Generalized Energy Storage Model-In-the-Loop Suitable for Energy Star and CTA-2045 Control Types

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Abstract: The paper proposes a generalized energy storage (GES) model for battery energy storage systems (BESS), electric water heaters (EWH) and heating, ventilation, and air-conditioning (HVAC) systems. The analogies, including state of charge versus water temperature differential, are identified and explained, and models-in-the-loop (MIL) are introduced, which are compatible with the Energy Star and CTA-2045 general specifications and command types. Emphasis is placed on the proposed EWH model as it needfully fulfills a gap in present literature. The corresponding MIL has been implemented in the DER integration testbed, which was originally developed by EPRI, and satisfactorily validated against experimental results. A case study is included to illustrate that the daily "energy content" and "energy take" for BESS and EWH with mixing valve technology are comparable for typical residential ratings. The BESS, which requires more initial investment, has advantages in terms of flexibility for contributing to grid services, which are illustrated through a combined simulation and experimental study based on data collected from a field demonstration site with four smart homes.

***Index Terms*—Battery Energy Storage System (BESS), Electric Water Heater (EWH), Heating, Ventilation, and Air-Conditioning (HVAC), Energy Storage, ANSI/CTA-2045-B, Energy Star, Home Energy Management (HEM), Co-simulation.**

I. Introduction

The advancement of smart home and grid technologies and the associated electric power system integration studies relies on individual and combined simulators for buildings, such as EnergyPlus, and circuit networks, e.g., OpenDSS, MATPOWER, GridLAB-D, etc. [1]. The Distributed Energy Resources (DER) integration testbed, which includes open-source simulation software, was originally developed by the Electric Power Research Institute (EPRI), comprises multiple layers for controls, devices, and circuits, and is able to communicate using protocols that are typically employed for hardware components [2], [3]. Using this technique, the DER integration testbed can be used with a combination of real physical devices and/or with their equivalent model-in-the-loop (MIL) software implementation. The advantages of the MIL approach include cost-effective development and testing in a realistic set-up and the ability to largely scale-up studies with minimal hardware [4], [5].

Energy storage devices and systems, which can be electric, such as battery energy storage systems (BESS), or thermal, such as electric water heaters (EWH) or heating, ventilation and air conditioning (HVAC) systems, are essential in order to ensure an optimal energy management and power flow within the modern grid with DER. To support technology development and standard-type implementation that would enable wide scale industrial and utility deployment, Energy Star, a program conducted by the Environmental Protection Agency (EPA) and Department of Energy (DoE), provides general specifications for energy parameters and demand response (DR) functionalities [6].

For EWH, these specifications are typically implemented using the Consumer Technology Association (CTA) 2045 standard [7], and success has been reported at the individual residential and utility aggregated levels [8], [9]. In principle, the combined Energy Star and CTA-2045 specifications and concepts such as "energy capacity", "energy content", and "energy take" and DER commands, such as "load shed", etc., can be extended to any energy storage device and system, enabling a unified approach at system level. The current paper brings new contributions by discussing the analogy as energy storage among a BESS, an EWH, and a HVAC system, based on a generalized energy storage (GES) concept and by proposing associated MILs, which are implemented and exemplified in a testbed set-up.

The testbed, which utilizes MILs to simulate DERs, enables the study of home energy management (HEM) system implementation at the residential and community level. HEMs may coordinate various DERs such that energy use and cost is optimized. Algorithms developed for such optimization may shift energy usage of controllable loads, such as HVACs, EWHs, and electric vehicles (EVs), and utilize rooftop solar photovoltaic (PV) generation with BESS such that the distribution system experiences a significant combined effect that may drastically reduce total energy use and peak load for the utility [10], [11].

In addition to the distributed optimization and control approach of these DERs, behind-the-meter (BTM) transactive

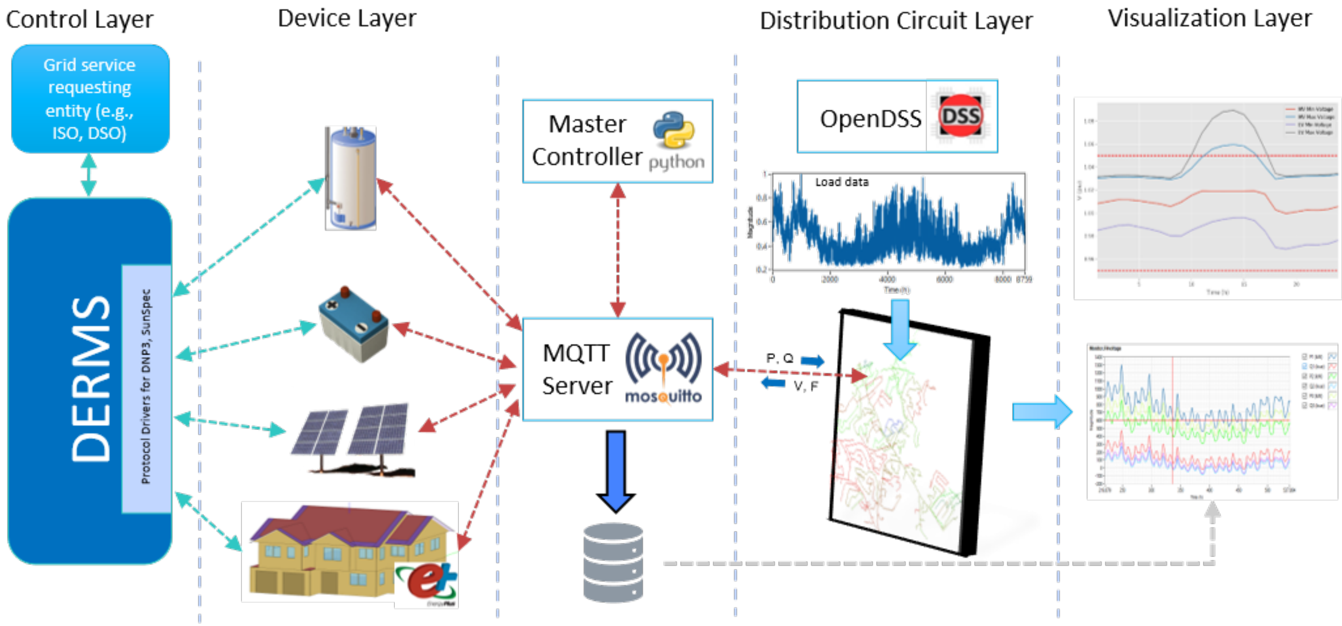

Figure 1. The architecture of EPRI's DER integration testbed. Models-in-the-loop (MIL) are employed at the device layer. The paper proposes unified models for the battery energy storage systems (BESS) and electric water heaters (EWH) suitable for Energy Star and CTA-2045 control types, which are issued by a distributed energy resource management system (DERMS). The MILs are to communicate with the distribution system simulator, which is OpenDSS for this study, through the Message Queuing Telemetry Transport (MQTT), which enables distribution-level simulation of control schemes.

control may be employed with HEMs for energy use reduction in residences by coordinating home appliances in market schemes that also consider human comfort [5]. Furthermore, optimal management methods for typical residential devices have potential to accommodate for the drastic change in that distribution load profiles will likely experience due to the increasing popularity of EVs in the automobile market [12].

II. EPRI's DER Integration Testbed

The EPRI's DER integration testbed simulates power system models with real world communication systems and DER models. The testbed can assess the control functionality and communication interoperability of the Distributed Energy Resources Management System (DERMS) and can evaluate different control strategies for any circuit. It also supports real world communication systems by incorporating industry standard protocols, such as the CTA-2045 standard, Energy Star specifications, DNP3, and SunSpec Modbus. The testbed can simulate scenarios that include a variety of DERs, feeders, load conditions, weather, and DER penetration levels.

The DER integration testbed has four layers in its architecture: control, device, circuit, and visualization and analytics (Fig. 1). The circuit layer contains a power system simulator, such as OpenDSS or Cyme, to model the feeder and calculate powerflow. The visualization and analytics layer provides the user with actionable information to analyze the full system. The control layer manages DER in the device layer using control strategies that may be user-built or commercial.

OpenDERMS is an EPRI developed reference control tool that can aggregate, optimize and manage large number of DER to provide grid services while enabling customer benefits. The devices in the device layer are implemented as software simulators that emulate real world DER characteristics and incorporate built-in commercial communication interfaces for common industry protocols. The device and circuit layers communicates through the Message Queuing Telemetry Transport (MQTT) protocol, which is an effective communication tool for IoT devices and has great potential for facilitating co-simulation of multiple DER ecosystems [13]. The way in which these layers are interconnected provides a high level of modularity and scalability to the testbed. Utilizing this tool enables distribution-level simulation of demand response (DR) control schemes and co-simulation of the distribution system simulator, MIL, and other device-level simulators such as EnergyPlus, a whole building energy simulation program.

The EPRI's DER integration testbed for energy storage systems is of particular interest for this study as it was utilized for the simulation of an EWH that is treated as an energy storage system [3]. The simulator is capable of various smart functions, such as connection/disconnection, charging/discharging, volt-VAR curve input, and generation level and power factor adjusting. The EWH MIL was simulated in the paper and connected to EPRI's DER integration testbed (Fig. 2).

III. Energy Storage Definitions

The Generalized Energy Storage (GES) in a residence includes BESS, EWH, and the HVAC system. For a BESS, the "current available energy storage capacity" is calculated as follows:

$$E_{C,B}(t) = \overline{E_{B,R}} \cdot (SOC_{B,max} - SOC_B(t)), \qquad (1)$$

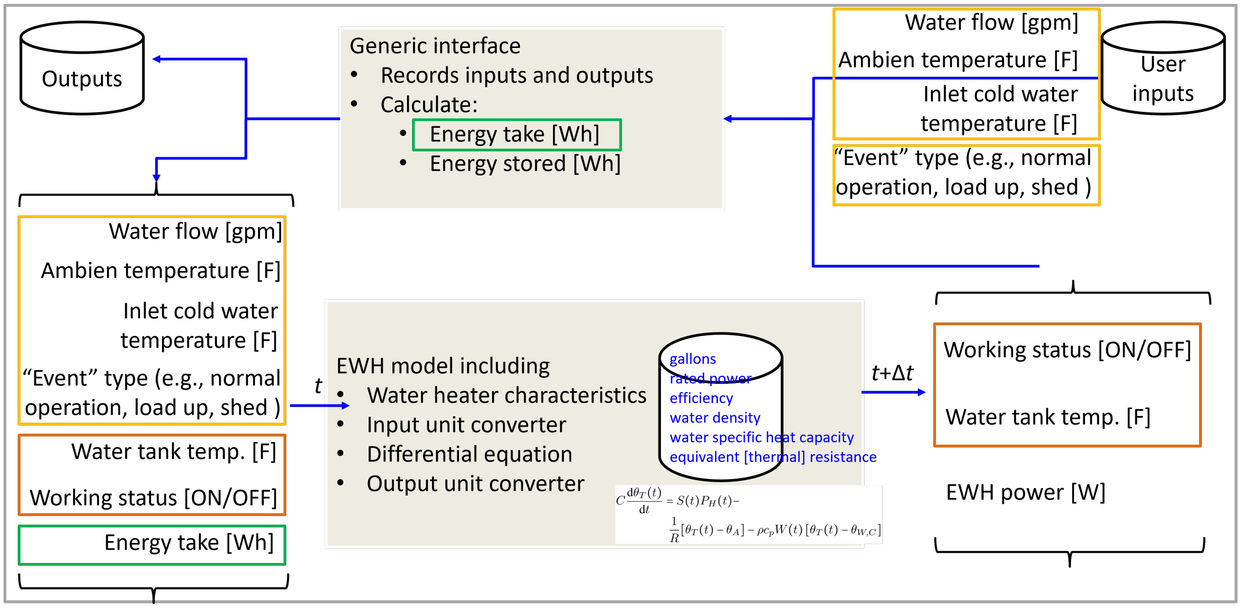

Figure 2. Schematic of the Model-In-the-Loop (MIL) for an Electric Water Heater (EWH). The computer code is implemented in C# under Visual Studio 2020 and communications with the EPRI's DER integration testbed follow the CTA-2045 standard for Energy Star commands.

where $\overline{E_{B,R}}$ is the rated energy capacity of the BESS; $SOC_{B,max}$, the maximum allowed SOC.

For most of the academic work, the water temperature in the tank was used to represent the current status of the energy storage for the EWH. Practically, the water temperature is hard to measure as it is stratified inside the tank. Therefore, most CA-2045 available EWH only provide the "energy take" by manufactures based on their undisclosed algorithms.

In this paper, the "energy content of the stored water" for the EWH is defined as:

$$E_W(t) = V\rho c_p \theta_T(t), \tag{2}$$

where V is water tank volume; ρ, density of water; c_p, specific heat capacity of water; θ_T, the average temperature in the water tank. Based on (2), the "current available energy storage capacity" for a water heater is calculated by referring to the set point, as follows:

$$E_{C,W}(t) = \overline{E_{W,S}} - E_W(t), \tag{3}$$

where $\overline{E_{W,S}} = V\rho c_p \theta_{T,S}$ is the maximum energy capacity for the EWH, defined by $\theta_{T,S}$, the set point. The "energy take" is defined as follows:

$$E_{T,W}(t_2 - t_1) = E_W(t_2) - E_W(t_1). \tag{4}$$

The HVAC system is regarded as an energy storage and its equivalent SOC is defined as:

$$SOC_H(t) = \frac{\theta_{max} - \theta_I(t)}{\theta_{max} - \theta_{min}}, \tag{5}$$

where the θ_{max} and θ_{min} are the maximum and minimum room temperature, respectively; θ_I, the indoor temperature. The energy storage capacity of the HVAC system, $\overline{E_{H,C}}$, is defined as the input electricity needed to change the room temperature from the maximum to the minimum with a fixed outside temperature [14]. The "current available energy storage capacity" for the HVAC system calculated as:

$$E_{C,H}(t) = \overline{E_{H,C}} \cdot (1 - SOC_H(t)). \tag{6}$$

IV. Case Study and Simulation Results

Two cases, which were based on experimental results, were studied to validate the EWH as a MIL in the EPRI's DER integration testbed. In the first case, the simulation results of a resistive EWH was validated against the experimental data from an EPRI performance test on a CTA-2045 compatible EWH [8]. The tank temperature and the "energy take" values were monitored as the EWH responded to the "Shed Event" signal (Fig. 3). The simulation has satisfactory results compared with the experimental data (Fig. 4).

The value of "energy take" has different ranges which correspond to the types of DR signal. Under normal operation, the range of "energy take" is [0, 900Wh]. When the value of "energy take" is more than 900Wh, the EWH turns ON until the value reaches 0 (Fig. 3). The temperature and water draw are referred in p.u., where the base values for temperature and hot water flow are 140 F and 1 gallon per minute (GPM), respectively.

At 3:10, the EWH responded to the DR signal "Shed Event" by setting the "energy take" range to [2,000Wh, 2,200Wh]. The DR signal "Shed Event" postponed the heating process by allowing more energy to be taken from the tank by the hot water while maintaining occupant comfort. The "Shed Event" ended at around 4:10 and the EWH was turned ON immediately to bring the "energy take" value to 0. For

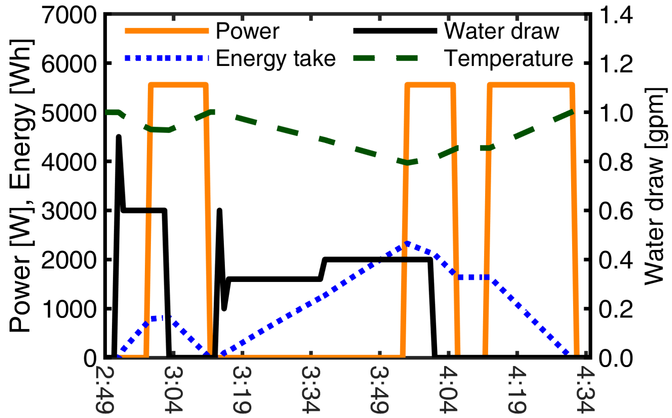

Figure 3. Example of simulated EWH ”Shed Event” corresponding to the experimental data illustrated in Fig. 4. Based on DR control signals, the “energy take” capacity was increased from 900Wh to 2,200Wh, resulting in a shift/delay of the water heating process.

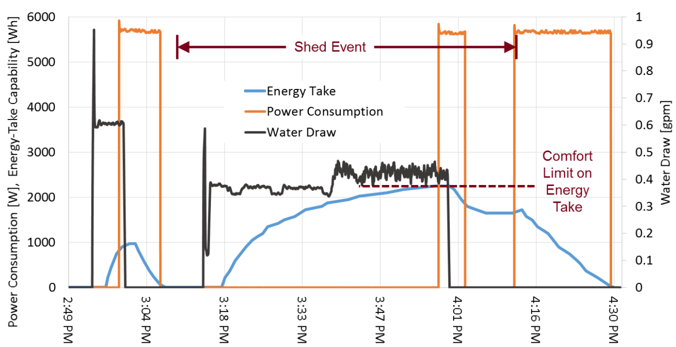

Figure 4. Experimental data, previously reported by NREL/EPRI [8], and employed for the satisfactory validation of the proposed EWH MIL. The “Shed Event” occurs from 3:10 to around 4:10, which causes the “energy take” range to increase and the heating process to be postponed while maintaining occupant comfort.

comparison, an illustration of the experimental data for the “Shed Event” case reported in [8] is provided in Fig. 4.

The second case was based on the experiment from the SHINES program, which was launched in 2016 by the DoE to develop and demonstrate technologies that enable sustainable and holistic integration of energy storage with solar PV [15]. In this paper, the EWH loads of the two houses, as well as the BESS, solar PV, pool pump and HVAC were tested in the field. The different EWH loads and BESS charging schedule as well as the corresponding energy and aggregated power of the two EWHs are provided for a comparative study (Fig. 5).

The example charging schedule for the BESS resulted in a similar power rating when compared to the EWH DR power. This example shows that the BESS and EWH are comparable when considering their energy content as GES. The average temperature of the water was monitored in the case studies and shown in Fig. 6. When the peak in the morning was shifted, the temperature in the tank was still above the commonly acceptable user comfort level, which is 115F. Mixing valve technology was used to guarantee occupant safety when the

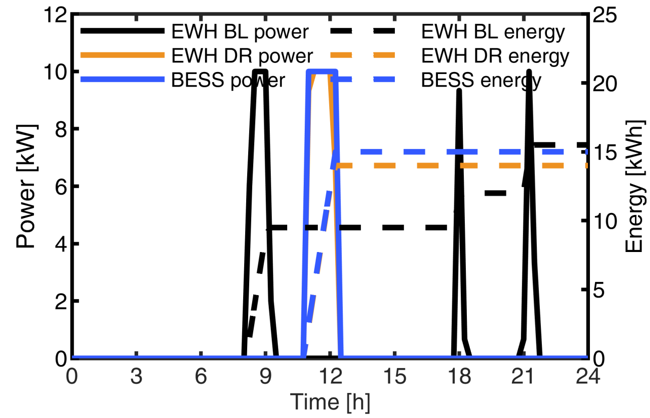

Figure 5. Comparative study of energy storage with BESS and EWH, including typical/normal base line (BL) and demand response (DR) schedules. For BL operation, the EWH has a morning and two evening peak power cycles. The BESS schedule was adjusted to allow comparison with a EWH study for DR load shifting around noon, which may align well with PV generation, if available.

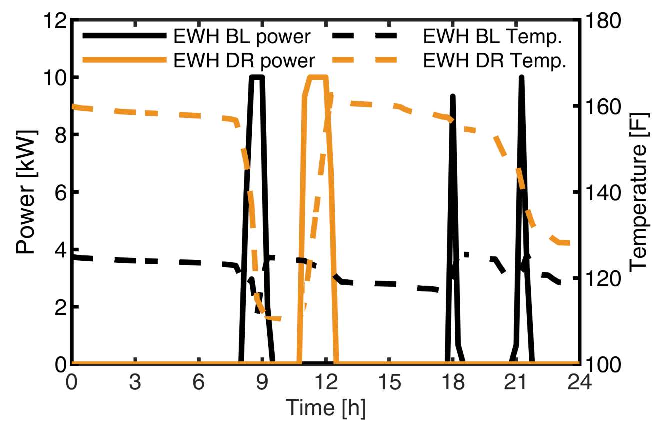

Figure 6. Power draw and water tank temperature for an EWH operating under BL and DR studied schedules. The high water temperature in the tank may be enabled by special mixing valve technologies.

temperature in the water tank was high. The EWH under DR can be programmed at night to boost the tank temperature to the same value as the beginning of the day.

The EPRI SHINES project provides timely data with a resolution of 15 minutes for the power flow at the transformer where four houses were connected. Two of the four houses have their own solar PV installations, HVACs, pool pumps, and other non-DER loads monitored by the SHINES project. The non-DER loads of the monitored houses were added to the total power of the other two houses, and were labeled as “uncontrollable loads” at the distribution level (Fig. 7).

The EWH provided the energy storage capacity for the surplus PV generation as the BESS (Fig. 5). The net flow at the aggregated level was reduced due to the DR control, as shown in Fig. 8. Shifting the EWH load also reduced the peaks in the afternoon and evening.

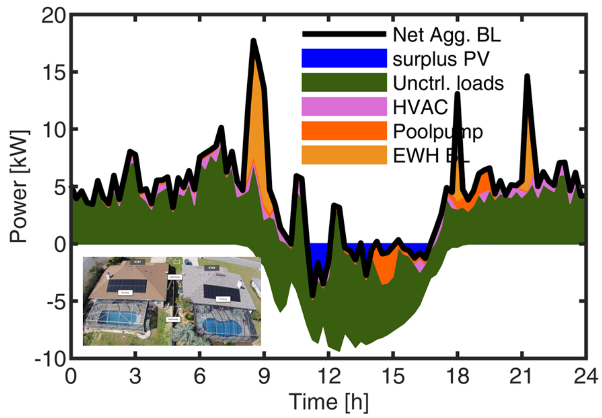

Figure 7. Combined experimental and simulated power flow on an example February day for two smart homes, which are located in Florida and were developed as part of the EPRI SHINES DoE project (photo inset). The EWH simulations were performed with the proposed MIL.

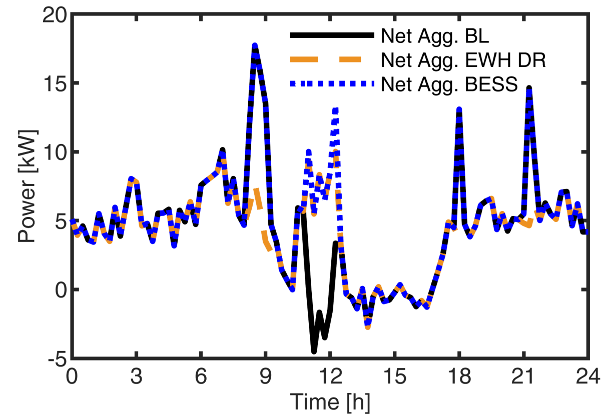

Figure 8. Case studies for the aggregated net power flow at the distribution level. For the proposed control, during the day, a substantial portion of the solar PV generated energy was locally stored in the EWH or BESS.

V. Conclusion

This paper proposes a generalized approach to energy storage that enables all such systems and devices, not only batteries but also electric water heaters (EWHs) and, in principal, heating, ventilation, and air conditioning (HVAC) systems, to be controlled with the same variables, namely "energy capacity" and "energy take". Such controls, which were implemented through the Electric Power Research Institute (EPRI) Distributed Energy Resources (DER) integration testbed comply with the specifications of Energy Star and CTA-2045, which can ensure a platform for industrial and utility adoption. Two case studies were implemented with this generalized approach, both of which yielded satisfactory results, to confirm its validity with EWH models-in-the-loop.

In the first case, the EWH model successfully responded to a "Shed Event" demand response (DR) signal by postponing the heating process while also maintaining occupant comfort. It was found in the second case that the example BESS and EWH are comparable when considering their energy content as generalized energy storage (GES) with occupant safety from high water temperatures guaranteed through a mixing valve solution. This comparability supports the validity of the generalized approach to energy storage at the system level. It should be noted that emphasis was placed on the EWH model in particular, as this contribution helps to fulfill a gap in present literature.

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