A Secondary Use – Plug-and-Play Energy Storage System Composed of Multiple Energy Storage Technologies

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***Abstract*— Low-cost, grid-connectable energy storage technologies represent a significant challenge for the electric grid of the future. Energy storage technologies are in rapid development with targets to reduce the storage medium cost. However, a significant cost to deployment also comes in the integration. This paper presents the development of a plug-and-play system for supporting secondary use multiple battery systems into a single grid connectable unit. Results of the system design are demonstrated in a controller hardware in the loop (CHIL) platform. Simulations of two energy storage systems operating in parallel and dispatched optimally are presented.**

Keywords—plug and play, power electronic systems, peer-to-peer

I. Introduction

Energy storage technologies have been increasingly recognized as a critical electric grid asset. Today, energy storage systems are often examined for applications to improve resiliency and reliability through voltage management and islanding, improving generation emissions through continued renewable integration, and cost reduction by mitigating electric grid expansion [1]. As energy storage systems continue to be adopted, use cases continue to grow. A recent Department of Energy roadmap effort for energy storage use cases suggests the need to examine energy storage technologies to support energy resiliency for remote communities, grid impact mitigation due to electric vehicle extreme fast charging, and support of critical infrastructure [2].

In transportation, energy storage systems also perform a critical role in electric vehicle and hybrid electric vehicle adoption [3]. Electric vehicles and hybrid vehicles not only curb the consumption of fossil fuels, but also support a reduction in emissions [4]. However, as these vehicles age and are retired, the current energy storage technology, lithium-ion batteries, must be either recycled, repurposed, or reevaluated for reuse to ensure these systems do not harmfully impact the environment [5]. Reuse of these batteries to support electric grid applications has been coined “secondary use” and has a unique set of design considerations [6]. One challenge to integrating secondary-use battery systems into the electric grid comes in supporting batteries of multiple chemistries (various forms of lithium-ion and nickel metal hydride) and ages. This creates requirements on hardware that should be capable of various input voltage and power ratings [7]. Hence, adoption of secondary-use energy storage systems without spurring significant engineering cost will require development of rapid integration approaches to the electric grid.

An agent-based approach for rapid integration of energy storage systems has been presented in previous work for a single battery chemistry and power electronic integration [8]. This was further expanded into full residential use case demonstrations in [9] and adopted into other system integration efforts [10]-[12]. In this work, a distributed architecture to support multiple plug-and-play agent systems as energy storage blocks for the integration of different battery chemistries and ages is presented. The presented architecture supports rapid integration of secondary use battery systems into a grid connectable system.

II. Architecture

A. System Topology

The development of system level integration to support plug and play systems requires multiple levels of hardware and software integration. In the presented design concept, AC/DC and DC/DC converters are utilized to link the various battery technologies into a single system for grid integration. This is presented in Fig. 1. The DC/DC conversion stages provide flexibility in adopting different energy storage systems with various system voltages into a single DC link (nominal voltage of 1000Vdc). The AC/DC conversion stages provide redundant interconnection to a grid interconnection (3-phase, 480V) which can be integrated with other resources or be used as a stand-alone system with a transformer. For this design to function, dispatch of the separate converter systems must be coordinated through setpoints and control modes to ensure optimal and stable system operation. In this work, a framework of agents is used.

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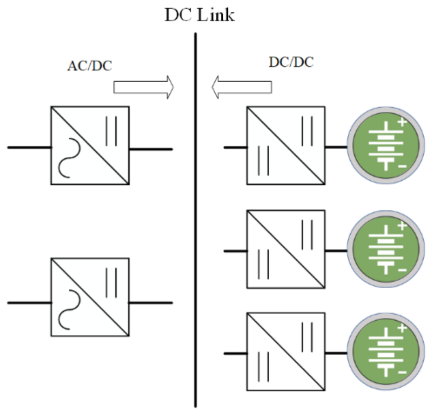

Fig. 1. Plug-and-play concept of energy storage system integration

B. *Distributed Controllers of Agent System*

For each conversion stage, a plug-and-play solution has been adopted to integrate a digital signal processing (DSP) controller and power electronic converter to a central system, independent of the type of converter design [12]. This framework utilizes a Raspberry Pi as a computer node that supports an agent-based system and a DSP for direct closed loop control of the power electronic converter as shown in Fig. 2. A standardized implementation of a User Datagram Protocol (UDP) has been developed for communication between the DSP and computational node (CN) and supports automatic integration and system configuration. The communicated data includes specification, available control modes, and converter ratings to name a few [12]. Hence, independent of the converter and integrated DSP, the agent system can adopt the technology without any initial setup.

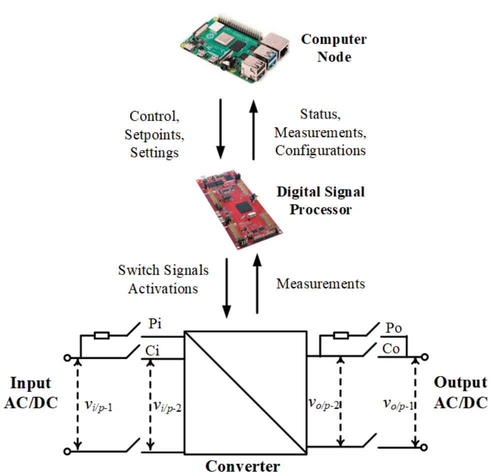

Fig. 2. Data flow between DSP and computational node [12]

The employed agent system presented in [11] is contained with the computer node as presented in Fig. 3. The agents use a locally hosted broker (message bus) to support a Message Queueing Telemetry Transport (MQTT) for agent communication within a single computational node. The Source/Load agent communicates and interacts with the source or load interconnected to the converter (in this case a battery management system), obtaining source/load specifications. The Converter agent communicates to the DSP through UDP sending control commands and receiving converter data. The Intelligence agent acts as the local orchestrator of commands to the converter and source/load. The Intelligence agent also confirms that the converter and source/load are compatible assets by comparing device ratings and configurations. The Interface agent is used to link the CN to a central controller. The central controller hosts another MQTT broker for CN to central controller communication and plug-and-play adoption as shown in Fig. 4. Through approaches such as self-discovery [13], each converter system can register and configure with the central controller without any need for pre-configuration. The auto-configure capability and modularity of the agent system enable the plug-and-play integration of different secondary use battery systems into a single energy grid-connectable energy storage system.

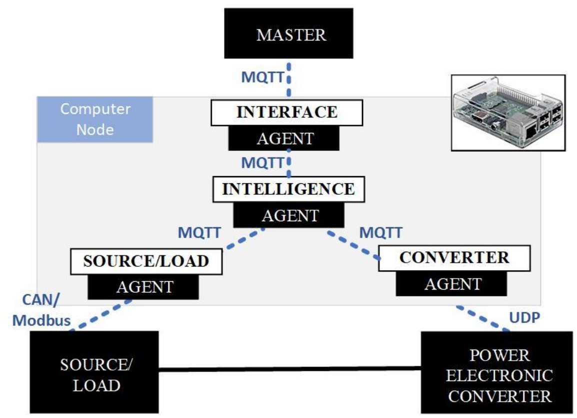

Fig. 3. Configuration of general converter [11].

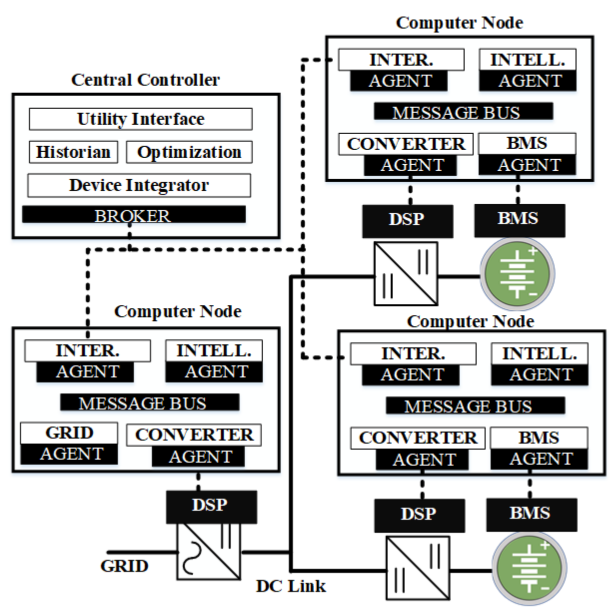

Fig. 4. System agent architecture to support integration of multiple energy storage systems.

C. Central Controller

The central controller hosts several services to support grid-connectable energy storage system integration: automatic system integration, optimization of available resources while considering stability, data collection and record keeping, and communication with an outside entity such as a utility. The system controller can automatically recognize local connections of DC/DC converter energy storage systems and DC/AC grid connected converters to a common DC bus via the MQTT communication framework. A user activation is required for the full commissioning process of the system.

D. Real Time Data Visualization and Operation of Each Converter System

Each converter system contains fault and error system detection and diagnostics to ensure that the system can commission and operate safely. Converters respond to electrical faults or errors automatically and independently of the central controller. These conditions are shared with the central controller upon occurrence to support continued optimization and operation of the unit. The error and fault codes are visually observable in the historical data and in real-time through the central controller via a hypertext markup language (HTML) graphical user interface (GUI) hosted within each raspberry pi. This GUI is limited to the local communication network internal to the energy storage system. Only a single connected communication port is available to the outside (Utility Interface) through the master controller to limit potential cyber security vulnerabilities.

The strategy for commissioning the multiple converter system is to evaluate the available control modes for each converter system (confirm which assets can support DC stability) and ensure that the assumed generation resource (energy storage or grid) is larger than the load resource. Maintaining DC bus voltage capacity requires sufficient generation compared to load among other requirements. Each converter system is commissioned and started individually within the network in an optimized sequence through the central controller. For continuous operation, an optimization routine is called periodically (every 5 minutes). Details on the optimization are not discussed in this paper but will be presented in future work.

For resilient operation, the distributed control approach supports *limp home* features by allowing the agent system to shut-down a failed single system (unless a fault significantly impacts the DC link voltage). As a result, the central controller can continue to operate the system at a potentially reduced rating by removing the failed system from the optimization problem.

III. Controller Hardware-in-the-Loop Simulation

To demonstrate that the architecture supports full functionality as described, the system was modelled, deployed, and validated in a controller hardware-in-the-loop (CHIL) system. The descriptions of the model and discussion on interactions between the hardware and model are described in the following sections.

A. Simulation within Typhoon

The overall system block schematic of the converter system modeled is shown in Fig. 5. Two DC/DC converter stages and energy storage systems and a DC/AC converter were captured within the simulation platform Typhoon HIL. Detailed schematics of the converters as modeled are presented in Figs. 6 & 7. The modelled systems included filtering components, precharge and contactor circuitry, and system measurements as shown.

To provide closed loop control capabilities, the analog measurements from the circuit model are scaled to the voltage range limited by the external analog I/O ports on the Typhoon system. These ports are interconnected to analog I/O ports on the DSP and scaled to represent the measurements of the system. The nominal parameters for voltage, frequency, and power at each node of the overall system are tabulated in Table I. Digital I/O ports on the Typhoon are used to distribute power electronic module pulse width modulation (PWM) and contactor control signals to the modeled components. These signals are generated by the DSP digital I/O ports for converter control.

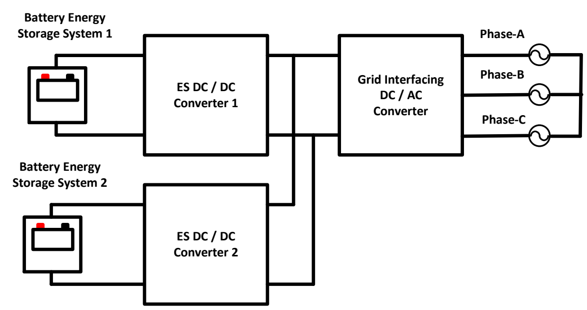

Fig. 5. Simplified Block Schematic of Grid Integrated 100 kW Energy Storage System modelled in CHIL

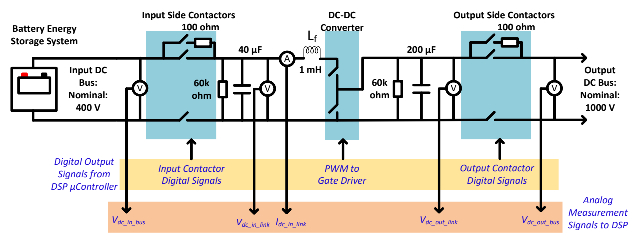

Fig. 6. Simplified circuit schematic of 50 kW Energy Storage DC-DC Converter for Battery Energy Storage (BES) 1 / 2

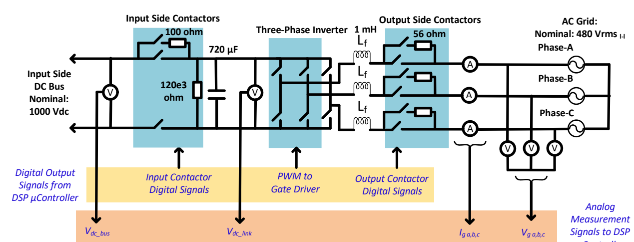

Fig. 7. Simplified circuit schematic of 100 kW Grid Interfacing DC-AC Converter

TABLE I. ELECRICAL NETWORK CIRCUIT NOMINAL PARAMETERS

	Electrical Parameters		
	Description	***Value***	***Unit***
Grid	Grid Voltage (Low Voltage-AC) RMS, $V_{ll(rms)}$	480	V
	Line Frequency, f	60	Hz
	Rated Power, P_{griddc}	100	kW
BES-1/2 (DER)	Rated Discharging Power, P_{battdc}	50	kW
	Nominal Battery Voltage (DC), V_{batt}	400	V
	Energy Storage Capacity	50	kWh
DC Bus Voltage	Nominal DC Voltage, V_{dc}	1000	V

B. Hardware Integrated Systems

Texas Instruments (TI) digital signal processors (DSPs) are utilized to perform the closed loop controls of the converters modelled within the HIL simulation environment. UDP was supported by ethernet communications between the CN (in this case a Raspberry Pi 3.0 B+ single board computer) and DSP. SPI (Serial Peripheral Interface) to ethernet adapters were used to link the serial interface to the CN ethernet port.

MQTT communication exchanges occur through a separate (isolated) communication network and network switch between the CNs and central controller (Notebook Computer). USB to ethernet adapters were used to on the CN to provide additional ethernet communication links.

The central controller performs the system optimization, coordinated dispatch, and data collection via onboard data historian. All the developed code and utilization of optimization is based on open-source references. The data historian is based on a Structured Query Language (SQL-Lite) open source interface and optimizer Pulp and COIN-OR [14]-[15].

C. System Opertions in CHIL environment

The DSP, CN, and central controller represent the main hardware components of the CHIL system. All electrical components within the energy storage system are represented by models within the Typhoon system.

There are several system wide states that represent the system including commissioning, startup, shutdown, error, fault, and normal operations. For commissioning, the central controller awaits individual sub-system (grid-connected inverter and energy storage system) commissioning and registration [12]. The registration is fully implemented outside of the simulation environment within the communication networks: 1) DSP communicates to the CN information regarding the system configuration, 2) agent system as part of a system commissioning process constructs single system representation by evaluating integrated resource and converter configuration, 3) agent system registers with central controller.

Once the individual sub-systems have registered and have been accepted by the user, the central controller provides a startup option to the user. The startup sequence utilizes both the hardware and simulation environments. Configuration and status data provided by the CNs is used in a startup optimization within the central controller that ensures enough voltage control resource has been started and allocated to the DC bus before activating real power injection resources. Upon solving the optimization problem, the central controller sends control (mode and startup) and setpoint (voltage or kW) commands via the MQTT network to the sub-systems in the sequence determined by the optimization. The interface agents receive these commands and push the control and setpoint requests to the local MQTT communication bus for the agent systems. The intelligence agents receive the startup commands and use these to determine contactor engagement and PWM activation which are communicated to the DSP. The DSP sends signals via the digital I/O to the Typhoon system to engage the contactors and perform the PWM. Verification of contactor closing is done through the voltage measurement within the simulation. Measurement data from the simulation environment is collected by the DSP and reported to the agent system and relayed to the central controller. At this stage, the optimization formulation is updated based on the new data. In the next section, simulation results of the CHIL platform are presented along with final discussions.

IV. RESULTS

To establish and verify the plug-and-play framework and system architecture with communications and distributed control, a system startup and 24-hour economic optimization were performed. The cost information is based on a Georgia power commercial building summertime time-of-use rate [16] as presented in Table II. The control modes programmed within the DSP controllers for the converters is presented in Table III.

TABLE II. GEORGIA POWER COMMERCIAL PRICE INFORMATION [16]

	Time of Use – General Service Demand Schedule	
	Time Window	***Price***
On Peak	2:00 pm - 7:00 pm	$0.1223/kwh
Shoulder	12:00 pm - 2:00 pm, 7:00 pm – 9:00 pm	$0.06251/kwh
Off Peak	Other hours	$0.02354/kwh

TABLE III. DSP PROGRAMED CONTROL MODES ENACTED

	Control Mode Descriptions	
	Description	***Control Mode***
AC/DC DSP	Regulation of DC Bus	Vdcreg
DC/DC DSP	Constant real power injection	P

Sub system startups orchestrated by the central controller are shown in Fig.8, while 1 represents for ‘Standby State’, 2 for ‘Startup State’, and 3 for ‘Normal State’. As shown, the grid-connected inverter is activated first to regulate the DC bus voltage. Energy storage systems are started one by one to complete the full startup sequence.

Results of a 24-hour run are shown in Fig. 9 – Fig. 11. The presented data is based on DSP data collected from the Typhoon system and captured in the central controller historian.

As shown, the energy storage system is initially set to approximately 50% SOC and is discharged to a minimum set threshold of 20% during the on-peak period. The energy storage system is charged starting at 21:00 hours (9:00 pm) during off-peak hours to full SOC limit of 90%. During this entire event, the DC voltage is regulated. As observed in the graphs, small charge and discharge requests are issued to the energy storage systems due to the control accuracy error associated with the DSP measurement error at a zero power request.

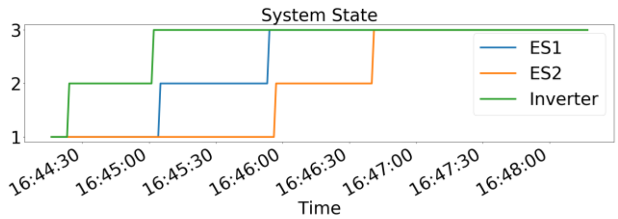

Fig. 8. Sub system Startups

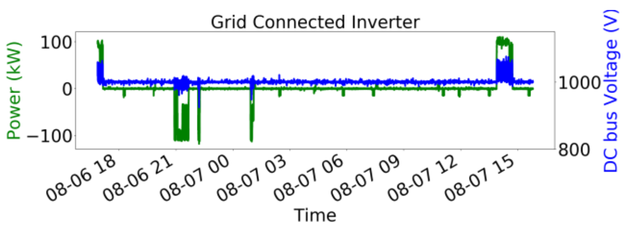

Fig. 9. Grid Connected Inverter Power and DC bus Voltage

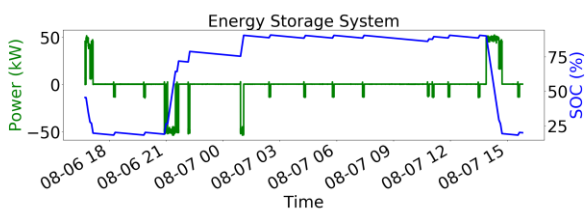

Fig. 10. Unit 1: Energy storage power and state of charge

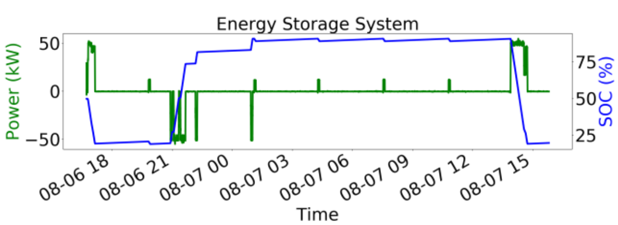

Fig. 11. Unit 2: Energy storage power and state of charge

V. Conclusion and Future Work

A secondary system architecture with the potential to support multiple battery systems of different chemistries and ages has been demonstrated. This system leverages previous agent-based systems concepts to create a distributed architecture to allow for automatic integration of energy storage modules into a single system without the need for significant pre-configuration. The architecture was implemented within Raspberry Pis and digital signal processors linked to a Typhoon CHIL environment. Communications, optimization, and controls were run over a continuous 24-hour window and the results are presented.

Work is in progress to demonstrate the architecture in full hardware. The same DSP and computer node architecture demonstrated will be implemented in the hardware.

VI. Acknowledgements

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