GridMat: Matlab Toolbox for GridLAB-D to Analyse Grid Impact and Validate Residential Microgrid Level Energy Management Algorithms

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Abstract— **Residential microgrid has the capability to participate in the distribution grid as a very flexible and dynamic component for demand side energy management (energy efficiency, peak-load reduction, and demand response). Various hierarchical (appliance, home, and neighborhood level) advanced control algorithms need to be developed and validated for such residential microgrids. GridLAB-D is the most promising tool for power system modeling of a microgrid. However, it is limited in supporting advanced control algorithm development with debugging support and does not provide a user friendly interface for modeling the structural and behavioral aspects of a residential microgrid. Therefore, in this paper, we present a new Matlab toolbox (GridMat) to integrate the capabilities of domain-specific modeling & simulation tools from power system (GridLAB-D) and control (Matlab). The GridMat tool supports user friendly model creation, robust debugging, and intelligent grid impact analysis utilities. To demonstrate the capability of GridMat, we have implemented three different levels of energy management controllers (including direct load control) for a residential microgrid using this tool to reduce and shift peak load according to *Time-Of-Use* (TOU) electricity rate.**

Index Terms-- **Co-Simulation, GridLAB-D, GridMat, Matlab, Residential Microgrid**

I. INTRODUCTION AND RELATED WORK

Microgrid is a localized and semi-autonomous group of electrical energy resources (storage and generators such as Photovoltaic) and loads (appliances) that connects to the traditional power grid (macrogrid). In physical and economic conditions, it can disconnect from power grid and operate autonomously (island power) [1]. Besides various active research and demonstration activities to deploy the microgrid concept at military installations, critical infrastructure areas (e.g. hospitals), and commercial & university locations, the possibility of deploying the microgrid concept at the residential level is also getting significant attention today [7,8,9,29]. Consumer *Electric Vehicle* (EV), roof-top photovoltaic, resident/building-scale energy storage, smart flexible appliances, and *Home Energy Management* (HEM) systems are the driving technologies in forming a residential microgrid [7].

Modeling a complex, large-scale, heterogeneous, multi-physics, multi-domain, and distributed system like a microgrid requires heterogeneous composition of physical, computational, and communication sub-systems including their causality, time semantics, and different physical domains. Various design challenges of modeling and simulation of a microgrid have been discussed in [11,29]. State-of-the-art distribution grid and/or microgrid modeling & simulation tools are domain-specific and are mostly capable of capturing only the physical components (power system and energy resources) of the model. Some of the tools that have been explored during this work are: OpenDSS developed by *Electric Power Research Institute* (EPRI) [10], MATPOWER [6], InterPSS [18], Network Analysis - Integrated AC & DC System [19] from ETAP, PSS®SINCAL [22], HOMER [14], WebOpt [20], and RETSCREEN [21]. However, common to all these tools is that they do not provide a test bed to simulate an energy distribution model like a residential microgrid where power system modeling at a very detailed level (e.g. at appliance level) is required. To solve this problem of modeling detailed residential power systems of a residential microgrid, we have used GridLAB-D [2,3], an agent-based power system modeling and simulation tool.
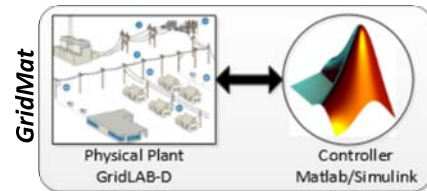

Figure 1. GridMat (Matlab Toolbox for GridLAB-D)

The state-of-the-art power system modeling tools including GridLAB-D mentioned above lack the capability to capture the cyber-components (control, software, communication, and embedded hardware) during modeling and simulation. To solve this problem, co-simulation of various domain specific tools (for example OpenDSS & OMNeT++ in [28] and Matlab & E+ in [13]) has been seen as the possible enabling technology [25]. With the same spirit of connecting the cyber and the physical worlds, we have developed a co-simulation platform between GridLAB-D [2] (power systems- physical world) and Matlab [24] (control – cyber world) using our in-house developed Matlab toolbox GridMat (see Figure 1). GridMat may be used to facilitate the control engineers for developing advanced and hierarchical

control algorithms for the residential microgrid. Some early works that have tried to co-simulate GridLAB-D with other domain-specific tools, their advantages/disadvantages, and our novelty compared to those approaches are discussed below.

In [12], a co-simulation of GridLAB-D and Matlab is used to model integrated renewable energy and *Demand Response* (DR). In this co-simulation, control developed in Matlab (slave of the simulation) is executed as a co-process of GridLAB-D (see Figure 3(a)) and cannot support a debugging utility function for the control engineers. In [17], authors have presented a technique of using functional mockup interface to integrate Modelica-based components with GridLAB-D. This work is limited to interfacing only. Authors in [16] have proposed a simulation framework named GridSpice by interfacing MatPower and GridLAB-D. The major objective of this work is to provide large scale simulation using parallelization techniques of jobs. The advanced control algorithm development capability using the toolbox of Matlab is missing in GridSpice. In [15], a co-simulation platform of communication and power systems (ns-3 [23] and GridLAB-D [2]) is presented. This work is orthogonal to our work and communication (ns-3) and may also be integrated in our tool. However this is out of the scope of this paper.

The rest of the paper is organized as follows: Section II presents the novel contributions and the key features of our proposed GridMat tool. Section III describes the GridMat tool in detail. Section IV discusses the GridLAB-D and Matlab co-simulation method. Experimental results are discussed in Section V with Section VI concluding the paper.

II. OUR NOVEL CONTRIBUTIONS

Our novel contributions are as follows:

1) A novel Matlab toolbox for GridLAB-D that supports modeling, simulation, grid impact analysis, and validation of power & control systems of a residential microgrid. The major features of our GridMat are:

- It equips designers with all Matlab toolboxes to design, develop, and debug advanced, hierarchical, and distributed control algorithms. Therefore, device-level and various *Supervisory Control And Data Acquisition* (SCADA)-level control algorithms may be developed for the residential microgrid very effectively.
- It provides a user friendly graphical interface for the state-of-the-art GridLAB-D tool.
- Model creator in GridMat tool helps designers to create the structural and behavioral models of a microgrid.
- Data analysis utility enables the designers to analyze the simulation results & the grid impact under various scenarios (e.g. EV charging) and allows for modifying the models & the controllers.

2) We present various multi-level control algorithms design, development, and validation use-cases to reduce & shift the peak load utilizing the proposed GridMat tool.

III. GRIDMAT ARCHITECTURE

GridMat deploys the full advantages of GridLAB-D to model and simulate the physical plant (power system), and takes full advantage of Matlab to control the physical plant of a distribution power grid (e.g. residential microgrid).
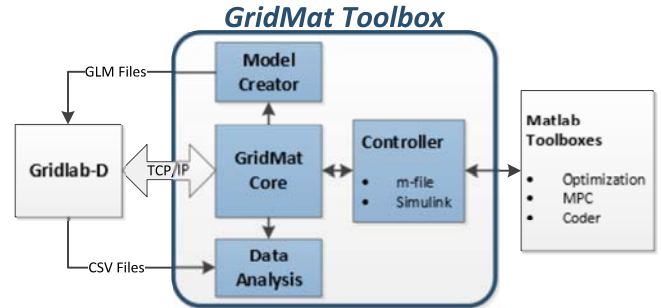

Figure 2.   High-level architecture of the GridMat

A.   Preliminaries about GridLAB-D

GridLAB-D (for details see [2]) is a DOE sponsored open-source, multi-domain modeling (power, weather, market), and simulation (it uses discrete event-based model of computation) tool for power systems (particularly suitable for distribution grid). GridLAB-D is an agent-based simulation platform where agents are characterized by a set of properties (termed as states) and actions for updating the states [2,3]. Agent concept at different granularity levels (there may be appliance-level agents and home-level agents) is used in GridLAB-D. GridLAB-D uses a concept called "module" to specify interacting agents. Agents can interact vertically as well as horizontally with other agents describing power system components. Therefore, a large scale power and/or distribution system can be built using these interacting agents by organizing these agents hierarchically.

During a simulation each instantiated agent calculates the next time stamp for updating its states. The simulation engine of GridLAB-D manages a global clock progression during simulation, monitors the states of the agents, and facilitates inter-agent communication through schedules associated with each agent [17].

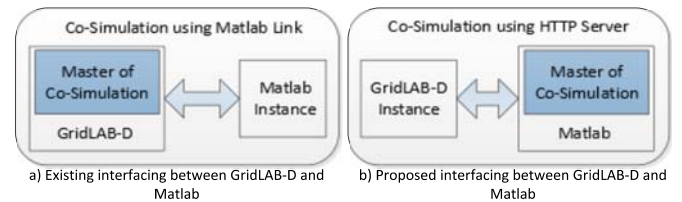| a) Existing interfacing between GridLAB-D and Matlab | b) Proposed interfacing between GridLAB-D and Matlab |

Figure 3.   Interfacing possibilities

B.   GridMat Structure

Figure 2 shows the basic architecture of the GridMat tool. GridMat is hosted in Matlab environment and has four major modules: 1) Model creator, 2) GridMat core, 3) Controller, and 4) Data analysis.

C. GridLAB-D and Matlab Interface

Figure 3 shows two alternative ways to connect GridLAB-D and Matlab tools. In Figure 3 (a) GridLAB-D is the master and controls the execution of the controller in Matlab. This is the existing connection available from GridLAB-D [2, 12]. The shortcomings of the current connection are: lower readability of the code, limitations of debugging capability for the control algorithm development, lack of existing toolbox support for control algorithm development, e.g. Matlab MPC toolboxes, etc.
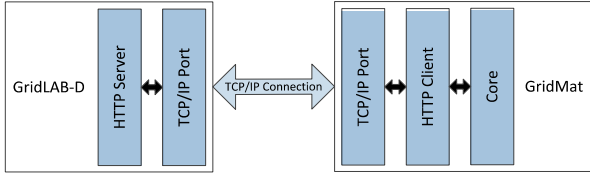

Figure 4.   Client/server communication for GridMat

To solve these problems, we have developed a novel GridLAB-D and Matlab   interfacing technique through a TCP/IP port by exploiting the existing HTTP server hosted in GridLAB-D. We have developed a HTTP client in the Matlab for this interfacing (see Figure 4 for the connection over the TCP/IP port). Moreover, this HTTP client handles the simulation runtime, sensor data reading, and writing of the set-points for the power systems agents. In this interfacing, Matlab is the master (see Figure 3 (b)) of the simulation and has full control of the simulation. Therefore, it supports fine-grained debugging of the developed control algorithms.
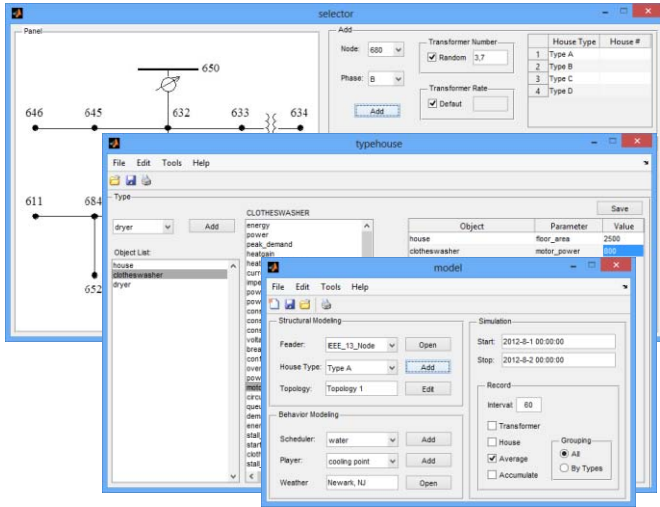

Figure 5.   Model creator for the structural and behavioral modeling of the residential microgrid

D. GridMat Utilities

The major purposes of GridMat are: 1) to provide an easy user interface to GridLAB-D that does not exist today to model the structural and behavioral properties of microgrid components, 2) to allow development and debugging of advanced control algorithms in Matlab, and 3) to allow a data analysis feature for grid impact analysis using the Matlab toolbox.

1) Model Creator

The model creator utility developed in GridMat allows generation of the microgrid model and generates the input (.GLM) file for GridLAB-D. Figure 5 shows various views of the model creator utility. We used a component-based approach by providing a library of IEEE PES distribution test feeders [4,5] as the template for creating the structure of a residential microgrid. The model creator allows modeling different types of houses with different appliances, house structure, etc. Moreover, it supports modeling behavior of each component including schedule, player, price, and weather.
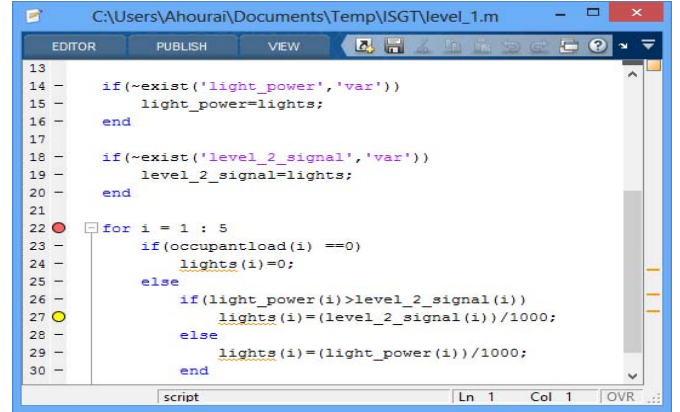

Figure 6.   GridMat debugging capabilities

2) Debugging in GridMat

GridMat provides the complete feature of Matlab's debugging capability (see Figure 6). It provides a standard breakpoint feature to stop the simulation at a specified line to debug control specific variables. A conditional breakpoint may also be used to stop the simulation in a specific control point given that a pre-defined condition is fulfilled. Another debugging feature of this utility is the timing breakpoint where GridLAB-D simulation is stopped at a specified time described in the Matlab control program. Finally, our GridMat debugging utility provides an error breakpoint capability where the simulation stops in any control point when it produces the specified type of warning, error, NAN, or infinite value.
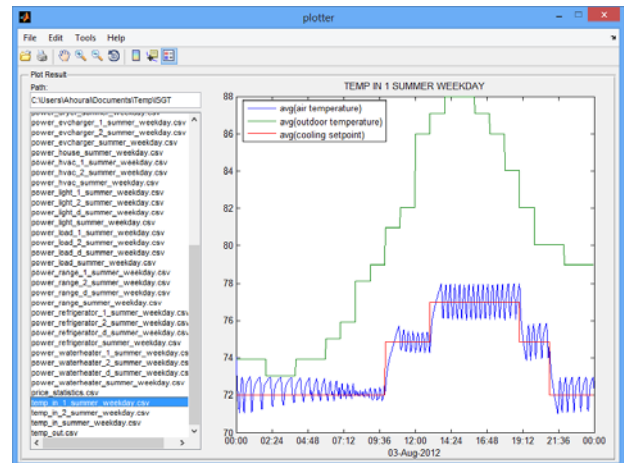

Figure 7.   Data analysis using GridMat

3) Data Analysis

The model creator utility creates necessary recorders to analyze the microgrid model. The Plotter utility of GridMat helps the developer analyze the results by exploiting the full capability of Matlab to plot and analyze data. Figure 7 shows an exemplary data analysis function.

IV. SIMULATION AND VALIDATION USING GRIDMAT

GridMat tool is used as a co-simulation tool for power systems and control algorithms. Through the user interface of the GridMat various input signals at different granularity of the agent organization specified in GridLAB-D may be exposed to the controller running at Matlab. The controller can also assign new set-point values to the actuators or to the control variables of the power system agents exposed to Matlab. Figure 8 shows various sequences of the co-simulation. During co-simulation, the GridMat core acts as the master of the simulation. GridMat core starts the simulation on GridLAB-D and pauses the simulation at each step time. In the beginning of each step, GridMat reads the sensor values from GridLAB-D. After that, GridMat executes the controller in Matlab with new sensor values. The controller then computes the new controlling signals according to the specified algorithm. Finally, GridMat writes the new controlling signals into GridLAB-D and resumes the simulation for another time step.
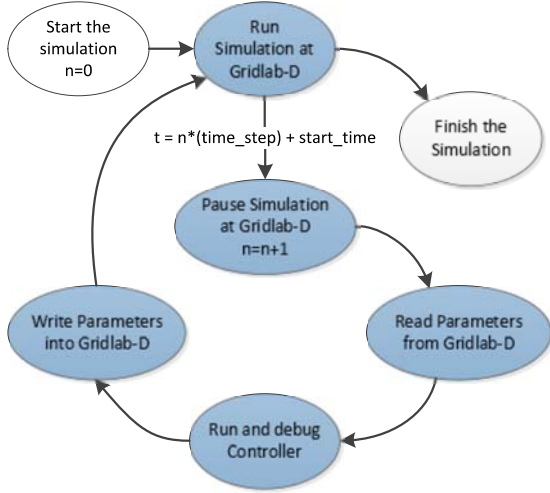

Figure 8.   GridMat co-simulation sequences

V. EVALUATION OF A RESIDENTIAL MICROGID USING GRIDMAT TOOL

For our experiments, we considered the microgrid model described in [26]. We implemented three levels of control algorithms in GridMat: 1) device level control, 2) *Home Energy Management* (HEM) level control, and 3) a microgrid level control. We developed a linear controller according to time-based DR programs from *Federal Energy Regulatory Commission* (FERC) [27] (time-of-use pricing) for both HVAC and lighting in HEM. For microgrid level control, we used an incentive-based DR program (direct load control) [27] to control the water heater and EV charging. To show the results, we have used the moving average technique.

Figure 9 shows an example of developing a home energy management control algorithm development capability of our GridMat tool. In this algorithm, ASHRAE-specified thermal comfort (room temperature between 72° F and 77° F [30]) is maintained for the occupants while energy usages are minimized almost by 5% and energy cost by 12.5% for a single home.
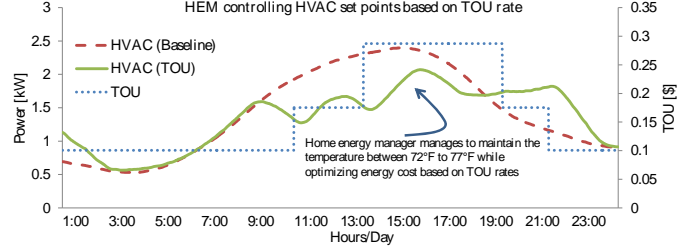

Figure 9.   HVAC control algorithm (HEM-specific set-point control) development in GridMat

Figure 10 shows an example of developing a hybrid lighting control algorithm where both lighting control based on occupancy presence (device level control for energy efficiency) and managing the lights from the HEM based on energy price (TOU rates) are presented. The HEM turns-off 400W (30%) of the installed power (this amount is part of the outdoor lighting, ambient interior lighting, and accent interior lighting) during the peak price.
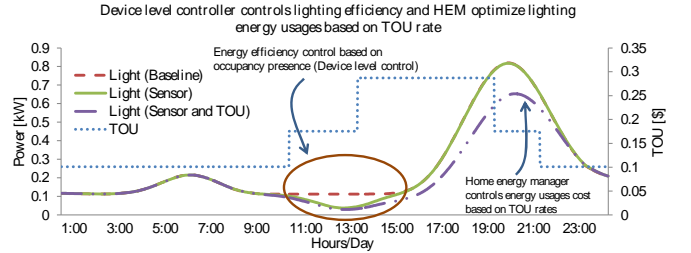

Figure 10. Hybrid lighting control algorithm (device-level for energy efficiency and HEM-level for energy optimization based on TOU rate) development in GridMat

We implemented a residential-level microgrid control algorithm where 5 houses are connected to a 25 KVA transformer and only one house has EV (charging rate 15A @ 240 V). This residential microgrid has prior contract with the Utility to respond to DR signals and therefore a microgrid-level controller may initiate direct load/appliance control from the transformer-level controller in each house of the microgrid based on a pre-defined priority-based schedule. Figure 11 shows how the microgrid controller works during a DR signal from Utility to save 3 kW of power between 5 PM and 9 PM. The microgrid controller first looks for reducing the EV charging as EV has the highest priority to be controlled in the presence of such a DR signal in this algorithm. However, the controller finds no EV at the beginning of the DR signal at 5 PM and therefore starts reducing water heater set point temperature to 125°F for all the houses (5 houses in this experiment) to fulfill the commitment of reducing 3 kW during this DR period. This experiment also shows that when EV becomes available to be charged at 6 PM the controller is able to adapt to this changing scenario and therefore increases

the water heater temperature to their previous set points and manages the EV charging to fulfill the DR commitment. This example shows the capability of our GridMat tool to develop control algorithms for a microgrid controller.
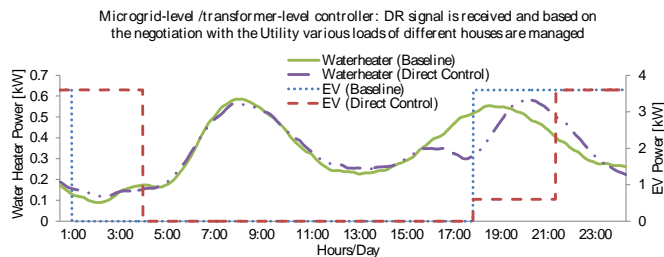

Figure 11. Microgrid-level SCADA control algorithm development using our GridMat tool

Our GridMat tool is able to develop multi-level hierarchical control algorithms for microgrid architecture. Figure 12 shows such an experimental result. We have implemented all three levels of control algorithms shown in Figure 9, 10, and 11 together and have achieved a complex microgrid management capability using our GridMat tool. By using this multi-level hierarchical control, we can reduce the average power consumption by 8.1% and also shift the peak load for additional energy cost saving (through DR).
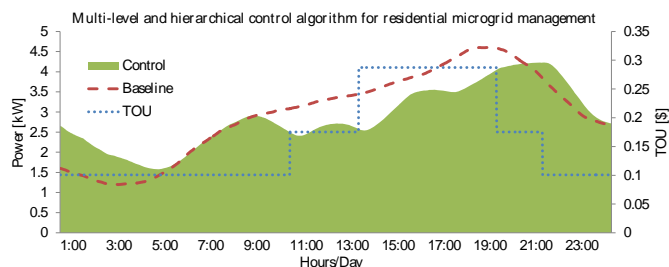

Figure 12. Multi-level controller using GridMat tool development

VI. CONCLUSION

We present a novel Matlab toolbox for GridLAB-D that support modeling, simulation, grid impact analysis, and validation of power & control systems of a residential microgrid. The powerful debugging capability of this GridMat tool may support control engineers to develop robust, hierarchical, and advanced control algorithm for the residential microgrid. The capability of the tool is validated using various use cases of control algorithm development. This tool will be made open-source to be used for academic and research activities shortly at (http://aicps.eng.uci.edu/research/CPES/Tools/GridMat.htm).

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