A Multi-Agent System Concept for Rapid Energy Storage Development

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***Abstract*— Many energy storage systems that use technologies such as batteries are composed of power electronics conditioning systems and battery management systems. These are often produced by multiple manufacturers and require hardware and software integration for full grid functionality. This paper proposes an agent-based framework to support the development of an energy storage system with standardized communications. This framework can be utilized with different power conversion systems with an appropriate hardware interface.**

***Index Terms*— energy storage, agents, batteries**

I. INTRODUCTION

Ubiquitous energy storage is rapidly coming to fruition. In small devices such as cell phones, the cost factor and energy utilization have easily achieved a marketable product. This is likewise true with home-automation, where many of the sensor technologies contain small batteries and are becoming more commonplace. For electric grid interconnected energy storage, the value proposition is still in flux.

While many studies have focused on the application of large scale energy storage systems for the utility customers to tackle factors such as demand charge, ancillary services, and deferral of system upgrades [1]-[3], opportunities have been presented at the residential level [4]-[6]. However, the cost of the system in comparison to achievable value is the determining factor. Costs of the energy storage technology such as lithium-ion have begun to significantly decline, leading to a potential revolution of grid connected energy storage systems. Still, other cost factors such as systems integration costs are now observed to play a much larger role [7]-[8]. Hence, to achieve a continued cost reduction in energy storage system technologies, a flexible hardware and software platform that allows for rapid integration of new technologies is needed.

In this paper, the concept of an agent-based energy storage system for rapid integration is discussed. This agent system proposes to tie the energy storage technology and the power conditioning technology into a common framework with communication to the outside. Several agent-based systems have been developed and proposed in the past. For example, in [9] an agent system was demonstrated to control electric vehicles. In [10]-[11], agent systems were created to collect building data and perform control. In [12]-[15], agent-based systems were proposed that performed widescale implementation and control of systems including energy storage and microgrids. Finally, in [16], an agent-based design of a battery management system was developed with individual agents monitoring the cells of a battery and managing the pack. However, the previous research did not focus on the integration of the power electronics and energy storage systems as a system for control. This paper will present an agent-based concept for integrating an energy storage technology and a power conditioning system.

II. BACKGROUND

An energy storage system is often composed of an energy storage element, power conditioning system, and supporting auxiliary systems. Most energy storage technologies utilize a system referred to as a battery management system (BMS) that provides information on the cell voltages and temperatures, and overall system state of charge (SOC) and often supports automatic protection systems for disconnection. The power conditioning system is responsible for converting the direct current (DC) from the energy storage technology to alternating current for grid connection (AC) and has a separate set of protection features and needs. The auxiliary systems provide other features that support both the energy storage technology and power conditioning system.

For an energy storage system to integrate to the grid and provide value, there are several functions and features that are expected including: control synchronization with the grid, safe operation, graceful failure under faults, automatic startup and shutdown, and dispatchability. The design for synchronization with the grid is a required function of control for grid-connected systems and usually is in the form of current control for the power electronic converter (PEC).

Dispatchability can come from various communication pathways including local communications such as Modbus, Message Queuing Telemetry Transport (MQTT), and Data Distribution Services (DDS), or web based internet of things (IoT) JavaScript Object Notation (JSON) to name a few [17].

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All these functions are often integrated through a hierarchy of hardware and software layers to complete an energy storage system. In the following sections, a description of an agent system that integrates this functionality is presented.

III. HARDWARE/SOFTWARE - AGENT FRAMEWORK

The proposed agent-based architecture is composed of multiple layers of communications and controls to support the needed operational considerations. A depiction of one implemented agent integration with hardware is shown in Fig. 1. The agents include a converter interface agent, battery management system (BMS) agent, an intelligence (INTEL) agent, and an interface agent. Detailed descriptions of the agent purposes are presented in TABLE I. The flow of generalized control and data is shown in Fig. 2. This interface agent acts as the receiver of various outside requests that can be delivered through different protocols. The intelligence agent processes the requests and decides on how the system should respond. For example, a request to start-up is broken down to actionable components between the converter interface agent and BMS interface agent that must be tightly coordinated to prevent erroneous faults and damage to the equipment. The converter agent and battery management system interface agents communicate and coordinate with the hardware.

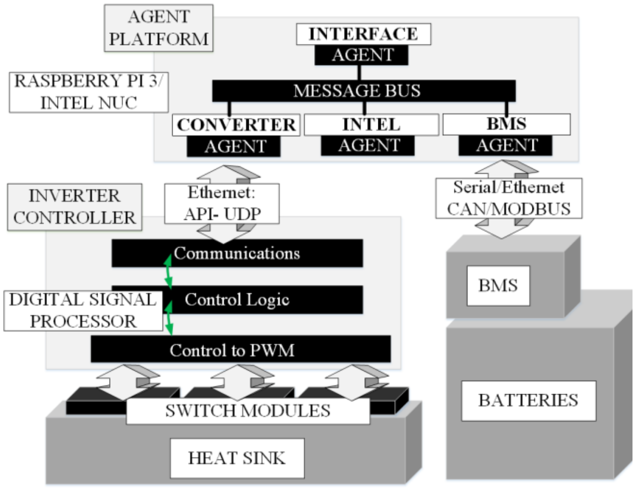


Fig. 1. General agent based system along with integration of hardware and communications architecture.

A. *Power Electronic Converter and Converter Agent*

In this architecture, the PEC digital signal processor (DSP) communicates to the converter agent through an ethernet connection. The presented option is a User Datagram Protocol (UDP) connection with a translation to ZeroMQ for the local message bus. However, for integration of a more standardized communication reference, a PEC with a Modbus communication that is Modular Energy Storage Architecture (MESA) compliant can also be utilized.

The UDP communication developed is simple in nature with 4 basic bytes representing different levels of information. The first byte corresponds to the category of data (system status, measurement data, control requests, and set control reference points). The second corresponds to the option within that category. For example, device ID, operation status, operation mode, control mode, grid connection status, fault status, DC contactor status, and AC contactor status are all with-in the system status category. The third and fourth bytes are used to represent data as in the case of measurement data and reference control points as a two-byte message.

TABLE I.
ENERGY STORAGE AGENTS

Agent	Purpose
Converter Interface	Communicates to the PEC, sends control and receives status and data, and converts the data to a communication base for a local message bus for sharing with other agents.
Battery Management System	Communicates to the battery management system, sends control and receives status and data and converts the data to a communication base for a local message bus for sharing with other agents.
Interface	Communicates to the outside, sends status information and receives control commands and converts data to a local message bus for sharing with other agents.
Intelligence	Converts the control commands from the interface to actionable control commands to the PEC and battery management system. Also responds to single error states and communicates to system-wide shutdown.

In this PEC implementation, significant control functionality has been inserted into the DSP to provide flexibility for the PEC utilization. For example, several different control modes have been adapted and tested including Real and Reactive Power, Voltage-Frequency, Real Power – Voltage, and Reactive Power – Frequency. The PEC also meets IEEE 1547 requirements such as fault ride through as well as resynchronization and islanding for off-grid support. The PEC also has fault detection diagnostics that automatically deactivate the PEC under detected fault conditions. Ramp rates are embedded within the control to ensure stability with reference control point changes. These inherent decisions are required to be very fast and are not orchestrated by the agent infrastructure, but instead agents are informed about key conditions and occurrences once they have occurred. The master intelligence agent suggests control mode changes and target reference point decisions while coordinating with the other agents to ensure system wide performance stability.

Fig. 2. Overall Agent interconnections in terms of data flow.

As an example, the intelligence agent may receive a command from the remote communication system to dispatch 20 kW on-grid. The intelligence agent recognizes that the PEC is only rated for 10 kW and communicates to the converter agent to perform a 10 kW dispatch. At the same time, a fault occurs, and the PEC has an override decision and immediately transitions into an islanded state to support continued operation. The DSP communicates the new state to the converter interface which informs the remote system of the updated system status.

A depiction of the implementation for a residential based system supporting a 240 V single phase connection is shown in Fig. 3. A graphical user interface (GUI) was developed to support visualization of the information communicated by the PEC and control requests coming from the intelligence agent. An Intel NUC was used to host the agent software which is created in Python 2.7 on Ubuntu Linux. However, the system has recently been demonstrated to function under the control of agents operating within a Raspberry Pi B+ 3.0.

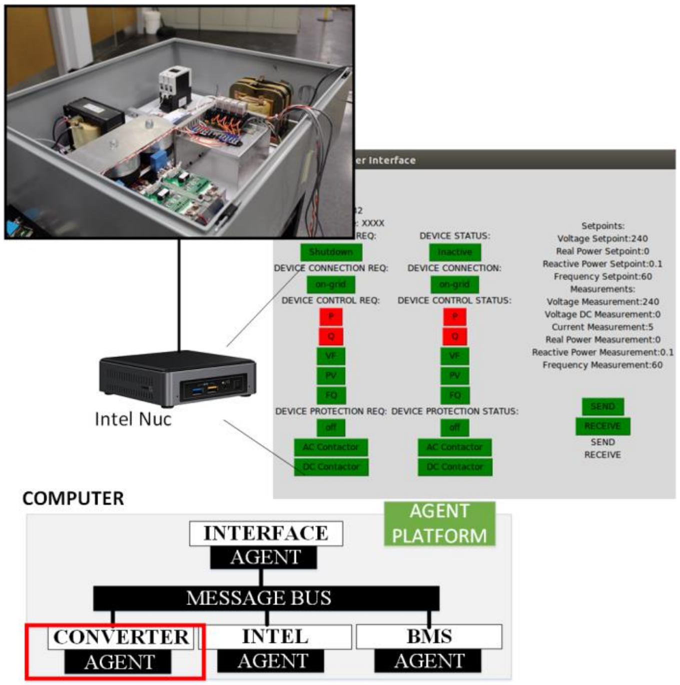

Setpoints:
Voltage Setpoint:240
Real Power Setpoint:0
Reactive Power Setpoint:0.1
Frequency Setpoint:60
Measurements:
Voltage Measurement:240
Voltage DC Measurement:0
Current Measurement:5
Real Power Measurement:0
Reactive Power Measurement:0.1
Frequency Measurement:60

Fig. 3. Converter agent and Converter

The PEC performance under normal operating conditions is shown in Fig. 4. These operating conditions can be achieved when connected to an energy storage system with a nominal DC voltage of 400 Vdc and operating range between 380 Vdc and 445 Vdc.

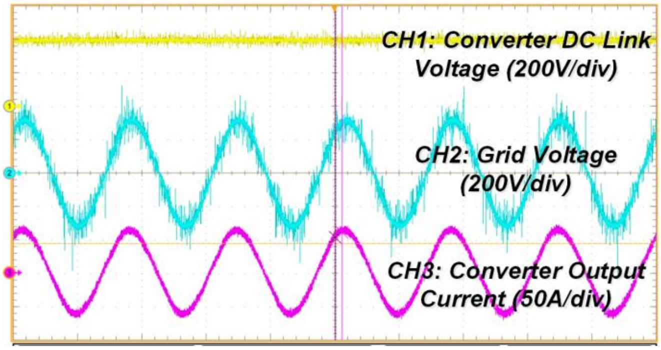


Fig. 4. PEC voltage and current waveforms under normal conditions

B. *Battery Management System and BMS Agent*

In this architecture, the BMS agent communicates to a BMS through a Controller Area Network (CAN) bus commonly utilized by electric vehicle OEMs and commercially available battery management systems. Other products use MESA compliant Modbus over TCP/IP or HTML based JSON communications

The battery system utilized for demonstration purposes was constructed by Spiers New Technologies (SNT) and was composed of secondary use Nissan Leaf Gen 1 batteries into a nominal 400VDC, 16kWh system. The system supports automatic protection mechanisms that isolate in the case of current transients above protection levels, voltage levels unsafe for the battery cells, or sustained current levels above the recommended rating for the battery. The battery management system agent was constructed to support both this system and other commercially available options with the finite state machine shown in Fig. 5. The primary purpose of the state space system is to automatically identify and provide information to the other agents upon issues with the battery system. The state-space system requires a subset of variables such as DC voltage, current, and temperature to manage the transitions between states and make decisions on the present system condition.

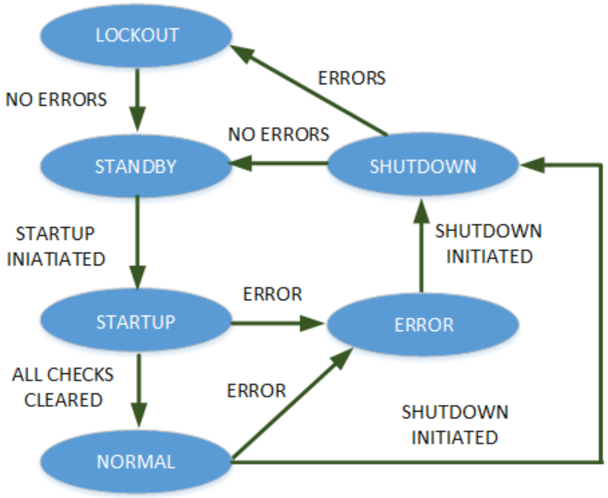
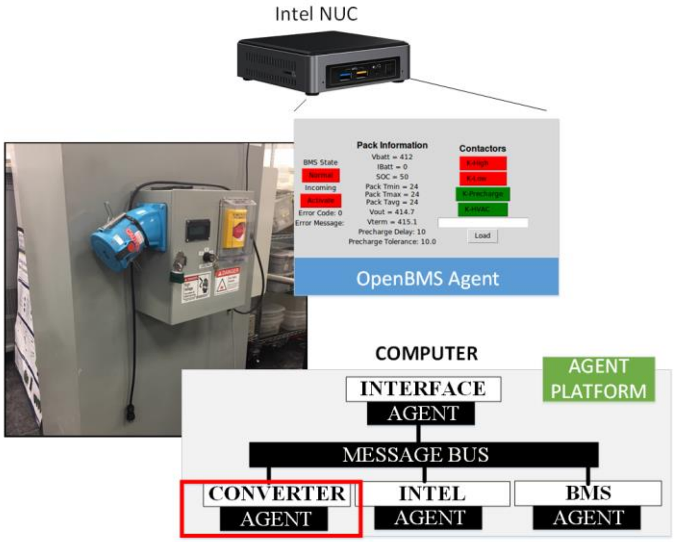


Fig. 5. General state space model BMS agents.

A depiction of the implementation is shown Fig. 6. As the case with the converter agent, a GUI was created to provide basic information to the user during operation.

C. *Interface and Interface Agent*

In the final stage of the architecture, the Interface agent was developed to support IoT functionality. In this case, a Host Server was created that supported a RESTful API and allows for separate optimization and control from another source in the cloud as shown in Fig. 7. The actual implementation utilized multiple computers within a sub-network as shown. For hosting IoT functionality, the control functionality was limited to on-grid only with real-power, control state (startup, shutdown), and reset request allowed. However, all the corresponding system data was reported back to the API for utilization by the Optimizer controller computer. This included states of all the contactors, operational mode, operational state (normal, shutdown, starting up, standby, lockout), any error codes or fault conditions, and measurements.



Vbatt = 412
IBatt = 0
SOC = 50
Pack Tmin = 24
Pack Tmax = 24
Pack Tavg = 24
Vout = 414.7
Vterm = 415.1
Precharge Delay: 10
Precharge Tolerance: 10.0
Error Code: 0
Error Message:

Fig. 6. Battery system and battery management agent.

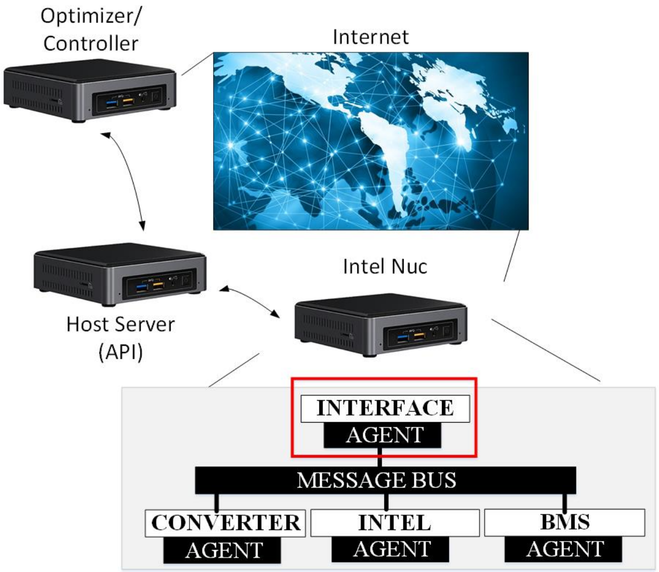


Fig. 7. IoT connection example of Energy Storage Agent.

The optimizer was programmed to automatically initiate the system transition from standby to normal operation and to stop upon error reporting. The energy storage system also reports basic metrics such as energy storage capacity and power rating based on all the subsystems to the API for supporting optimized dispatch decision making. Once normal operation has been achieved with the system and reported through the API, the optimizer sends a control dispatch request based on optimized results determined. The optimizer was programmed to support multiple case scenarios including energy arbitrage (buying energy at low cost and selling energy at high cost periods.) Additionally, a use-case testing application was developed which performs similarly to the optimization application. However instead of running optimized setpoints, the program runs a setpoint script which simulates prolonged system use in different scenarios. An example demonstration of this is presented in the following section.

IV. RESULTS

The system was run for several hours to demonstrate full system functionality and control via automatic dispatch from the remote system. In this case, the system ran a capacity calculation test where the unit is fully discharged, rested, fully charged, rested, and then once again fully discharge. Based on the rate of discharge versus the time-to-empty, the capacity of the battery system can be calculated in kWh. The results are shown in Fig. 9. and Fig. 8

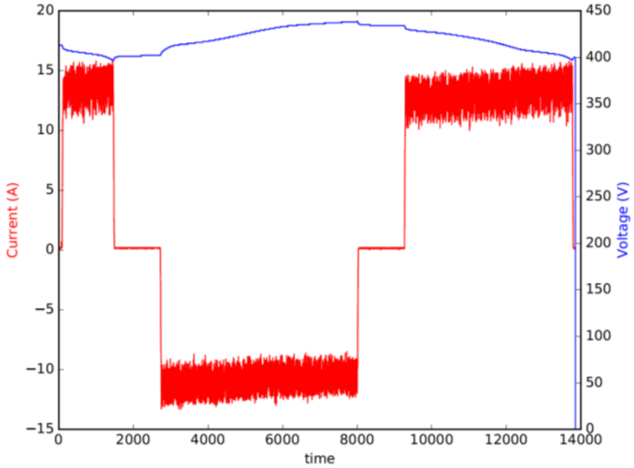


Fig. 8. Voltage and current of the battery system as recorded by the API during a use-case capacity test of the system.

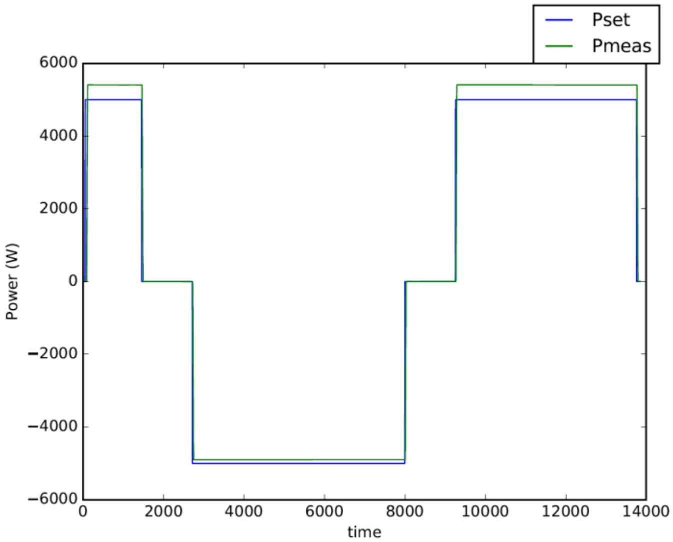


Fig. 9. Power dispatch versus power measured.

These results, recorded by the API server into a SQL database, demonstrate the ability of the system to automatically activate, perform a full charge/discharge cycle, and deactivate using a remote application controlling the battery system. The dispatch signal sent from the use-case application during this measurement is shown in Fig. 9 in blue while the actual system response as measured by the inverter is shown in green. This figure demonstrates the rapid response of the system to setpoint commands as they are sent. Differences in amplitude are mainly due to slight measurement inaccuracy by the system. External sensors connected to the unit confirmed that the setpoint was being reached within +/- 5% of the target.

V. CONCLUSION

This paper describes an agent-based architecture for an energy storage system that could be IoT ready upon hosting the API on a cloud-based system. This paper presents one approach for implementation of the communication interfaces to each of the components that could be very easily modified to host different energy storage and power conditioning system technologies or even host systems. This provides future opportunities to rapidly integrate other energy storage and power conditioning systems and reduce integration time and cost.

Results of the combined power electronic converter and energy storage system output are presented. This demonstrates that the architecture discussed successfully and autonomously operates an energy storage system with actual hardware.

VI. ACKNOWLEDGEMENTS

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