An Intelligent Power Electronic System for Secondary Use Batteries

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***Abstract*— This paper presents a plug-and-play power electronic system for integration of multiple energy storage system technologies. The system uses a communication and control architecture with individual developed modules to support scaling to larger systems for the electric grid. An optimization framework is also presented to demonstrate the functionality of the system. This system is shown to work in hardware with a constructed testbed to demonstrate different use cases and systems. Results are presented for a full efficiency cycle test.**

***Index Terms*—energy storage, power electronics**

I. INTRODUCTION

In the coming years, the electric grid is expected to face many challenges. Dynamic system needs due to growing adoption of variable energy resources, resiliency and reliability threats as a result of strong storms from climate change, and electric vehicle charging restrictions from grid infrastructure capacity limits [1]-[2] represent only a few. Low cost and ubiquitous energy storage solutions will be key to overcoming these challenges.

In recent years, lithium-ion technologies have observed significant cost reductions [3] paving the way for electric vehicle and grid integration solutions. The growth in demand for electric vehicles is particularly eye opening with hundreds of thousands of vehicles sold per year [4] and growing. This is tandem with the growing size of electric vehicle battery systems. Electric vehicle manufacturers are continually increasing the size of the battery systems to ensure range anxiety [5] is reduced. Increasing the size of the electric vehicle battery system also proposes to increase the life of the electric vehicle battery system and ensures a potential secondary-use following the electric vehicle life. A back of the envelope calculation of the potential cycling of the battery systems of these vehicles assuming a 13,476 miles/year [6] and a 4mile/kWh driving efficiency is presented in Fig. 1. While actual cycle life of a battery system is determined by many factors including temperature, depth of cycle, and current charge and discharge rates, the presented figures gives an idea of the potential increasing battery life (as related to the number of cycles) following a primary use.

Grid solutions considering energy storage technologies have been adopted and continue to be deployed for many different uses [7]. Yet, recent events have suggested that supply chain issues can become a challenge [8]. Hence, leveraging existing battery systems to their full life is not only acting as a good environmental steward but could be a prudent choice.

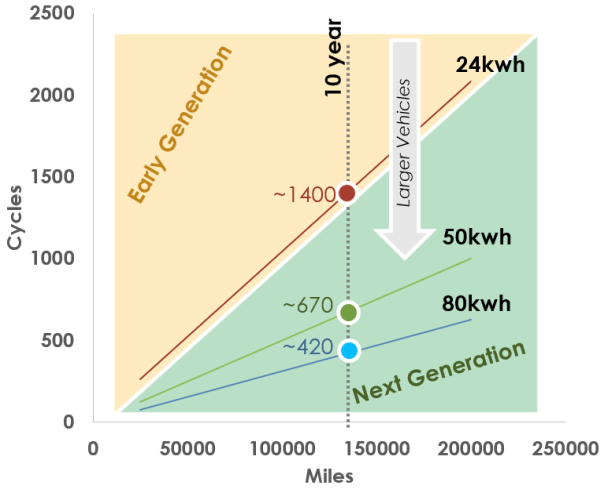

Figure 1: Potential battery cycling versus miles for different battery sizes.

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Still, the complexity of integration of different used battery systems must also be considered. Electric vehicle manufacturers utilize different types of battery technologies (prismatic, cells, pouches), chemistries, and voltages [9]-[10] which create incompatibilities with direct coupling of these systems. Furthermore, used electric vehicle batteries will arrive at second-use manufacturing facilities with different ages [11].

This work looks at adopting second-use systems with different power and voltage ratings into a single dispatchable energy storage (ES) technology. This work proposes a plug and play power electronic (PE) solution that can automatically, safely, integrate multiple battery systems to the grid and control to meet specific dispatch targets. This is key to keeping integration costs and technology costs low. A full hardware implementation is used to present a functional implementation and is presented as a working prototype. This system is novel in that:

- *A plug-and-play system for secondary use batteries considering integration of technologies from different manufacturers is shown,*
- *Subsystem optimization of battery modules to meet a specified power target considering system requests is presented, and*
- *The technology is presented to work in a hardware solution considering three different energy storage systems.*

In the following sections, the topology and system architecture are presented along with optimization and control decision making of the system. This is followed by discussion on the testbed and results of a platform use case.

II. Systems Level Approach

For rapid integration of ES systems (or plug and play capability), there are several key elements needed for integration: 1) flexible ES communication and control interfaces for PE integration, 2) a common communication and control integration layer between all of the systems, 3) safety limits addressed in the various hardware and software layers, and 4) ES stacks that provide the appropriate PE voltage and power (for this work, the scale is approximately 400V at 50kW). These have been incorporated into a proposed design and is discussed in the next sections.

A. System Overall Topology

The proposed multi-secondary energy storage system (MESS) design topology is provided in Fig. 2. This MESS system is composed of DC/DC converter stages (supporting the integration of ES to the shared 1000V DC bus) and a AC/DC converter (or grid tied converter that interconnects the shared DC bus to the 480V three phase AC grid). In the illustrated example only a single AC/DC stage and 3 DC/DC stages have been integrated, but these can be increased based on power and energy system requirements.

Each integrated PE and ES system is treated as an individual system based on an architecture of agents and controllers as described in [12]-[14]. This includes:

- *Battery management system (BMS) - responsible for monitoring the battery cells within the system and developing battery state and health information,*
- *Power electronic controller (PEC) – sends switching control signals to a gate driver based on closed loop control formulations tied to operational modes and setpoints; also provides measurement data*
- *Resource integration controller (RIC) – interconnects the functions of the BMS and PEC into a single system representation and communication interface; uses agent*

Through the RIC, a plug-and-play set of systems that interconnect the ES and PE systems with built-in safety checks and configurability has been developed [13]. Agents, within the RIC, utilize state machines and communication interfaces that tie individually to the different BMS and PEC systems to provide interoperable links to potentially different vendor products. The RIC performs safety checks to confirm compatibility between ES and PE system ratings and configurations before allowing the system to be started. System starting is based on activations of different pre-charge circuits to ensure system component exposure to transients is reduced increasing life and reliability of the system [12].

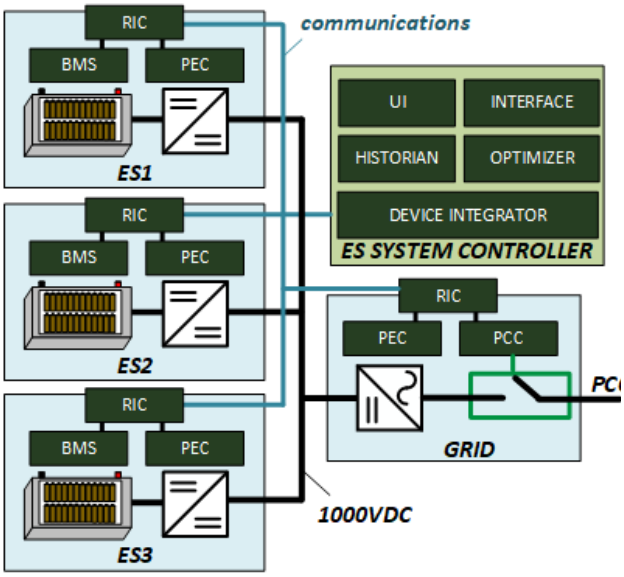

Figure 2: Energy storage system concept for integration of multiple energy storage technologies.

The control modes and setpoints for each converter within the system are determined and dispatched by the ES system controller (ESSC). A plug and play communication system using a Message Queueing Telemetry Transport (MQTT) protocol has been used to allow ES and GRID systems to register and provide configuration information such as ratings, control modes, bus interconnections, and resource information [12]. This is used in optimization formulations to dispatch the system for meeting respective targets. Control modes and converter topology for the PE converters are presented in previous work [15] and are not discussed in this paper. Within the ESSC a user interface (UI) and historian (using SQLite)

have also been adopted to provide ease of use and automatic data collection. The next section presents the optimization formulation applied within the ESSC.

B. System Control and Optimization

To meet ES developed use cases [1]-[2], the overall ES system is expected to be dispatchable (or control requests are converted into real and reactive power grid injections.) For the MESS, this requires coordination between the energy storage sub-systems (or ES1, ES2, and ES3 as shown) and their respective injections into the DC bus. Hence, an optimization framework has been developed and is used to individually dispatch the ES units.

The ESSC aggregates the available resource information into a single optimization formulation. This optimization formulation is developed considering multi-objective linear programming approaches with time intervals at 5 minutes. The primary objective function has been formulated to meet a dispatchability target and to ensure that the state of charge of the systems are not exceeded or (1):

$$min\ (\sum W_{ES}{}^{x} E_{AUX}{}^{t} + W_{PCC}{}^{x} U_{AUX}{}^{t}) \quad (1)$$

In (1), $E_{AUX}{}^{t}$ is an auxiliary variable associated with the energy capacity of the system and $U_{AUX}{}^{t}$ is the auxiliary variable associated with the operational dispatch target. The operational dispatch target is steered by considering the difference between the target power and the charge and discharge at the point of common coupling (PCC) or (2)-(4):

$$U_{AUX}{}^{t} \geq P_{T}{}^{t} - P_{CCC}{}^{t} + P_{CCD}{}^{t} \quad (2)$$
$$U_{AUX}{}^{t} \geq - P_{T}{}^{t} + P_{CCC}{}^{t} - P_{CCD}{}^{t} \quad (3)$$
$$U_{AUX}{}^{t} \geq 0 \quad (4)$$

In (2)-(4), $P_{T}{}^{t}$ is the target dispatch power (positive signifying and the system is discharging as a whole) and $P_{CCC}{}^{t}$ and $P_{CCD}{}^{t}$ represent the charge and discharge power to the PCC. The limits imposed on charging and discharging of the energy storage systems are captured by (5)-(7):

$$E_{AUX}{}^{t} \geq E_{ES}{}^{t} - E_{MAX}{}^{t} \quad (5)$$
$$E_{AUX}{}^{t} \geq E_{MIN}{}^{t} - E_{ES}{}^{t} \quad (6)$$
$$E_{AUX}{}^{t} \geq 0 \quad (7)$$

In (5)-(7), $E_{ES}{}^{t}$ is the measured energy capacity (as related by state of charge (SOC) and conversion to available energy) reported by the individual energy storage systems. $E_{MAX}{}^{t}$ and $E_{MIN}{}^{t}$ represent the maximum and minimum energy associated with the SOC operational boundaries. The associated power that the converters and ES can contribute to the DC bus are captured by (8)-(13):

$$P_{ESC}{}^{t} \leq b_{ESC}{}^{t} P_{MAXC}{}^{t} \quad (8)$$
$$P_{ESC}{}^{t} \geq 0 \quad (9)$$
$$P_{ESD}{}^{t} \leq b_{ESD}{}^{t} P_{MAXD}{}^{t} \quad (10)$$
$$P_{ESD}{}^{t} \geq 0 \quad (11)$$
$$1 \geq b_{ESC}{}^{t} + b_{ESD}{}^{t} \quad (12)$$

In (8)-(12), $P_{ESC}{}^{t}$ and $P_{ESD}{}^{t}$ represent the power charged and discharged to the individual ES systems, $P_{MAXC}{}^{t}$ and $P_{MAXD}{}^{t}$ the maximum charge and discharge limits, and $b_{ESC}{}^{t}$ and $b_{ESD}{}^{t}$ the charge and discharge binaries.

To capture the impact of charging and discharging as this relates to the energy within the system, (13) has been applied:

$$E_{ES}{}^{t} = E_{ES}{}^{t-1} + (\eta\ P_{ESC}{}^{t} - P_{ESD}{}^{t} / \eta)\Delta t \quad (13)$$

In (13), η represents the efficiency of the converter and storage as related to the converter and ES roundtrip and Δt the associated time step value for the optimization.

The grid converter charging and discharging is related to the input and output of the inverter which are separately designated to ensure converter inefficiencies or (14)-(22):

$$P_{GCIN}{}^{t} \leq b_{GCIN}{}^{t} P_{MAXC}{}^{t} \quad (14)$$
$$P_{GCIN}{}^{t} \geq 0 \quad (15)$$
$$\eta\ P_{GDOUT}{}^{t} == P_{GCIN}{}^{t} \quad (16)$$
$$P_{GDIN}{}^{t} \leq b_{GDIN}{}^{t} P_{MAXD}{}^{t} \quad (17)$$
$$P_{GIND}{}^{t} \geq 0 \quad (18)$$
$$P_{GDIN}{}^{t} == \eta\ P_{GCOUT}{}^{t} \quad (19)$$
$$1 \geq b_{GDIN}{}^{t} + b_{GCIN}{}^{t} \quad (20)$$
$$b_{GCIN}{}^{t} = b_{GDOUT}{}^{t} \quad (21)$$
$$b_{GCOUT}{}^{t} = b_{GDIN}{}^{t} \quad (22)$$

In (14)-(22), $P_{GCIN}{}^{t}$ *and* $P_{GIND}{}^{t}$ represent the input side of the inverter (or DC side) charge and discharge, $P_{GCOUT}{}^{t}$ and $P_{GDOUT}{}^{t}$ represent the output side of the inverter (or AC side) charge and discharge, $b_{GCIN}{}^{t}$ *and* $b_{GDIN}{}^{t}$ the binaries for input side charge and discharge, and $b_{GCOUT}{}^{t}$ and $b_{GDOUT}{}^{t}$ the binaries for output side charge and discharge.

The net bus power for the system is calculated as injections or in respect to the contributions from the various systems. The AC and DC buses are represented separately as (23) and (24) respectively:

$$0 = (P_{CCD}{}^{t} - P_{CCC}{}^{t}) + \sum (P_{GDOUT}{}^{t} - P_{GCOUT}{}^{t}) \quad (23)$$
$$0 = \sum (P_{ESD}{}^{t} - P_{ESC}{}^{t}) + \sum (P_{GDIN}{}^{t} - P_{GCIN}{}^{t}) \quad (24)$$

The injection to the PCC also has limits imposed which are captured with (25)-(29):

$$P_{CCC}{}^{t} \leq b_{CCC}{}^{t} P_{MAXC}{}^{t} \quad (25)$$
$$P_{CCC}{}^{t} \geq 0 \quad (26)$$
$$P_{CCD}{}^{t} \leq b_{CCD}{}^{t} P_{MAXD}{}^{t} \quad (27)$$
$$P_{CCD}{}^{t} \geq 0 \quad (28)$$
$$1 \geq b_{CCD}{}^{t} + b_{CCC}{}^{t} \quad (29)$$

In (25)-(29), $b_{CCC}{}^{t}$ *and* $b_{CCD}{}^{t}$ are the binaries associated with charging and discharging to the PCC.

The ESSC uses the optimized power flow to establish control modes, ensuring at least one mode is performing balancing type controls for stability (based on mode options available and provided by the device). In this work, the inverter has been programmed to offer DC regulation controls. Startup and shutdown optimization procedure have also been integrated and are discussed in [16]. The startup-shutdown

optimization performs the initial validation checks to ensure appropriate modes are available for the system to operate stably. The system hardware is discussed in the next section.

C. Hardware

Photographs of the different converters applied to construct a prototype are presented in Fig. 3. The AC/DC converters are constructed as three-legged traditional bi-directional inverters with filtering, contactors, and precharge circuitry. These converters have been programmed to support grid-following controls for the AC side and DC voltage regulation controls for the DC side. The DC/DC converters have been constructed as traditional bi-directional buck-boost converters with filtering, contactor, and precharge circuitry. These are programmed to support constant power delivery to the DC bus. In the next section, the experimental setup for the system is presented.

(a) (b)

Figure 3: Photographs of the converter systems: a) three phase inverter and b) dc-dc converter

III. Experiment Setup

For evaluation of the prototype, a testbed has been constructed to support testing of the MESS as shown in Fig. 4. For this work, the energy storage battery technology (or secondary use batteries) has been replaced with NHR electronic emulators (9300 series). Additional electrical isolation has been added between the emulators and building supply to reduce the potential for circulating currents between the grid emulators. A BMS emulator, or Raspberry Pi 4Bs that contains state machines and estimates battery parameters based on models, is used to provide data to the RIC and ESSC for optimization. The grid connection has also been replaced with a electronic emulator to isolate the electric grid and vice versa from any impacts of power quality issues. A Yokogawa WT5000 power analyzer is connected to the converters for measurement validation. This setup provides flexibility to run use cases and scenarios while evaluating control combinations and overall system response to events. Demonstration of the platform operating with a energy storage system for a residential single-phase AC design has been demonstrated in [14]. A snapshot of testbed and hardware prototype within the Grid Research Integration and Deployment Center (GRIDC) is presented in Fig. 5 [17].

The RIC controllers applied are Raspberry Pi 4Bs and PECs are inhouse developed digital signal processors (DSPs). A Dell Optiplex is used for running the ESSC and optimization. The developed code hosted within the ESSC utilizes open-source platforms for optimization including the linear programming interface PuLP [18] and solver COIN [19]. In the next section, the results of a full operational cycle of the system are presented.

IV. Results

For evaluation of the optimization and controls framework, a efficiency cycle test as defined in [20] has been performed. As proof of principle, the battery systems have been modeled as 2.5kWh so that the full test could be completed in a single hour to demonstrate the hardware is working. This test consists of starting the MESS at a 50% SOC, charging to a SOC of 90%, pausing for 30s, discharging to 20% state of charge, pausing for 30s, and charging again to 90% state of charge.

The measured power results for the DC/DC converters and AC/DC converter have been collected and are presented in Fig. 6. As shown measured power results for a system charge, discharge, and charge are shown with pause times included for balancing per the standard test. The optimization has been programmed to target a specified power for the system, which requires coordination of the dispatch of the various DC/DC conversion systems to meet that target while considering the capacity of the battery system. As shown, the optimization is

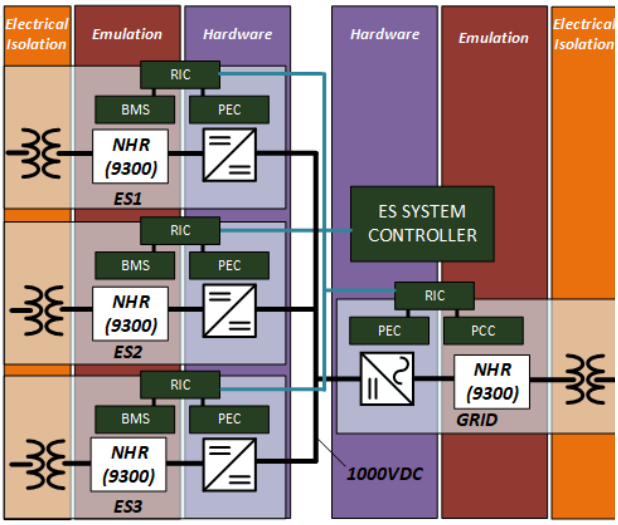

Figure 4: Schematic of hardware testbed.

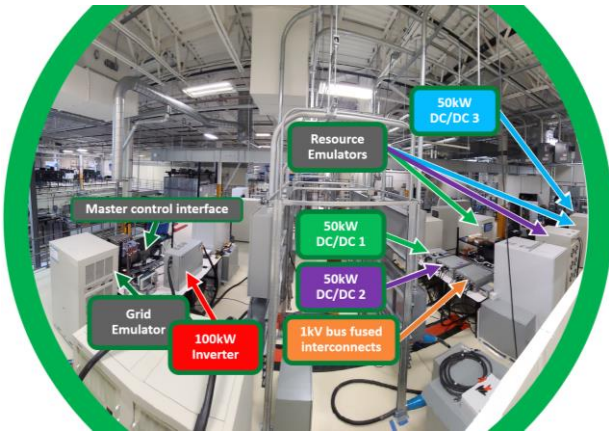

Figure 5: Testbed depictions with different DC/DC converters, inverters, emulators.

able to maintain constant power output by the inverter during the operational periods. Each DC/DC converter is dispatched independently based on the optimization and the sum meets the target. Fig. 7 presents the recorded SOCs for the separate

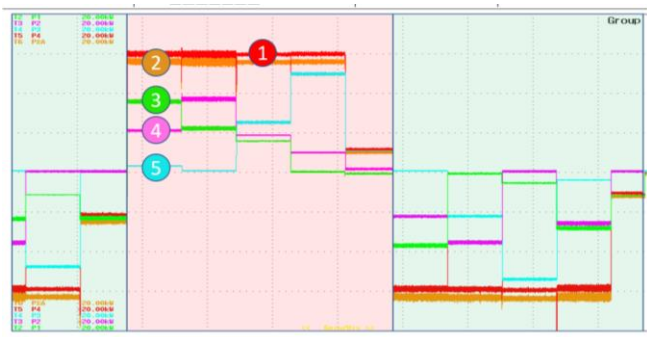

Figure 7: Measured power: 1) Inverter AC side power (red), 2) inverter DC side power (orange), 3) ES1 power (green), 4) ES2 power power (purple), and 5) ES3 power (blue)

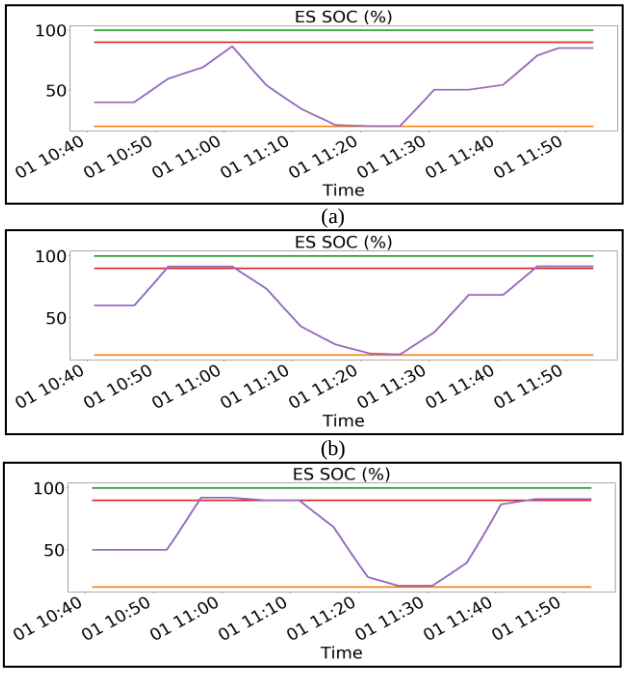

Figure 6: Corresponding SOC values associated with collected data from the central controller: a) ES 1, b) ES 2, and c) ES 3; reported SOC (purple) SOC max operational limit (red), and SOC min operational limit (orange)

systems as captured by the ESSC historian and used to perform the optimization. Each system is controlled within the respected operational SOC window.

V. Conclusion and Future Work

This paper presents a multi-secondary energy storage system power electronic integration technology that can couple battery systems for the purpose of constructing a utility scale energy storage system. This system employs a communication, control, and optimization framework that allows the system to be dispatched optimally considering individual battery state of charges and a system dispatch target. Early results of testing on a hardware system are presented for a energy efficiency test. Future work will look at additional use cases and control sequences as applied to further validate the system prototype.

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