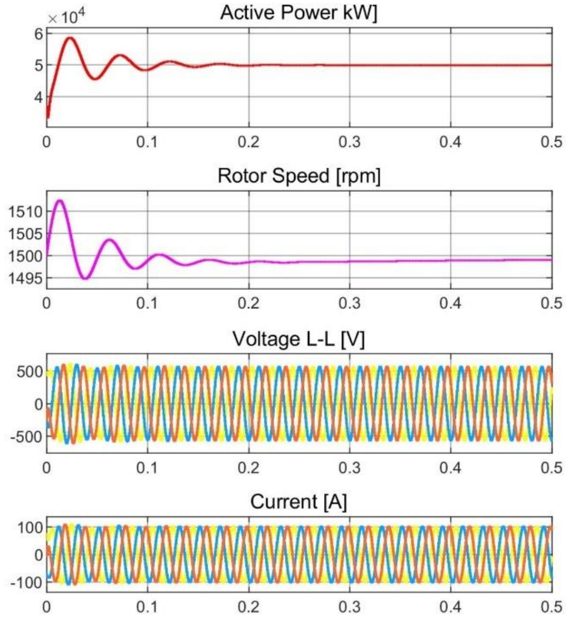
Is a controller required for this setup (see also below)?</td><td>

Simulink diagram of test system configuration

The simulation runs for 0.5 s. The “powergui” interface is configured in Discrete mode with a sample time of 50 µs.</td></tr>
<tr><td>Inputs and parameters

Specify the (exogeneous) inputs of the model used in this test. Also specify the model parameters used in this test. If necessary, attach this information as dataset (SmILES data format).</td><td>Model parameters:
Synchronous Machine
Pn = 6e4 VA
Vn = 400 V
Fn = 50 Hz
Xd = 2.24 p.u.
Xd’ = 0.17 p.u.
Xd’’ = 0.12 p.u.
Xq = 1.02 p.u.
Xq’’ = 0.13 p.u.
Xl = 0.08 p.u.
d axis = Short-circuit
q axis = Short-circuit
Td‘ = 0.012 s
Td‘‘ = 0.003 s
Tq‘‘ = 0.003 s
Rs = 0.037875 p.u.
H = 0.1028 s
F = 0.02056 p.u.
p = 2
Excitation system
Tr = 20e-3 s
Ka = 300
Ta = 0 s
Tb = 0 s
Tc = 0 s
Kf = 0.001
Tf = 0.1 s</td></tr>
</table>

	Efmin = -11.5 [p.u.] Efmax = 11.5 [p.u.] Kp = 0 Vt0 = 1 p.u. Vf0 = 1.9814 p.u. Inputs: **Pm:** 0.8792 p.u. Outputs: **w**, rotor speed **Pe**, electrical power Three-phase voltage and current
Control function (optional) *Specify any additional control functions used for this test.*	
Initial system state *Describe the initial state of the system.*	The initial state of the generator is presented in the "Initial conditions" section.
Temporal resolution *Provide information regarding the temporal resolution of the test simulation, such as integrator step size, time resolution for event handling, etc.*	A fundamental sample time of "auto" is used based on the equation below. Simulation result outputs are generated every 50 µs. $$h_{max} = \frac{t_{stop} - t_{start}}{50}$$
Evolution of system state *Describe (textual and/or graphical) the expected qualitative behaviour of the component model in this simulation.*	When the generator starts to feed the load, a rapid transient event will occur due to the change of power demand, then the rotor speed will decrease up to reach a close value to the rated velocity. If a disconnection event will be carried out, i.e., loss of load, the generator would start to accelerate above its rate speed because the mechanical power remains constants. This effect will also be appear reflected in a higher output voltage.
Expected results *Provide a quantitative description of the expected simulation output based on time series. This information must be comprehensive enough for someone else to validate his/her own implementation of this model. If necessary, attach this information as dataset (SmILES data format).*	The generator starts with a sudden reconnection of the load. This action provokes a transient event in the rotor speed and the output power, which is quickly damped at 0.25 s. As expected, the magnitude of the 50 Hz voltage stays at 567 V (400 V RMS).

	 *Figure: Results for synchronous generator starting assuming a total constant load of 50 kW and a mechanical power of 0.8792 p.u.* The numerical values are provided in the attached data file (*SynchronousMachine.slx*).

Sensitivity analysis (optional) *Provide additional information that enables others to validate their implementation of the same model. The goal is to understand how different sources of uncertainty in the component model input affect the model's output.*	
Narrative *Provide a simple description of the test specification.*	
Test system configuration *Describe the test setup, including:* *How long does the simulation run?* *Are there any other models required for this setup? If yes, provide a link to their description.* *Is a controller required for this setup (see also below)?*	
Source of uncertainty *Specify the source of uncertainty for this specific sensitivity analysis.*	
Inputs and parameters *Specify the (exogeneous) inputs of the model used in this test. Also specify the model parameters used in*	

this test. If necessary, attach this information as dataset (SmILES data format).	
Control function (optional) *Specify any additional control functions used for this test.*	
Initial system state *Describe the initial state of the system.*	
Temporal resolution *Provide information regarding the temporal resolution of the test simulation, such as integrator step size, time resolution for event handling, etc.*	
Evolution of system state *Describe (textual and/or graphical) the expected <u>qualitative behaviour</u> of the component model in this simulation.*	
Expected results *Provide a <u>quantitative description</u> of the expected simulation output. This information must be comprehensive enough for someone else to validate his/her own implementation of this model. If necessary, attach this information as dataset (SmILES data format).*	

Model harmonization *Provide information that enables others to compare the behaviour of similar models with this model. The results should be provided as KPIs, targeting a time resolution that is lower than that of the model itself. For instance, if the intrinsic time resolution of the model is seconds, then the provided KPI should measure a significant attribute of the modelled system on an hourly or daily basis.*	
Narrative *Provide a simple description of the test specification.*	Same as in model validation.
Test system configuration *Describe the test setup, including:* *How long does the simulation run?*	Same as in model validation.

Are there any other models required for this setup? If yes, provide a link to their description. *Is a controller required for this setup (see also below)?*	
Inputs and parameters *Specify the (exogeneous) inputs of the model used in this test. Also specify the model parameters used in this test. If necessary, attach this information as dataset (SmILES data format).*	Same as in model validation.
Control function (optional) *Specify any additional control functions used for this test.*	Same as in model validation.
Initial system state *Describe the initial state of the system.*	Same as in model validation.
Temporal resolution *Provide information regarding the temporal resolution of the test simulation, such as integrator step size, time resolution for event handling, etc.*	Same as in model validation.
Evolution of system state *Describe (textual and/or graphical) the expected qualitative behaviour of the component model in this simulation.*	Same as in model validation.
Expected results *Provide a quantitative description of the expected simulation output based on key performance indicators. This information must be comprehensive enough for someone else to validate his/her own implementation of this model. If necessary, attach this information as dataset (SmILES data format).*	

Additional Information

Provide any other additional information here.

Reference implementation	See Synchronous Machine pu Standard model (https://www.mathworks.com/help/physmod/sps/powersys/ref/synchronousmachinepustandard.html) See Simplified Synchronous Machine model (https://www.mathworks.com/help/physmod/sps/powersys/ref/simplifiedsynchronousmachine.html)
Similar / related models	See Synchronous Machine pu Standard model (https://www.mathworks.com/help/physmod/sps/powersys/ref/synchronousmachinepustandard.html) See Simplified Synchronous Machine model (https://www.mathworks.com/help/physmod/sps/powersys/ref/simplifiedsynchronousmachine.html)
Related publications	Simulink specification (https://www.mathworks.com/help/simulink/index.html)
Intellectual property concerns (if applicable)	