

About

Provide general information regarding the described model.

Model name	Grid-forming inverter
Author / organization	Alexandros Paspatis / ICCS
Short description	A grid-forming three-phase inverter, which is capable to form the voltage of an islanded microgrid. The inverter's real and reactive power injection is regulated according to the voltage and frequency, through the appropriate droop control mechanism, while it also achieves a smooth grid synchronization.
Present use / development status	The grid-forming inverter was developed for the purposes of the ERIGRID 2.0 H2020 project, based on existing literature.

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	<input type="checkbox"/> electrical storage <input type="checkbox"/> thermal storage <input type="checkbox"/> energy conversion device <input checked="" type="checkbox"/> other, please specify: DERs
Intended application (including scale and resolution)	The intended application is the electrical benchmark network that is being developed in ERIGRID 2.0 project. This model will aim to represent inverters that follow a grid-forming control philosophy, while its resolution lies in the range of ms.
Modelling of spatial aspects <i>Explain the approach of how this model describes the spatial distribution of the system.</i>	<input type="checkbox"/> lumped (single device) <input type="checkbox"/> discretized (single device) <input checked="" type="checkbox"/> averaged (multiple devices) <input type="checkbox"/> other, please specify:
	This inverter can represent multiple inverters as long as they are supposed to follow a grid-forming control philosophy.
Model dynamics <i>Explain how the model captures the dynamic behaviour of the system.</i>	<input checked="" type="checkbox"/> quasi-static <input checked="" type="checkbox"/> dynamic <input type="checkbox"/> other, please specify:

	<p>The controller controls the voltage at its connection point during both steady-state and transient conditions.</p> <p>A switching model is assumed for the three-phase inverter, using ideal switches.</p>
<p>Model of computation</p> <p><i>Explain how the model captures the system's evolution with respect to time and/or external stimuli.</i></p>	<p><input checked="" type="checkbox"/> time-continuous</p> <p><input checked="" type="checkbox"/> discrete-event</p> <p><input type="checkbox"/> state machine</p> <p><input type="checkbox"/> other, please specify:</p>
	<p>The controller continuously measures the inverter power injection and adjusts it to regulate the inverter's voltage and frequency close to their nominal points, according to droop control.</p>
<p>Functional representation</p> <p><i>Are the model functions explicit, i.e., of type $y = f(x)$, or implicit, i.e., of type $g(x, y) = 0$?</i></p>	<p><input checked="" type="checkbox"/> explicit</p> <p><input type="checkbox"/> implicit</p> <p><input type="checkbox"/> other, please specify:</p>
	<p>The controller functions are typical Proportional-Integral (PI) control functions.</p> <p>A switching model is assumed for the three-phase inverter, using ideal switches.</p>

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.

<p>Input variables</p> <p>(name, type, unit, description)</p>	<p>V_pcc, PCC voltage, [V]</p> <p>P_set, Reference real power, [W]</p> <p>Q_set, Reference reactive power, [Var]</p>
<p>Output variables</p> <p>(name, type, unit, description)</p>	<p>Three-phase inverter output voltage</p>
<p>Parameters</p> <p>(name, type, unit, description)</p>	<p>PI controllers' gains</p> <p>Droop gains</p> <p>Current limit of the inverter, I_max, [A]</p>
<p>Internal variables</p> <p>(name, type, unit, description)</p>	<p>PI controllers' states</p>
<p>Internal constants</p> <p>(name, type, unit, description)</p>	<p>N/A</p>
<p>Model equations</p>	<p>Governing equations</p>

<p>Formulate or provide references to the model's governing equations (describing the system state) and the constitutive equations (describing material properties)</p>	<p>Controller:</p> <p>Droop control (input to voltage controller):</p> $v_{pccd}^{ref} = V_{nom} + n(Q_{set} - Q)$ $\omega = \omega_{nom} + m(P_{set} - P)$ <p>Voltage controller (input to current controller):</p> $i_d^{ref} = i_{gd} + \left(k_{pv} + \frac{k_{iv}}{s}\right)(v_{pccd}^{ref} - v_{pccd}) - \omega C v_{pccq}$ $i_q^{ref} = i_{gq} + \left(k_{pv} + \frac{k_{iv}}{s}\right)(-v_{pccq}) + \omega C v_{pccd}$ <p>Current controller (input to PWM generator):</p> $v_d = v_{pccd} + \left(k_{pi} + \frac{k_{ii}}{s}\right)(i_d^{ref} - i_d) - \omega L i_q$ $v_q = v_{pccq} + \left(k_{pi} + \frac{k_{ii}}{s}\right)(i_q^{ref} - i_q) + \omega L i_d$
	Constitutive equations
	N/A
Initial conditions	Before grid connection, zero power injection from the inverter to the grid.
Boundary conditions	Controller: m_abc (duty ratio) in the range [-1,1]
Optional: graphical representation (schematic diagram, state transition diagram, etc.)	N/A

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

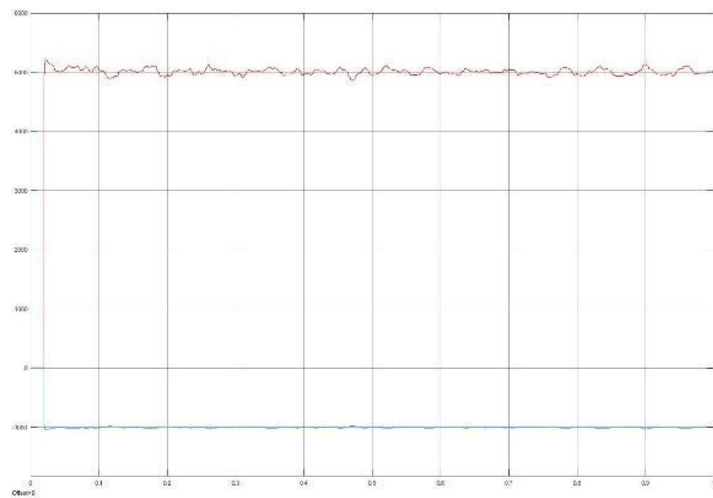
<p>Model Validation</p> <p>Provide the description of a test setup (i.e., simulation) that enables others to validate their implementation of the same model. The results should be provided as <u>time series</u>.</p>	
<p>Narrative</p> <p>Provide a simple description of the test specification.</p>	<p>The 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 maintain proper voltage and frequency</p>

	regulation, while during grid faults, the controller limits the inverter current to its maximum value. When an islanding is required, the inverter is capable to govern the microgrid voltage and frequency (grid-forming operation).
Test system configuration <i>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)?</i>	This inverter represents the grid-connected inverters of the electrical benchmark power system developed through ERIGRID 2.0 project, which are also responsible to form local islanded microgrids. The simulation may run for some ms up to many hours.
Inputs and parameters <i>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.</i>	Same as in mathematical model.
Control function (optional) <i>Specify any additional control functions used for this test.</i>	N/A
Initial system state <i>Describe the initial state of the system.</i>	Same as “Initial conditions” in the mathematical model.
Temporal resolution <i>Provide information regarding the temporal resolution of the test simulation, such as integrator step size, time resolution for event handling, etc.</i>	Sampling time in the MATLAB/Simulink environment is accordingly selected as $T_s=1e-3$ to capture power system transient phenomena.
Evolution of system state <i>Describe (textual and/or graphical) the expected <u>qualitative behaviour</u> of the component model in this simulation.</i>	The inverter power injection is zero before the grid connection. When the inverter is connected to the grid, the inverter’s controller adjusts the power injection according to the grid voltage and frequency. In the case of a grid voltage drop, the current is driven to its maximum value due to unavailability of injection of the reference power. Saturation units in the reference currents maintain the current inside its thermal limits. If islanding is dictated, the controller ensures the local microgrid voltage formation.
Expected results <i>Provide a <u>quantitative description</u> of the expected simulation output <u>based on time series</u>. This</i>	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 real and reactive power to their reference values. Moreover, it is

information must be comprehensive enough for someone else to validate his/her own implementation of this model. If necessary, attach this information as dataset.

shown that when a grid fault occurs the inverter current is limited at its maximum value to avoid damages to the inverter device. Finally, in an islanded microgrid scenario the grid-forming inverter form the local voltage.

Indicative result: Inverter power injection during islanded microgrid formation by the grid-forming inverter (Red-real power [W], blue-reactive power [VAr]):



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