Developing a Campus Microgrid Model utilizing Modelica and the OpenIPSL Library

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***Abstract*—This paper describes the development of a phasor-based campus microgrid model utilizing the Modelica language and the OpenIPSL library. The phasor-based modeling approach was chosen because the resulting microgrid model would yield faster simulation run times when compared to models developed using electromagnetic transient (EMT) methods. Beyond the benefits of simulation performance, this becomes necessary when attempting to understand dynamic phenomena arising under emergency conditions across time scales ranging from milliseconds to hours, which will aid in developing resiliency improvement plans for the real-world campus microgrid that the model represents. Considering the increasing number of distributed energy sources (DERs) being added to power grids across the world and the paradigm shift on how electrical grids can operate with more DERs, the implementation of such a microgrid campus model can help in the development and testing new control strategies to support new operational approaches while guaranteeing system stability and resiliency. The added benefit of having the microgrid model in Modelica is that it can be simulated in any Modelica complaint tool (both proprietary or not), preserving an open-source code, unlocked for the user to explore and adjust the implementation as well as observe and edit the mathematical formulation. This enables not only nonlinear time simulation, but also linear analysis techniques and other approaches to be applied.**

***Index Terms*—Microgrid, Phasor Modeling, Simulation, Modelica, OpenIPSL, Power Systems.**

I. INTRODUCTION

The conventional power system design adopted around the world is prescribed by the large centralized power plant paradigm, composed of massive rotating machines that generate electricity (a commodity that is utilized in real time), and consumed by industrial facilities and residential buildings [1]. These power plants are typically constructed far from the consumer, and as such requires a reliable electrical grid (comprised of transmission lines, transformers, etc.) that is capable of transferring the generated power to the consumer. Due to this design philosophy and historical reasons, fossil fuel based energy sources are the main energy producing plants in the world, accounting for more than 80 percent of global energy production, although alternative sources are gaining ground [2].

Despite the dominance of today's conventional grid architecture, alternative architectures involving Distributed Energy Resources (DERs) are being considered, with numerous solutions being implemented and tested as an alternative to the current grid architecture [3]. In the last decade, the concept of localized small grids, called microgrids, has been introduced with the prospect of equal or even increased system resiliency and reliability [4], [5]. Another major benefit of microgrids is related to its increase in energy efficiency when compared to the conventional power system. The centralized energy system deals with high amounts of losses, specifically energy dissipated in the conductors (e.g. transmission lines), of around 22 to 30% [6]. Thus, microgrids have the potential to save the losses from transmission and distribution lines.

To develop new methods for optimization and control of microgrids, the use of simulation models is attractive to minimize cost and time during concept development and algorithm prototyping compared to working with a hardware platform [7]. While there are several tools for microgrid simulation [4], each of the modeling paradigms that underpin them have advantages or drawbacks. An alternative approach to modeling using Modelica is proven to be successful and suggested for further usage [8]. Using physical or signal connectors, the Modelica Language standard defines an object-oriented equation-based language for describing cyber-physical systems [9], [10]. For that reason, Modelica models from different Modelica-based library sources can be linked together forming multi-library multi-domain models. Another key advantage of using Modelica is the fact that users can import and export models among tools compliant with the Functional Mock-up Interface (FMI) standard specification. The FMI enables dynamic model exchange between different simulation software tools for model/software/hardware-in-the-loop simulation, for cyber physical systems, and other applications [11].

As such, this paper presents a real-world university campus microgrid model implemented utilizing the Modelica language and the Modelica-based Open-Instance Power Systems Library (OpenIPSL) [12], that can be used to study the dynamic interaction between the different distributed energy sources that comprise a microgrid, such as gas and steam Turbines, as well as renewable sources like inverter-based photovoltaic (PV) systems. Not only that, the microgrid model can also

This paper is in part, based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Advanced Manufacturing Office, Award Number DE-EE0009139, and in part by the National Science Foundation Award No. 2231677.

979-8-3503-3682-5/23/$31.00 ©2023 IEEE

be used for numerous other studies, such as control strategy development, electrical contingency studies, to develop resilience plans, and even to test the interaction between different physical domains within a model, e.g. electrical grid and thermofluidic system interaction, as shown in [13]. The contributions of this work are:

1) Description of how the implementation of a phasor domain microgrid model was conducted, utilizing the the Modelica language [10] and the Modelica-based OpenIPSL library [12].
2) The development of a phasor domain microgrid "virtual" testbed that can be used for both testing new design, operation and control concepts as well as integrating new components that could be employed to increase the real-world microgrid resilience. The microgrid model provides another use case of the library adding to those in [13]–[18].
3) Exemplify some of the studies that can be conducted with the microgrid "virtual" testbed in a Modelica-compliant modeling and simulation environment, i.e. Dymola [19].

II. MICROGRID MODELING PHILOSOPHY

The first topic to be addressed before starting the modeling phase is related to its modeling philosophy, i.e. the mathematical modeling of the components. Because a model is a mathematical representation of the physical world and, as every model has limitations depending on the objectives of the modeling task, choosing the best fitting solution towards a problem is key. In the realm of possibilities, two modeling strategies arise as possible candidates: Electromagnetic Transient (EMT) based models, or Phasor domain (RMS) based models. Electromagnetic transient studies provide great insight into expected power system over-voltages and over-currents resulting from lightning phenomena, switching operations and fault conditions [20]. EMT models depict electromagnetic disturbances in the system and for that reason rely on the waveform representation of currents and voltages. Phasor models, on the other hand, are known as averaged switching dynamic representations of the system and are used to model electromechanical oscillations in the system. The main advantage of using phasor over waveform representation is its practicality in solving circuit problems. The second major advantage in using phasor models (also known as Root-Mean-Squared (RMS) models) is expected simulation time, which are magnitudes faster than EMT simulations. This concept is covered in depth in paper [21], where comparisons of the simulation run time necessary to simulate the same model in three distinct approaches are made: phasor, cycle-by-cycle average waveform (CCA), and simplified average waveform. As expected, the simulation run time for phasor modeling was tens to even hundreds of times faster than its counterparts.

For this reason, the microgrid model implemented and described in this paper utilizes a phasor representation. It is important to note that OpenIPSL does not suffer the limitations of traditional phasor domain tools, as it provides interfaces to model unbalances [22] and physics-based interfaces to couple more detailed EMT-type models [23]. In addition, because the microgrid model is being developed in Modelica, this opens up the possibility for its use in time-scales ranging from milliseconds to hours, contrary to that of power system dynamic simulators, which would restrict the use of these models to tens of seconds. This is because Modelica-based tools provide a vast array of numerical solvers, including those with variable time-step, which allows to run long-term simulations of processes taking place in 10s of minutes to even hours, such as those involved in tertiary frequency and voltage control [24] or to adequately model the in-time-stochastic variability of loads [25].

III. MICROGRID COMPONENT MODELS

The microgrid model consists in a phasor domain representation of a real-world university campus microgrid located in the United States. It is comprised of different energy sources, including photovoltaic systems, gas and steam turbines. For this reason, this section details the modeling architecture of each source component and how they were parameterized to best represent the real-world microgrid elements. It is worth mentioning that in order to share the system model, when no data was available from the university's facilities team, generic parameters for its system components were obtained from similar real-world plants [26] and literature according to the component's capacity and type [27]. Although the model parameters may not exactly match those corresponding to the installed energy sources, the authors diligently searched for similar sized generator, turbine, and excitation system parameter values in order to keep a reasonable level of fidelity.

A. Gas Turbine Unit

The university campus microgrid accommodates two Mitsubishi MF-111 Gas Turbines. Both gas turbines are single shaft and have nominal operating speeds of 9,660 RPM, reduced to 3,600 RPM by means of a reduction gear. The generator is a two pole machine, rated at 15,000 kW, 13.8 kV at 0.90 lagging power factor while operating at 60 Hz. The excitation system of the generator is a shaft mounted main and pilot permanent magnet brushless exciter with rotating fused diodes. The turbine governor is a Woodward 2301A Dual Fuel Control, of which little information is disclosed. Figure 1 displays the icon view of the gas turbine component in OpenIPSL. The blue rectangle is a Modelica acasual `connector`[1] from the OpenIPSL called `PwPin` that allows coupling that is ubiquitous to all of the electrical component models in the library, allowing library components to be connected together [29].

Models in Modelica have four views, the "Icon" view provides a graphical representation, the "Diagram" view is meant to graphically compose system models using multiple components, the "Text" view where a component's equations are defined, and the "Documentation" view that provides

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[1] The `typewriter` font indicates Modelica language syntax, see [28].

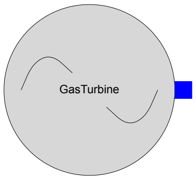


Fig. 1: Icon view of the Gas Turbine Unit

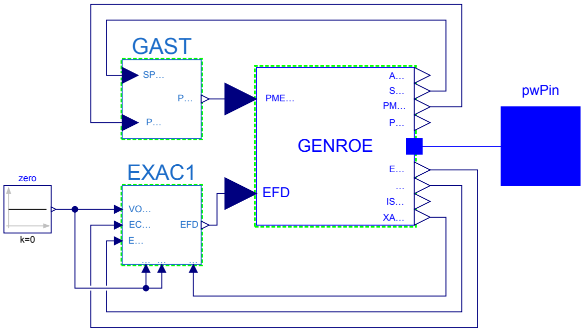


Fig. 2: Diagram view of the Gas Turbine Unit

information about the model [28]. Based on the aforementioned components that comprise the gas turbine unit and its technical description, the authors selected one generator, one turbine-governor, and one excitation system component from the OpenIPSL library that best matches the real life equipment description. The generator is modeled through a **GENROE** component (round rotor induction generator), the turbine-governor is modeled through a **GAST** component (gas turbine-governor), and the excitation system is modeled through a **EXAC1** component (IEEE Type AC1 Excitation System) [30]. For more information on the modeling aspects of the components, refer to [12], [29], [31]. The aforementioned components from OpenIPSL are displayed in Fig. 2, properly connected and ready to be used in the system model.

B. Steam Turbine Unit

The unit is comprised of a Siemens Dresser-Rand steam turbine, connected via rotor to a Kato Engineering Synchronous Generator. The generator is a brushless field revolving generator with direct connected rotating brushless exciter. The turbine's nominal operating speed is 4,700 RPM, with a single reduction parallel shaft speed reducer that decreases the rotor speed to 1,800 RPM. The generator construction is defined by a four-pole machine, with a nominal power of 3,580 kW, 13.8 kV at 0.8 lagging power factor, operating at 60 Hz.

Although the icon is similar to the one for the gas turbine unit, the diagram view is different because of the components that represent a steam turbine. Once more, the authors chose one generator, one turbine-governor, and one excitation system component from the OpenIPSL library that best matches the real-life equipment description. The generator model chosen is the **GENROE** component, the turbine-governor is modeled through a **TGOV1** component (steam turbine-governor model), and the excitation system is modeled through a **EXST1** component (IEEE Type ST1 Excitation System) [30]. The steam turbine model setup is displayed in Fig. 3.

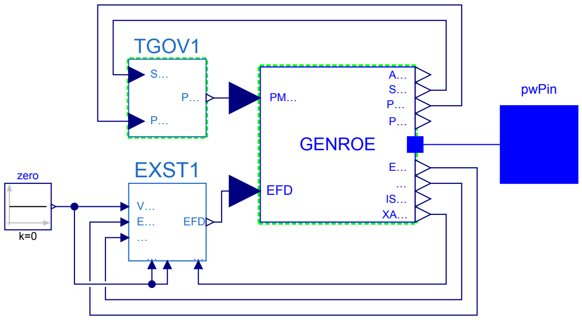


Fig. 3: Diagram view of the Steam Turbine Unit

C. Photovoltaic System Unit

The university campus microgrid has five distinct photovoltaic systems (PV) spread through the microgrid, ranging from a few kW to roughly 900 kW in nominal power. The terminal voltage of the photovoltaic installation is 0.6 kV, which is increased to 13.8 kV by means of a step-up transformer (to match the microgrid's voltage magnitude). For the development of these photovoltaic site models, the authors utilized reference materials from the Western Electricity Coordinating Council (WECC) on how to model and simulate PV panels [32]. Figure 4 displays the icon view of the photovoltaic panel component in OpenIPSL.

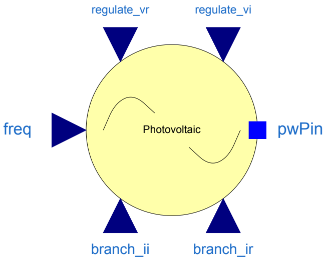


Fig. 4: Icon view of the Photovoltaic Unit

Figure 5 illustrates the diagram view of the photovoltaic unit model. It has five new connectors compared to the icon view of the gas and steam turbine, shown in dark blue triangles. These casual Modelica `connectors` from the Modelica Standard Library called `RealInput` that define unidirectional real valued input variables. They are used in the PV model to acquire distribution line voltage and current values as well as frequency in order to operate under plant-level control. The five new connectors are utilized when the user wishes to model a photovoltaic plant, where control over an aggregate of PV panels is desired. If the user only wishes to emulate local control, it can toggle the local control option within the PV model and the aforementioned connectors are automatically removed.

The sunken gray Modelica components in Fig. 5 are `replaceable`, meaning that the user has the option of selecting different extendable models based on a common

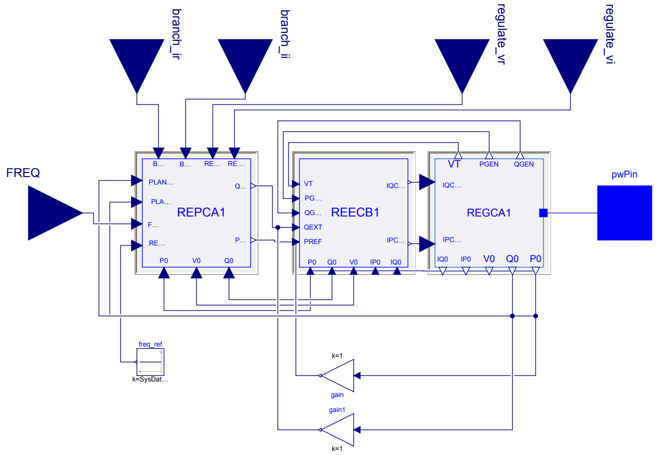


Fig. 5: Diagram view of the Photovoltaic Unit in OpenIPSL

base class component, making the PV model structure generic and quickly reusable [10]. The photovoltaic unit is modeled through a **REGCA1** component (renewable generator/converter model), a **REECB1** component (renewable electrical controller), and a **REPCA1** component (renewable plant controller). For information on the control schemes and how the components were implemented, refer to [33]. For the purpose of this work, the photovoltaic plant control configuration is set to power factor control, this is to reflect the fact that utility-scale plants have contracts that explicitly require curtailment or control to a certain power factor in their Power Purchase Agreements (PPAs) and Interconnect Agreements (IAs) [32], [34].

IV. SIMULATION RESULTS

The microgrid model presents electrical loads, distribution lines, transformers, gas and steam turbine-based generators, and photovoltaic units as shown in Fig. 6. There are exactly ten loads (**L1 - L10**) that represent an aggregation of building electrical loads. The **UTILITY** component represents the point of coupling of the microgrid to the utility grid. The component is modeled as an infinite bus (a synchronous generator with large inertia), meaning that it represents an infinite source of active and reactive power at a constant voltage magnitude and angle. Lastly, the **pwFault** component represents a three-phase to ground fault in a test system model, which is used to simulate a transient in order to assess the system's response. The simulations are split into two different tests and are described in the following subsections. The key data-sets for the reader to grasp the microgrid simulation setups are:

- **PV1 - PV5**: photovoltaic generation units injecting respectively 310, 10.8, 7, 9, and 600 kW of active power at 0.95 lagging power factor. The injection values are deemed constant for such a small period of time, although the renewable models developed in OpenIPSL can also accommodate irradiance-based power references for simulating longer time periods [33]. The control strategy adopted by all of the photovoltaic units is constant power factor.

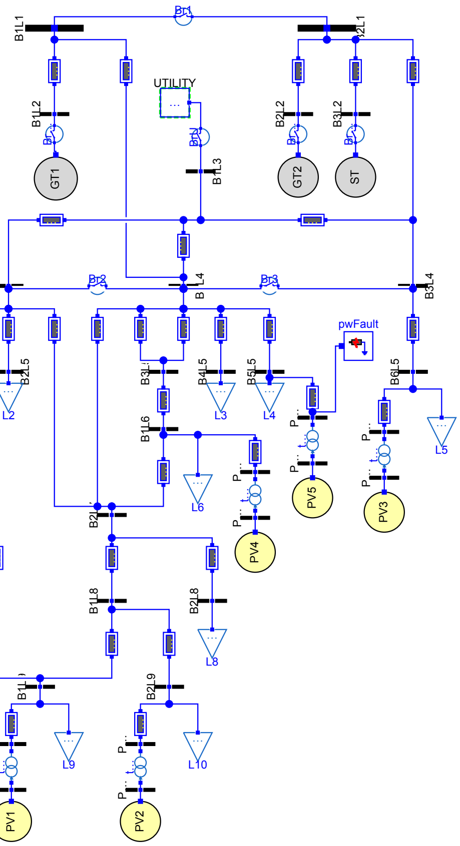
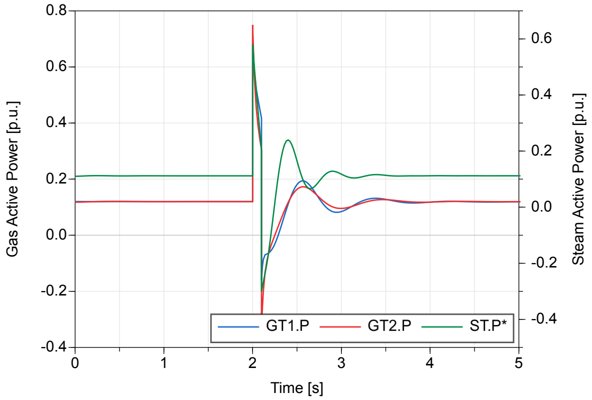


Fig. 6: Campus Microgrid "Virtual" Testbed Model.

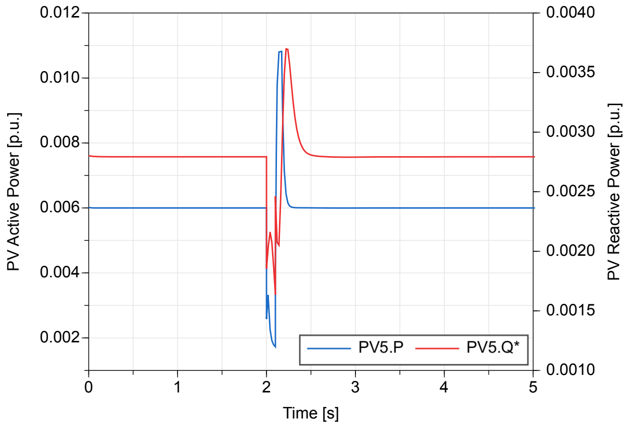
- **GT1 & GT2**: each gas turbine injects 2 MW of active power while consuming 8 and 2.39 MVar, respectively.
- **ST**: the steam turbine is small, limited to injecting 0.5MW of active power.
- **UTILITY**: is an infinite bus model from the OpenIPSL library and represents the utility grid. The initial active and reactive power supplied by the utility is 5.70 MW and 15.12 MVar.
- **L1 - L10**: the loads are aggregations of groups of buildings that can be traced back to a specific feeder. The total sum of active and reactive power load consumption in the microgrid is 8.366 MW and 4.212 MVar.
- **pwFault**: short circuit impedance $\tilde{Z} = 0.5 + j0.5$ [p.u.].

A. Simulation 1 — Three Phase Fault at High Voltage Side of PV Source 5 Transformer

The first simulation aims to assess the microgrid's response to a three-phase to ground fault at the high voltage side of the **PV5** transformer. The renewable sources are all set to have a constant power factor control scheme, keeping a constant 0.95 lagging power factor. The contingency is applied at $t = 2$ [s] and eliminated at $t = 2.1$ [s]. Figure 7(a) displays the dynamic response of the gas/steam turbines, and Fig. 7(b) displays the dynamic response of the largest photovoltaic source from the microgrid. The simulation displays a damped oscillation in the active power injection of the microgrid sources, starting the simulation from a steady-state condition that is regained



(a) Gas/Steam Turbine Active Power Injections.



(b) Photovoltaic Active & Reactive Power Injection

Fig. 7: Active Power Injection in all gas/steam turbines 7(a), and Active Power Injection in the largest photovoltaic source **PV5** in 7(b).

after the transient response of the electrical sources. Because the system is comprised of both inertia and inertia-less energy sources, the frequency of the grid is not defined only by the rotational speed of the turbines but also through the power electronic interface of the photovoltaic source. Because phasor domain models do not model the electromagnetic transients of switching components in converters/inverters, there is no actual way of "measuring" the PV output frequency value. Thus, the overall frequency of the grid requires estimation, which is done through a wash out filter. The estimated frequency of the grid based on angle measurements from bus **B5L5** is shown in Fig. 8, in [25] frequency estimation method is described. The system frequency begins at steady-state (60 Hz) and regains its steady-state value once more after the transient due to the contingency being damped.

B. Simulation 2 — Microgrid Model Eigenvalue Analysis

The infinite bus is modeled as a generator with a large inertia, and for that reason, linearization techniques will always point to zero eigenvalues, which due to numerical precision may generate eigenvalues with positive real part and thus misinterpreted as unstable. The result is three stiff states with immensely large time constants, namely *delta* (rotor angle), *omega* (rotor speed), and *eq* (electromotive force) [35]. The solution to this issue can be achieved through utilizing an ideal voltage source component from the OpenIPSL Library [12]. The ideal voltage source component also gives the user the flexibility to modify the voltage phasor over time. If phasor measurements are available, then the user can use it to "emulate" the utility. Dymola has the ability to perform linearization using the Modelica Linear Systems 2 library [36] that is built into the software. It allows the user to perform symbolic linearization on the model at any point in time, generating the A, B, C, and D matrices and performing eigenvalue analysis. Figure 9 displays the eigenvalues in pole/zero form of the microgrid system at $t = 0$ [s], totaling 87 states.

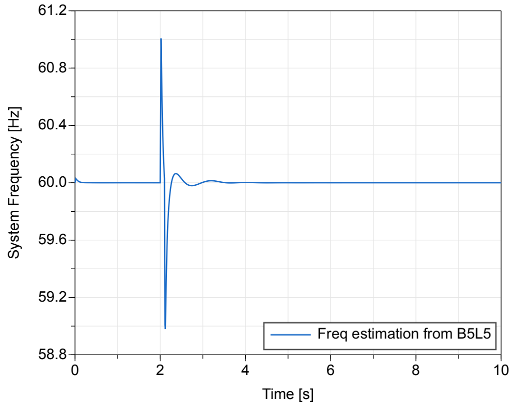


Fig. 8: Grid Frequency Estimation

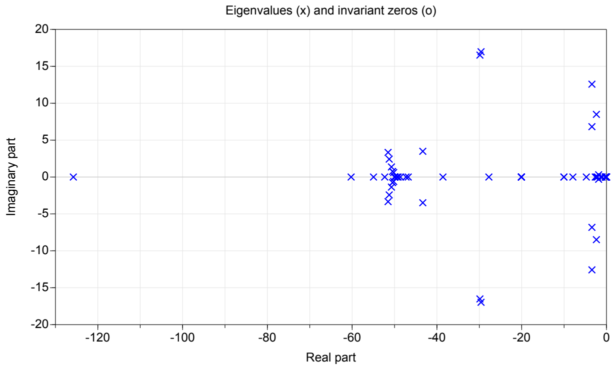


Fig. 9: Poles and Zeros from the linearized model

All the real components of the system's eigenvalues are negative, being able to infer that the system is stable. With a stable model as described above, the user can utilize the state-space formulation for control design, such as Model Predictive Control [37], which will be subject of our future work.

V. CONCLUSION

This work presented the description and rationale behind the phasor domain model of a real-world University Campus Microgrid using the Modelica language and the OpenIPSL library. With microgrids gaining more traction, the study/implementation of such microgrid models and the documentation of the step-by-step modeling process is of value to the power and energy community. The model is based on open-source software, that is reusable and generic, and capable of being used as an entry model for system analysis.

The model will be used in the development of resiliency plans, as part of the project "Optimal co-design of integrated thermal-electrical networks and control systems for grid-interactive efficient district (GED) energy systems" funded by the U.S. Department of Energy. The authors are also developing grid forming converter models that will address the challenging task of islanded operation of inverter-only microgrids. The sample results in this paper point to the success of the modeling task of the project. The microgrid model will be released as open source by integrating it into a future version of the OpenIPSL library. The library can be found at: https://github.com/OpenIPSL/OpenIPSL.

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