About

Provide general information regarding the described model.

Model name	VariableSpeedAsynchronousMachine
Author / organization	Andrés Felipe Cortés Borray / TECNALIA
Short description	A model of an asynchronous machine fed by pulse width modulation (PWM) voltage sourced converter (VSC)
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 is a simple open-loop AC drive controlling an asynchronous machine.

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 the variable speed control of a three-phase asynchronous machine by using forced-commutated electronic switches such as IGBTs, which are controlled by pulse width modulation (PWM). 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 squirrel-cage asynchronous machine fed by pulse width modulation (PWM) voltage sourced converter (VSC).
Model dynamics	☐ quasi-static

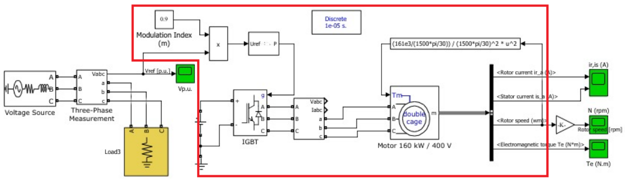
Explain how the model captures the dynamic behaviour of the system.	☒ dynamic ☐ other, please specify:	
	The electrical part of the machine is represented by a fourth-order state-space model and the mechanical part by a second-order system. All electrical variables and parameters are referred to the stator. All stator and rotor quantities are in the arbitrary two-axis reference frame (dq frame). The model is able to capture several variables such as rotor angle and speed, rotor and stator current, and electromagnetic torque when any voltage disturbance at the electrical network occurs. It is assumed a quadratic torque-speed characteristic (fan or pump type load) for the motor.	
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 *Are the model functions explicit, i.e., of type y = f(x), or implicit, i.e., of type g(x,y) = 0?*	☒ explicit ☐ implicit ☐ other, please specify:	

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)	• PWM Generator (2-Level) **Uref**, Real, [p.u.], the vectorized reference signal used to generate the output pulses • Universal Bridge **g**, Boolean, [p.u.], the gate input for the controlled switch devices.

	{+, -}, Real, [V], DC voltage supply at the positive and negative terminals • Asynchronous Machine **Tm**, Real, [Nm], mechanical torque at the machine's shaft, specified as a scalar.
Output variables (name, type, unit, description)	• PWM Generator (2-Level) **P**, Boolean, [p.u.], six pulse signals used to fire the IGBTs of a three-arm converter. • Universal Bridge **{A, B, C}**, Real, [V] [I], the three-phase voltages and the three-phase currents flowing through the six power electronic devices • Asynchronous Machine The main output variables are listed below. See Simulink models for the remaining variables. **theta**, Real, [rad], rotor angle **Te**, Real, [N m], electromagnetic torque **w**, Real, [rad/s], rotor speed
Parameters (name, type, unit, description)	• PWM Generator (2-Level) See Simulink documentation for the list of parameters. • Universal Bridge See Simulink documentation for the list of parameters. • Asynchronous Machine See Simulink documentation for the list of parameters.
Internal variables (name, type, unit, description)	• Asynchronous Machine **w**, Real, [rad/s], 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
	• PWM Generator (2-Level) Stefanos N. Manias, 6 - Inverters (DC–AC Converters), Editor(s): Stefanos N. Manias, Power Electronics and Motor Drive Systems, Academic Press, 2017, Pages 271-500, ISBN 9780128117989, https://doi.org/10.1016/B978-0-12-811798-9.00006-8 • Universal Bridge Stefanos N. Manias, 6 - Inverters (DC–AC Converters), Editor(s): Stefanos N. Manias, Power Electronics and Motor Drive Systems, Academic Press, 2017, Pages 271-500, ISBN 9780128117989, https://doi.org/10.1016/B978-0-12-811798-9.00006-8

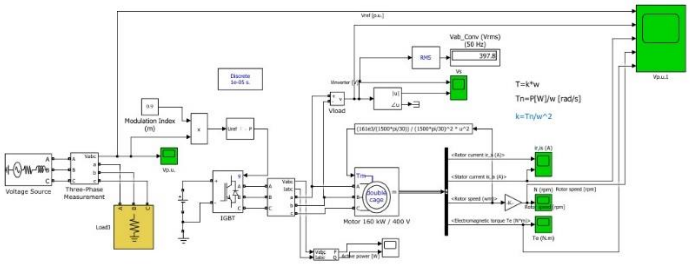
	• Asynchronous Machine See Simulink documentation for the Double Squirrel-Cage Machine.
	Constitutive equations
Initial conditions	**Tm** = 0 [N m] **w =** 0 [rad/s]
Boundary conditions	-
Optional: graphical representation (schematic diagram, state transition diagram, etc.)	 *Simulink model diagram*

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.*	The machine rotor is short-circuited, and the stator is fed by a PWM inverter, which is in turn fed by a DC power source. The base frequency of the sinusoidal reference wave is set at 50 Hz, and the triangular carrier wave frequency is set at 1650 Hz. This frequency corresponds to a frequency modulation factor ***mf*** of 33 (50 Hz x 33 = 1650 Hz). The voltage reference in p.u. comes from the equivalent AC power source at 400 V 50 Hz. The machine is connected to a variable load where the torque Tm is proportional to the square of the speed ω.

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)?*	 *Simulink diagram of test system configuration* The simulation runs for 1 s. The "powergui" interface is configured in Discrete mode with a sample time of 10 µs.
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).*	Model parameters: • PWM Generator (2-Level) Generator type: Three-phase bridge (6 pulses) Mode of operation: Unsynchronized Frequency: 1650 Hz Initial phase: 0° Minimum and maximum values: [-1 1] p.u. Sampling technique: Natural Sample time: 10e-6 s • Universal Bridge Number of bridge arms = 3 Rs = 1e5 Ohm Cs = inf Power Electronic device = IGBT / Diodes Ron = 1e-3 Ohm Forward voltages = [0 0] V • Asynchronous Machine Pn = 1.6e5 VA Vn = 400 V Fn = 50 Hz Rs = 0.0305 Ohm Lls = 0.0001481 H Rr1' = 0.008155 Ohm Llr1' = 0.00032 H Rr2' = 0.08948 Ohm Llr2' = 0.0001481 H Lm = 0.005787 H J = 10 kg m^2 F = 0.05658 Nms p = 2 slip = 0

	th = 0° ia, ib, ic = 0, 0, 0 A pha, phb phc = 0°, -120°, 120° Inputs: • **Tm**: Implement the torque-speed characteristic of the motor load based on the following function: (160e3/(1500*pi/30)) / (1500*pi/30)^2 * u^2 where u^2 is the dynamic rotor speed, which comes from: $$T = k \times \omega^2$$ $$T_n = \frac{160000\ W}{1500\ rpm\ \times \pi/30} = 1018.6\ N\ m$$ $$k = \frac{T_n}{\omega^2} = \frac{1018.6\ Nm}{(1500\ rpm\ \times \pi/30)^2} = 0.041$$ • **{+, -}**: The voltage value of the DC power source is computed based on a nominal line to line voltage of 400 V: $$V_{LL-RMS} = \frac{\text{mf}}{2} \times \frac{\sqrt{3}}{\sqrt{2}} V_{DC}$$ $$V_{DC} = \frac{400\ V}{0.9 \times 0.612} = 726\ V$$ Outputs: • u^2 = ω^2, rotor speed • Three-phase voltage at the PWM inverter
Control function (optional) *Specify any additional control functions used for this test.*	
Initial system state *Describe the initial state of the system.*	**Tm** = 0 [N m] **w** = 0 [rad/s]
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 10 µs. $$h_{max} = \frac{t_{stop} - t_{start}}{50}$$
Evolution of system state *Describe (textual and/or graphical) the expected qualitative behaviour of*	When the PWM inverter starts to feed the motor based on the three-phase voltage reference from the low voltage network, a very high peak current at the stator occurs due to the direct starting. Because the stator is fed by a PWM

<table>
<tr>
<td>the component model in this simulation.</td>
<td>inverter, a noisy torque will appear. After few seconds, the machine's speed going from 0 rpm to a value close to its nominal speed. As the velocity increase, the motor's torque is damped to its rated value. If there is any variation in the voltage level of the network, it will be appear reflected in all the variables of the motor.</td>
</tr>
<tr>
<td>Expected results

Provide a <u>quantitative description</u> of the expected simulation output <u>based on time series</u>. 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).</td>
<td>The motor starts and reaches its steady-state speed of 1487 rpm (155 rad/s) after 0.9 s. At starting, the magnitude of the 50 Hz current reaches 3734 A peak (2640 A RMS) whereas its steady-state value is 371 A (262 A RMS). As expected, the magnitude of the 50 Hz voltage contained in the chopped wave stays at 565 V (400 V RMS). Also, it is noticed strong oscillations of the electromagnetic torque at starting. In steady-state, it can be observed a noisy signal with a mean value of 1016.8 N m, corresponding to the load torque at nominal speed. Because the stator is fed by a PWM inverter, a noisy torque is observed. The nominal speed is slightly lower than the synchronous speed of 1500 rpm, or ws = 157 rad/s.

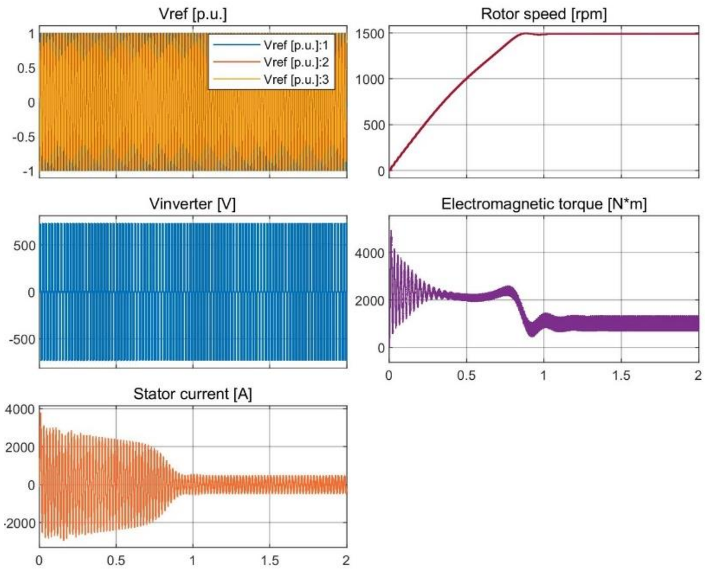


Figure: Results for motor starting assuming a mechanical load (fan) with a 10 kg m^2 (3.32 [motor axis] + 6.68 [fan]) moment of inertia.

The numerical values are provided in the attached data file (VariableSpeedAsynchronousMachine.slx).</td>
</tr>
</table>

<table>
<tr>
<td colspan="2">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.</td>
</tr>
<tr>
<td>Narrative</td>
<td></td>
</tr>
</table>

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 qualitative behaviour of the component model in this simulation.*	
Expected results *Provide a quantitative description 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?* *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)?*	Same as in model validation.
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.*	
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	Same as in model validation.

Describe (textual and/or graphical) the expected qualitative behaviour of the component model in this simulation.	
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 Asynchronous Machine model (https://www.mathworks.com/help/physmod/sps/powersys/ref/asynchronousmachine.html?s_tid=doc_ta) PWM Generator (2-Level) model (https://www.mathworks.com/help/physmod/sps/powersys/ref/pwmgenerator2level.html?s_tid=doc_ta) Universal Bridge model (https://www.mathworks.com/help/physmod/sps/powersys/ref/universalbridge.html?s_tid=doc_ta)
Similar / related models	See Asynchronous Machine model (https://www.mathworks.com/help/physmod/sps/powersys/ref/asynchronousmachine.html?s_tid=doc_ta) PWM Generator (2-Level) model (https://www.mathworks.com/help/physmod/sps/powersys/ref/pwmgenerator2level.html?s_tid=doc_ta) Universal Bridge model (https://www.mathworks.com/help/physmod/sps/powersys/ref/universalbridge.html?s_tid=doc_ta)
Related publications	Simulink specification (https://www.mathworks.com/help/simulink/index.html)
Intellectual property concerns (if applicable)	