A Modelica-based solution for the simulation and optimization of microgrids

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Abstract

By integrating a high share of distributed generation units, microgrids can accelerate the shift to a more sustainable power grid. This transition is however not free from challenges. The variability and uncertainty of the renewable energy sources as well as the absence of large-scale dispatchable storage systems pose challenges for the integration and operation of this new type of power grid. Model-based engineering can provide valuable tools to develop design and control strategies that do not jeopardize the stability and reliability of the power supply. This paper presents elements of a Modelica-based workflow for the design and operation of microgrids. The framework allows for a multi-fidelity modeling approach and is therefore suitable for solving a large variety of engineering problems, from early component design to the verification of component and control design using detailed models. This paper illustrates the flexibility of the framework with respect to the user interface, the models and the analyses.

Keywords: microgrid, power systems, controls, dynamic optimization, renewables, battery

1 Introduction

Environmental considerations and increasing awareness of infrastructure sensitivity have led to reconsiderations of how energy system should best be configured. The current, highly centralized systems were developed for large production units such as nuclear and fossil power plants, and are not suitable for renewable, intermittent and distributed energy sources such as wind and solar (Fathima and Palanisamy, 2015).

A microgrid is a group of interconnected energy sources, loads and storage devices that can operate both connected with the surrounding electricity grid, and disconnected in islanding mode. It has the potential to offer increased self-sufficiency and reliability at low cost and reduced environmental impact (Eto et al, 2018). Microgrids typically include smaller production units such as photovoltaic arrays, wind turbines, microturbines and generators (combustion engines) and storage devices such as flywheels and batteries. Their comparably smaller investment cost makes them attractive to install in remote areas and their capacity for reducing transmission congestion makes them interesting for energy suppliers (Venkatraman and Khaitan, 2015).

In a previous paper (Windahl et al, 2019), the authors identified the need for a flexible and collaborative platform that allows different stakeholders to analyze microgrid systems, from the early system design based on site-specific data to the detailed verification of the complete system including controls. The authors considered Modelica as suitable technology candidate thanks to its ability to describe multi-physics systems with various fidelity levels and thanks to the openness of the standard that allows for model customization to fit specific application needs.

The goal of this paper is to share the latest development of Modelon's microgrid solution, especially for the detailed electrical transient analysis. Additional examples for optimal design and operation are also provided to further illustrate the flexibility of the approach.

2 Modelica based framework

In this section we briefly present the different components of the proposed Modelica solution for the analysis of microgrid systems. The framework consists of three elements: Modelica libraries with models of various fidelity levels, a computational engine for simulation and optimization over different time horizons and finally user interfaces to conveniently formulate and solve various engineering tasks on the microgrid models. As explained in (Windahl et al, 2019), the framework tightly integrates the components through a common architecture.

2.1 Modelica libraries

2.1.1 Low fidelity models

The low-fidelity models that describe the microgrid behavior in terms of energy and power flows are available in the Thermal Power Library, commercial product of Modelon. A brief overview is given in (Windahl et al, 2019). The component models are typically implemented as efficiency curves and are suitable for simulation and optimization over long horizons, typically from one day to one year.

2.1.2 High fidelity models

The high-fidelity models are targeting mechanical and electrical transient analysis over short horizons, in the range of microseconds to minutes. The core libraries used for that purpose are two:

2.1.2.1 Electric Power Library

Electric Power Library by Modelon is a general-purpose library for the simulation of electric power systems. It contains all required components to describe various configurations of DC and AC grids – 1 phase, 3 phase, balanced and unbalanced: lines, loads, machines, and inverters. Concerning the converters, a core component for the integration of renewable energy sources, it exists in different versions to capture the fast dynamics of switching gates or just the average dynamics for slower transients. Examples of application using the library can be found in (Olenmark et al 2014), (Enerbäck et al, 2013), (Magnúsdóttir et al, 2017), (Pettersson et al, 2012). Figure 1 shows for instance how to describe the electro-mechanical transient of a wind power plant and its connection to the main grid using back-to-back converters and two controllers. The machine side converter maximizes the power drawn from the wind whereas the grid side controller maintains a stable DC voltage.

The library has recently been adapted to the specific needs of microgrid system modelling. This includes the implementation of typical blocks such as Phase-Locked-Loop, typical controllers implemented in the dq frame for inverter-interfaced distributed energy resources (grid forming, grid feeding and grid supporting). With these additions, it is possible to describe and simulate arbitrary DC and AC microgrids in either islanded or connected mode.

2.1.2.2 Electrification Library

Electrification Library by Modelon is a multi-physics Modelica library for the design, verification and control of electrified systems. The fidelity level of its component models is somewhat lower than the one of Electric Power Library, but it is possible to adapt the level of detail of the electrical, mechanical and thermal dynamics to cover time scales from fast electrical to slow thermal and even aging dynamics. With a large set of battery models, it is a good complement to Electric Power Library when modelling battery energy storage systems in microgrids.

Using a simple adaptor, Electrical Power and Electrification libraries can be combined on the DC side, as it is shown in Figure 2 that represents a battery – from Electrification Library – connected to the main grid through a grid-feeding inverter – from Electric Power library.

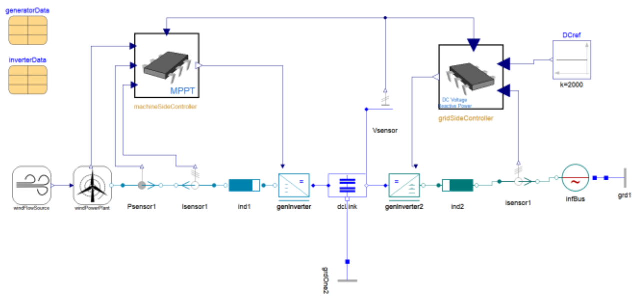

Figure 1. Electro-mechanical Modelica model of a wind power plant connected to an AC grid through a back-to-back inverter. The machine side controller is in power mode and maximizes the power extracted from the wind whereas the grid side controller maintains the voltage level at the DC link.

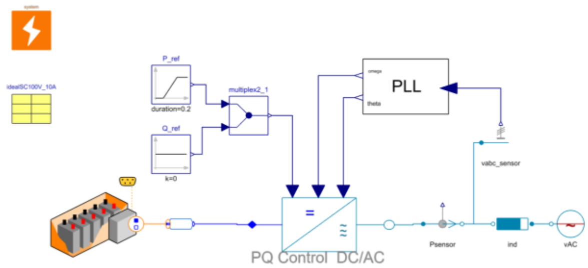

Figure 2. Model of a battery connected to a stiff AC grid via a grid-feeding inverter block, getting the reference phase and frequency from a Phase-Locked-Loop component.

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2.2 Computational engine

Optimica Compiler Toolkit by Modelon is a Modelica compilation and execution environment with applications beyond dynamic simulation, most notably steady-state simulation and optimization. It supports the Optimica language (Åkesson et al, 2008) (Magnusson et al, 2015) which is an extention to Modelica to allow formulation of optimization problems. Applications include for example district heating (Schweiger et al, 2017).

The optimization framework has also been demonstrated in industrial applications as described in (Dietl et al, 2018) where the approach is applied to optimize in real-time the start-up of a gas combined cycle power plant.

In addition to the usage described here, it is used as Modelica engine in several system simulation tools on

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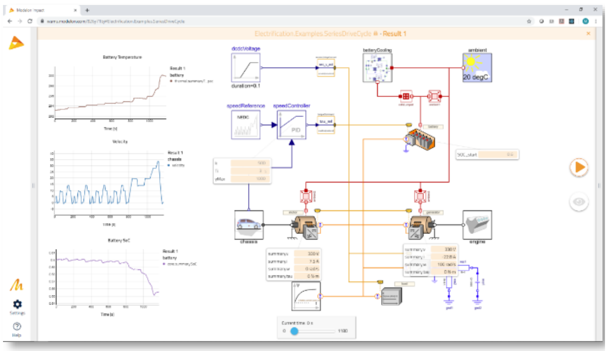
the market, including for example ANSYS Twin Builder.

2.3 User interface

Three types of user interfaces are available, each one being accessed from a web-browser and targeting a specific user profile with his own engineering tasks and access rights:

- Model centric view for building the microgrid model in a web-browser by drag and dropping components from the previously mentioned libraries. A dashboard view, as a simple interface for the deployment of the tool to less technical end-users. Figure 5 shows a web-app to setup, simulate and optimize a microgrid system. Results can be visualized in tables or as time trajectories.



- Figure 3 shows an electric vehicle model based on Electrification Library.
- Workflow centric view to implement advanced engineering tasks to perform various computations and exchange data between the different steps, see Figure 4 for an illustration.
- A dashboard view, as a simple interface for the deployment of the tool to less technical end-users. Figure 5 shows a web-app to setup, simulate and optimize a microgrid system. Results can be visualized in tables or as time trajectories.

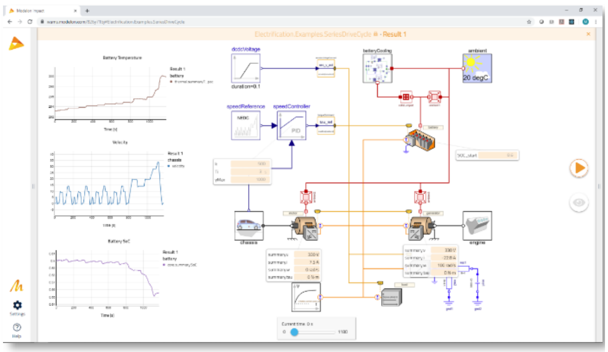


Figure 3. Model authoring interface to create and parameterize system models from a web-browser. Post-processing views are simply created by drag-and-drop to the canvas and can be saved to be applied on other simulation setups.

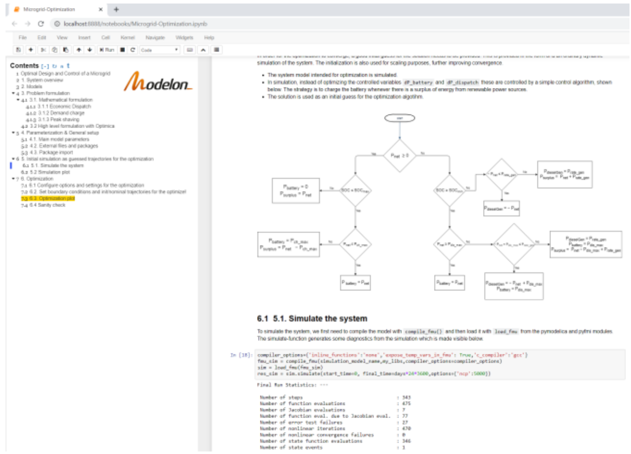


Figure 4. Jupyter notebook as interface for implementing and executing complex engineering workflow, also from a web-browser.

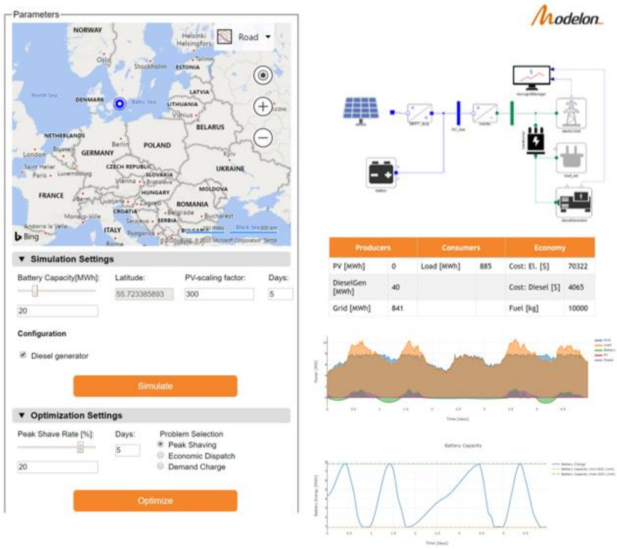


Figure 5. Web-app for deployment of microgrid analysis and design tools to less technical end-users. An open rest API makes it possible to access the main features of Modelon compiler, e.g. parameter settings, compilation, simulation, from customized html dashboards. A widget has here been integrated to conveniently set the microgrid location from an interactive map, which determines the power produced by the PV panels.

3 Use cases

3.1 Optimal design and operation

3.1.1 Platform capability

In (Windahl et al, 2019) and (Akhlagi, 2019), the authors list various types of microgrid optimization problems that can be formulated and solved using the Modelica platform. This includes optimal design problems such as battery or photovoltaics sizing and operational problems such as demand charge reduction or economic dispatch. It is also possible to solve hybrid problems in the sense that they combine physical domains - e.g. microgrids with cogeneration plants and thermal loads - or that they combine design and operation problems. The peak shaving formulation is for instance looking for the minimal battery size (design problem) when optimally operating the remaining assets (control problem). For longer time horizons, Model Predictive Control can be applied, see (Axelsson et al, 2015) for the implementation details.

Compared to previous work, the optimization package has been improved as follows:

1. For an improved user-friendliness and readability, the complete optimization problem including constraints, cost function and the degrees of freedom is specified from the graphical user interface of the authoring tool instead of being added in a separate Optimica file and Python code.
2. CO2 emission is computed in the diesel engine component and environmental constraints in terms of overall allowed emission by the microgrid can be therefore introduced in the optimization problem.
3. An electrical vehicle component has been added to represent a car park charging station with forecast on the cars' parking schedule and battery charging requirements.

3.1.2 Optimization of a microgrid with multiple gensets

Let's now consider the economic dispatch problem of a fictive grid-connected system represented in Figure 6. The microgrid includes the following units:

1. A PV power station
2. Two diesel engines of 750 kW capacity and identical efficiency curve but different fuel properties
    a. Genset 1 with a fuel characterized by a cost of 0.33 USD/l and a CO2 emission of 2.5 kg/l
    b. Genset 2 with a cheaper fuel (0.25 USD/l) but emitting more CO2 (5 kg/l).
3. A load with its associated power forecast over the optimization horizon
4. A battery of size 40MWh with operational constraint in terms of max and min state of charge (0.1 and 0.9 respectively) and a maximal charge/discharge rate of 2 MW.

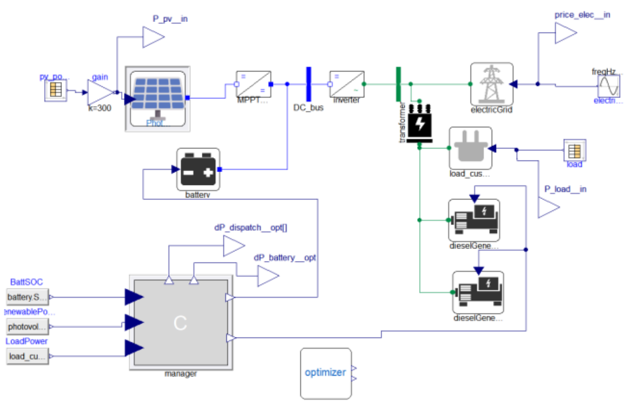


Figure 6. Microgrid system used for the economic dispatch formulation. It consists of two engines with their specific fuel and emission characteristics, a battery, a PV panel a load and the grid. The optimizer block contains the formulation of the cost function and the overall CO2 emission constraint.

The goal is to minimize the operational cost from the grid power import and the engine fuel usage while satisfying the following operational and environmental constraints:

- A maximum power grid import of 8MW
- A maximum overall CO2 emission of 25 tons

Forecast for electricity price, load and solar irradiation are given by 15 min sampled trajectories over the 2 days long optimization horizon.

The optimization workflow has been implemented as a jupyter notebook and the functionality has also been made available from the model authoring tool. It contains the following steps:

- Experiment setup by mainly specifying the files with the forecast data
- Compilation of the simulation model
- Initial simulation for generating the guess trajectories for the optimization,
- Setup and compilation of the optimization model
- Optimization
- Post processing for results visualization and comparison with reference case

The problem is initialized with a simulation using a simple control strategy aiming at charging the battery during overproduction and prioritizing the diesel engine with cheapest fuel.

The results are shown in Figure 7 and Figure 8. The optimal cost (not shown) is slightly lower than the reference one but the constraints in terms of maximal power and CO2 emission is fulfilled. Using the optimization framework, it is possible to investigate the trade-off between operational cost and environmental footprint.

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The solution time for this problem is 25 s, using a standard laptop. Similar performance has been achieved for all considered problems with similar sampling time and optimization horizons.

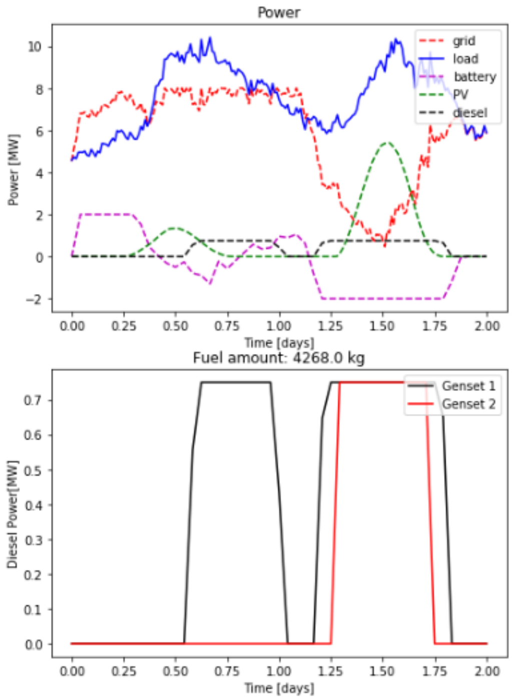

Figure 7. Economic dispatch results. The top figure shows the optimal power trajectories. Note that the grid import has been shaved to satisfy the maximal grid import of 8 MW. The bottom plot shows that the genset with more expensive fuel is prioritized due to its lower CO2 emission constraint. When electricity is expensive around 1.5 day (not shown), both engines are used.

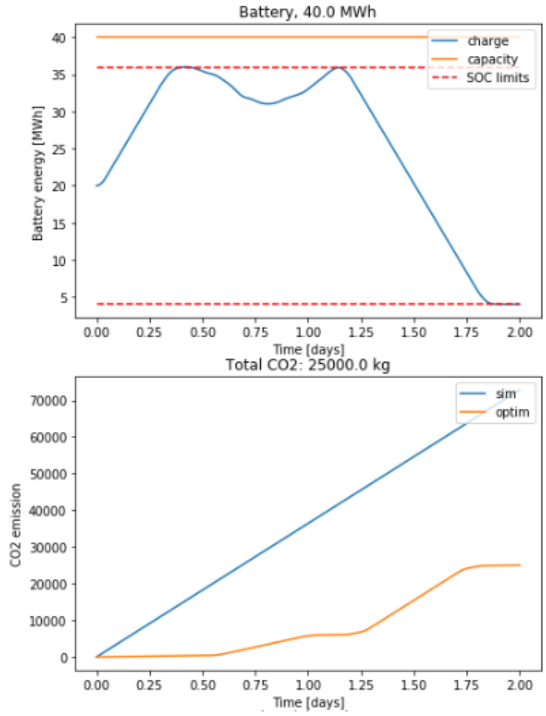

Figure 8. Economic dispatch results. The top plot shows the battery energy together with the operating limits. The battery usage follows the electricity price (not shown): it is charged at low tariffs and discharged at high ones. The lower plot shows the CO2 emission reduction compared to the reference case.

3.2 Electrical transients

As explained in Section 2.1.2, detailed electrical transients can be simulated within the platform by using off-the-shelf libraries. Some additional control components have lately been implemented to apply typical control strategies for inverter-interfaced energy sources. This comprises phase-locked-loops, low level current and voltage controllers to be used in grid feeding, grid forming and grid supporting inverters. Figure 9 shows for instance the synchronization block that is used to match phase and voltage of a microgrid in islanded mode before its connection to the main grid. The Modelica implementation is similar to the one in (Biswarup et al, 2019) and consists mainly in PID controllers, PLL and logical blocks.

To illustrate the libraries' ability to simulate detailed power transients, the low voltage, three phase AC system shown in Figure 10 has been modelled and simulated in a specific scenario. The system comprises

- a genset with a first order governor, a first order exciter and a third order generator model
- a renewable energy source operating in grid feeding mode and represented by an ideal DC source. The inverter switching dynamics is not considered here and it is described by an average model. The PQ controller is implemented in the

dq frame. Note that higher fidelity models could be used to describe the DC transients on the production side.

- an impedance load consuming a given active and reactive power at nominal voltage
- a stiff AC grid represented by a three-phase voltage source
- Impedance lines

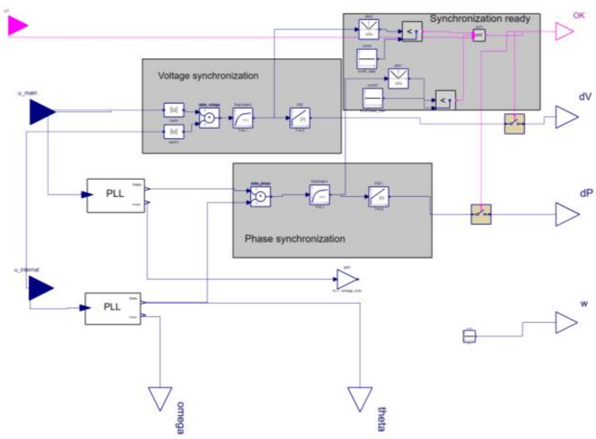

Figure 9. Modelica implementation of a grid synchronization block including phase-locked-loops to track the phase and frequency of the internal and main grids, and PID to adjust voltage and power level of the units.

Note that the grid frequency has been arbitrarily lowered to 7 Hz to better follow the synchronization process when comparing the voltage signals in the inertial frame. The library allows for the simulation of networks operating at arbitrary frequency.

The scenario is defined as follows:

1. From t=0 s to t=1 s, the microgrid is operating in islanded mode. The REN source is increasing its load to a nominal value of 1MW whereas the genset takes care of frequency and voltage control.
2. The grid synchronization is activated at t=2s and the grid waits for the synchronization criteria to be satisfied to close the switch., which takes approximately 200 ms.
3. At t = 3.5 s, the load is increased by 30% in 200ms and the grid takes care of this disturbance
4. At t = 5 s, the grid is suddenly disconnected from the main grid as if a fault had occurred. The diesel engine quickly reacts to compensate for the power outage, the frequency and voltage levels stay under control.

4 Conclusion

An update of Modelon's web-based framework for microgrid design and analysis has been presented. Compared to its early version, focusing on long term analysis and on a limited set of optimal design and operation problems using low fidelity levels, the new version is able to simulate the fast current and voltage transients of various microgrids during islanded and grid-tied modes. The optimization package has also been upgraded for an improved user-friendliness and to include CO2 emission and a new component for electric car charging stations. Examples have been presented to illustrate the framework in two use cases: economic dispatch of a grid with PV, battery and gensets as well as detailed simulation of an AC grid during transition between islanded and connected modes.

5 Future work

Future work includes the support of the following features:

- More advanced control blocks for grid-supporting inverters with the implementation of droop controllers
- Implementation of a flexible grid architecture with templates and interfaces to allow for user-friendly reconfiguration
- Automatic Modelica code generation to easily define microgrid from specifications in a simple interface such as a web-app
- Optimization of microgrids in islanded mode and during mode transition

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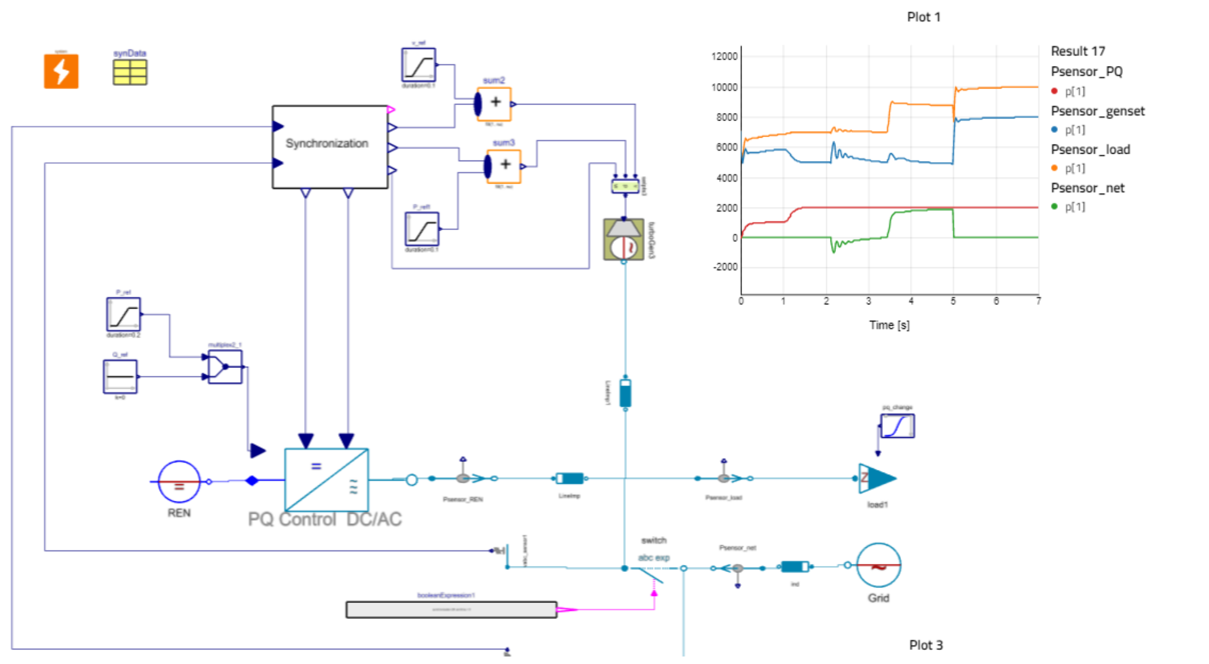

Figure 10. Three phase microgrid system implemented using Electric Power Library components. It is composed of 4 units: an ideal DC source controlled in PQ mode to represent a renewable energy source, a diesel engine, an ideal impedance load and an AC voltage source to represent the main grid. The microgrid is first operated in islanded mode. At t=2 s, the synchronization process is initiated, and synchronization occurs after 200ms. A load change occurs at t = 3.5 s. At t =5 s, the microgrid is suddenly disconnected from the grid and the diesel engine reacts to maintain the internal frequency and voltage levels.