About

Provide general information regarding the described model.

Model name	Grid-following converter
Author / organization	Riccardo Lazzari / RSE
Short description	The model represents a three-phase voltage source inverter, with its own LCL output filter, controlled as grid-following converter. The control regulates the real and reactive power injection to the reference values, while it also achieves a smooth grid synchronization.
Present use / development status	The model was developed for the purposes of the ERIGrid 2.0 H2020 project, starting from the RSE's internal library of electrical components.

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: DERs
Intended application (including scale and resolution)	This model can be used for the simulation of a grid-following converter that interfaces a DC source with the AC electrical grid.
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:
	This control scheme can be employed at multiple grid-connected inverters as long as they are supposed to follow a grid-following control philosophy.
Model dynamics *Explain how the model captures the dynamic behaviour of the system.*	☒ quasi-static ☒ dynamic ☐ other, please specify:
	The model of the converter is simplified to reduce the simulation effort: the DC source is considered constant and the three-phase bridge inverter is replaced with three

	controllable sinusoidal voltage generators. This model takes into account all the converter dynamics, but it doesn't represent the high frequency components due to the PWM. Its resolution lies in the range of ms.
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:
	The controller continuously reads the voltage at the point of common coupling and adjusts the inverter current injection to meet the reference real and reactive power.
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

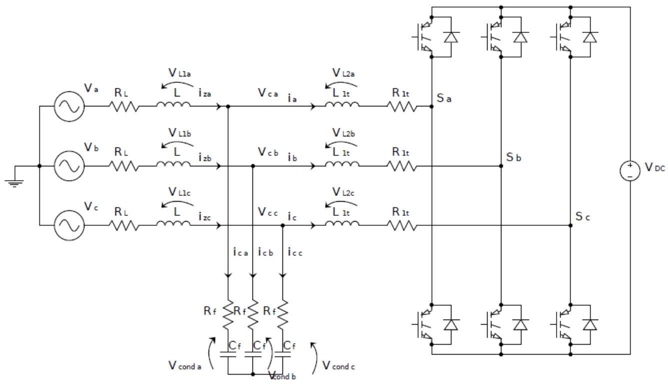
This section provides information about the actual mathematical model by specifying variables, parameters and equations. Variables and parameters should be specified with *<u>type</u>* *(Real, Integer, Boolean, String) and (physical)* *<u>unit</u>*. *In case the equations are too complex to be reproduced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

Input variables (name, type, unit, description)	V, PCC voltage, [V] P_set, Reference active power, [W] Q_set, Reference reactive power, [VAr]
Output variables (name, type, unit, description)	Output active power [W] Output reactive power [VAr]
Parameters (name, type, unit, description)	Max Active Power Pmax [W] Max Reactive Power Qmax [Var] DC bus voltage Vdc [V] Filter inductance Lf [H] Output inductance L1t [H] Filter capacitance Cf [F] Switching Frequency f [Hz]
Internal variables (name, type, unit, description)	PI controllers' states

<table>
<tr><td>Internal constants
(name, type, unit, description)</td><td>PI constants, PLL constants, LP filter bandwidth. All these constants can be modified acting on the dedicated block masks.</td></tr>
<tr><td>Model equations

Formulate or provide references to the model’s governing equations (describing the system state) and the constitutive equations (describing material properties)</td><td>Governing equations

Considering the following figure:



the time domain model in Synchronous Framework is:

$$\begin{cases} \dot{i_{z_d}} = \frac{1}{L} \cdot (\omega \cdot L \cdot i_{z_q} - R_L \cdot i_{z_d} - v_{c_d} + v_d) \\ \dot{i_{z_q}} = \frac{1}{L} \cdot (-\omega \cdot L \cdot i_{z_d} - R_L \cdot i_{z_q} - v_{c_q} + v_q) \\ \dot{i_d} = \frac{1}{L_{1t}} \cdot (\omega \cdot L_{1t} \cdot i_q - R_{1t} \cdot i_d - s_d + v_{c_d}) \\ \dot{i_q} = \frac{1}{L_{1t}} \cdot (-\omega \cdot L_{1t} \cdot i_d - R_{1t} \cdot i_q - s_q + v_{c_q}) \\ \dot{v_{cond_d}} = \frac{1}{C_f} \cdot (\omega \cdot C_f \cdot v_{cond_q} + i_{z_d} - i_d) \\ \dot{v_{cond_q}} = \frac{1}{C_f} \cdot (-\omega \cdot C_f \cdot v_{cond_d} + i_{z_q} - i_q) \\ v_{c_d} = v_{cond_d} + R_f \cdot (i_{z_d} - i_d) \\ v_{c_q} = v_{cond_q} + R_f \cdot (i_{z_q} - i_q) \end{cases}$$

where L and R_L are the output inductance and its equivalent series resistance, L_{1t} and R_{1t} are the primary filter inductance and its equivalent series resistance, C_f and R_f are the filter capacitance and its equivalent series resistances.

Moreover, the active and reactive power, respectively P and Q, are controlled by the following two equations:

$$P = \frac{3}{2} \cdot \left(v_{C_d} \cdot i_d + v_{C_q} \cdot i_q\right)$$

$$Q = \frac{3}{2} \cdot \left(v_{C_q} \cdot i_d - v_{C_d} \cdot i_q\right)$$

</td></tr>
<tr><td>Initial conditions</td><td>At the beginning of the simulation the converter is disconnected from the grid.

Input to PI controller is set to zero and the PCC voltage is forwarded to the three controllable generators until the three-phase breaker is closed.</td></tr>
<tr><td>Boundary conditions</td><td>m_abc (duty ratio) in the range [-1,1]

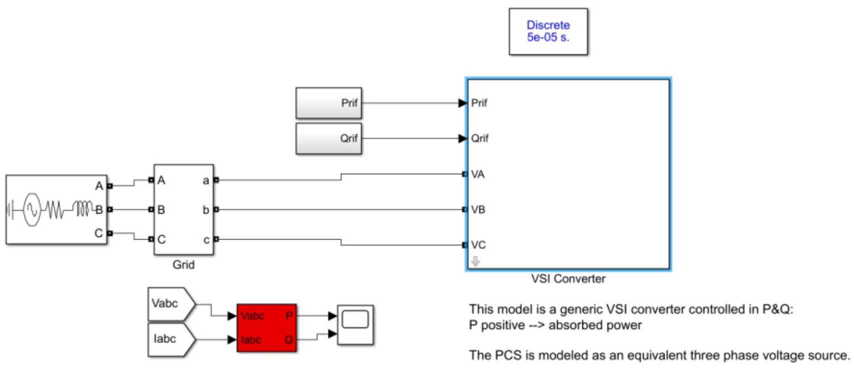
P in the range [-Pmax,Pmax]

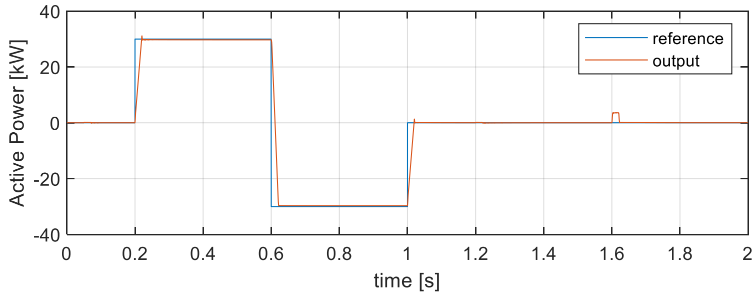
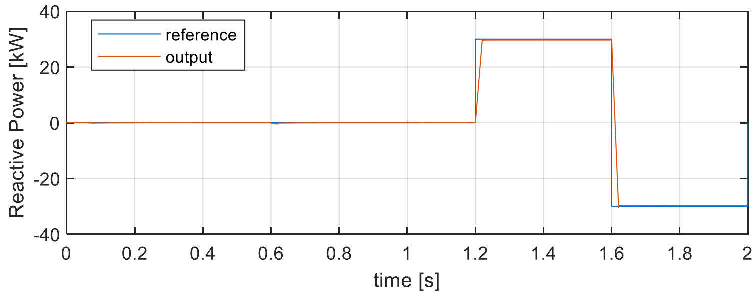
Q in the range [-Qmax,Qmax]</td></tr>
</table>

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 controller ensures the safe synchronization of the inverter with the power grid. After the connection to the grid, the controller regulates the power injection of the inverter to its reference values.
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)?*	The controller is applied to grid-connected inverters of the electrical benchmark power system developed through ERIGRID 2.0 project. The whole power converter was tested connecting it to a three phase voltage source with an internal impedance (emulating the grid behaviour). 
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.*	Same as in mathematical model. Default parameters are used. Max Active Power Pmax = 50 kW Max Reactive Power Qmax = 50 kVAr DC bus voltage Vdc =760 V Filter inductance Lf = 0.64 mH Output inductance L1t = 0.063 mH Filter capacitance Cf = 0.1 mF Switching Frequency f =5 kHz
Initial system state	Same as "Initial conditions" in the mathematical model.

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.*	Sampling time in the MATLAB/Simulink environment is accordingly selected as Ts=1e-3 seconds to capture transient phenomena.
Evolution of system state *Describe (textual and/or graphical) the expected <u>qualitative behaviour</u> of the component model in this simulation.*	The inverter power injection is zero before the grid connection. When the inverter is connected to the grid, the controller regulates the power injection to the reference active and reactive power values. In the case of a grid voltage drop, the current is driven to its maximum.
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.*	The simulation results of the electrical benchmark network show that the controller manages to synchronize the inverter safely to the grid and also regulate the active and reactive power to their reference values.   Relevant simulation results are provided in the main body of the deliverable.

Additional Information

Provide any other additional information here.

Reference implementation	N/A
Similar / related models	See ERIGRID 2.0 Github
Related publications	N/A
Intellectual property concerns (if applicable)	N/A