Secondary Use Energy Storage System Design Considerations

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ABSTRACT

Energy storage technologies are expected to revolutionize the electric power grid by reducing energy costs, providing means to integrate renewables, and increasing grid reliability and resiliency. The wide adoption of electric vehicles could help reduce capital investment costs of storage deployment. The electric vehicle market has seen a spur of innovation and growth that has led to a revolution of battery systems, especially lithium-ion. As greater numbers of electric vehicles can be found on the road, the fate of EV batteries after they are no longer useful in vehicles has become an important question. This paper provides a review of secondary use EV battery systems in terms of potential life balance of system costs.

Keywords: repurposed EV batteries, secondary use systems, technoeconomic analysis and benchmarking, electric vehicles, system integration

1 INTRODUCTION

Electric grid demonstration projects of energy storage technologies have already established the ability for energy storage systems to increase grid reliability and resiliency, reduce power system costs, and enable the integration of renewables[1]–[5]. However, energy storage system and integration capital investment costs have largely limited the wide-scale deployment of these technologies to niche cost effective applications.

In the last two decades, the electric vehicle market has seen a spur of innovation and growth that has led to a revolution of battery systems, largely of the lithium-ion variety. Still, these battery systems have an expected life and finding a role for these systems following the electric vehicle application is critical. There are three R's have been derived to support this research: remanufacture, repurpose, and recycle. Remanufacturing the battery systems into new electric vehicle battery systems can be done but usually only applies to lightly aged systems where capacity has seen only minor degradation. Recycling of these battery systems is typically expensive and is usually considered when the battery systems have reached end-of-life or not economically viable for grid applications. For the remaining end-of-life electric vehicle systems, repurposing the battery systems for new applications such as for the electric grid appears to be an opportunity [6]. This concept has been named secondary use energy storage technology.

Repurposing electric vehicle batteries for application to the electric grid offers many design considerations, each with potential system life and cost impacts. The battery system must be integrated with utility grade power electronic conversion systems (PECS). These PECS convert the direct current (DC) from the battery system to the required alternating current (AC) for electric grid interconnection, often require electrical isolation, and must follow a different set of codes and compliances than present with vehicles. Since the battery system is no longer part of the electric vehicle, separate enclosures and thermal management systems must be considered to support long-term stationary type applications. Finally, new software and hardware layers need to be introduced that provide integration the battery system, inverter systems, and with electric utility system communications or internet of things (IoT) frameworks for dispatchability.

In this paper, an examination of the varying design options for secondary use systems will be discussed. An attempt at establishing the needed additional hardware cost with these designs will be made. In this paper, the different susbsystems of a secondary use system which includes the battery management system, battery module stacking, power elecronics hardware interface and the software integration platform will be discussed. Also, examples of prototypes illustrating the designs will be presented.

2 ENERGY STORAGE SYSTEM DESIGN

The fundamental components of a grid connectable battery systems are comprised of combinations of software and hardware. A depiction of the overall system architecture and subssytems of an example energy storage system are presented in Figure 1. These subsystems include, the PECS which comprises of power stage, a digital signal processor (DSP) for controls and an hardware interface that provides protection for the power components. The other susbsystems are the battery modules and battery management system (BMS), and a software interfacing system supporting integration of all the subsystems and provides means for utility level communications. For this type of design, the power stage or inverter block can be a commercially off the

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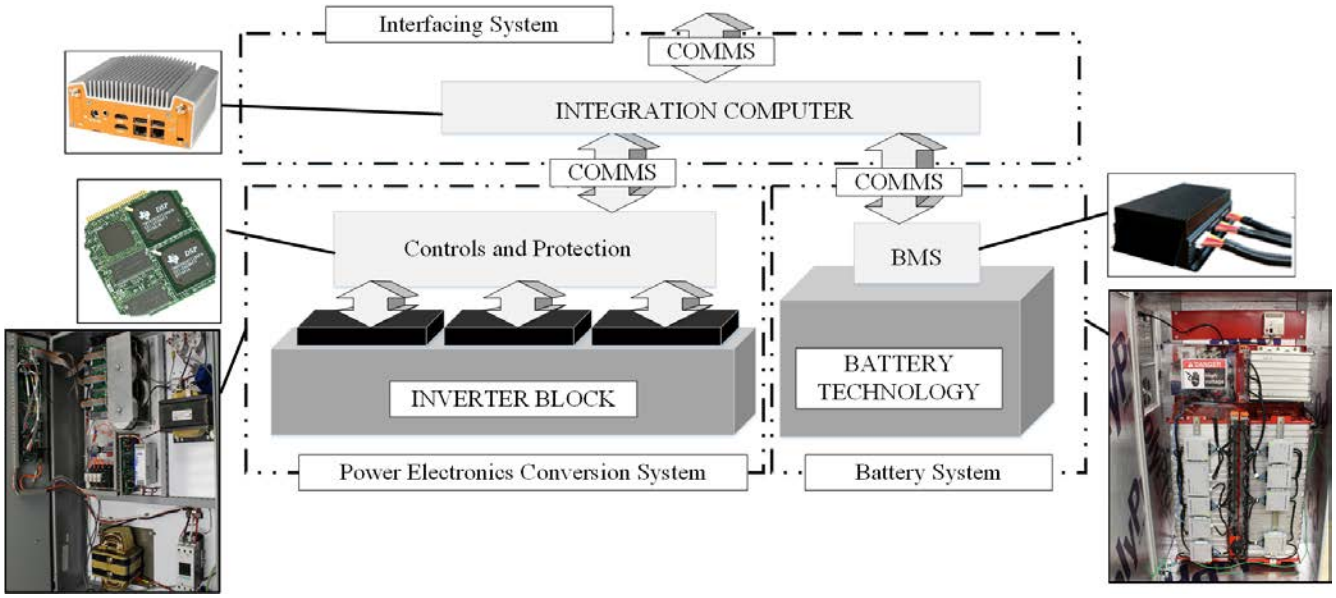

Figure 1. Example of Energy Storage System Construction

shelf (COTS) component and supported by different vendors. A design of this nature provides plug and play like features assuming communication modfications between layers. A controls interface board for different power stages can be used that will work with communication protocols to be integrated into a common software platform. All of these systems provide the energy storage with a hierahical protection architecture that interfaces with all the susbsystems. The protection subsystems are critical safety elements that provide the fast acting hardware based layer under transient conditions during start-up and normal operations.

For secondary use energy storage systems, the battery system (battery modules and BMS) is the key technology integration element that will be unique compared to traditional storage system architectures. The fundamental objective in developing the design must try to minimize the cost versus life feature of the design.

3 SECONDARY USE ENERGY STORAGE CONSIDERATIONS

The repurposing of electric vehicle batteries continues to be researched as cost targets for energy storage continue to drop. There are a number of options on construction of a new system that should be considered and be evaluated in respect to impacts on cost and life. In the following subsections these options are discussed.

3.1 Battery Management System

The battery management system (BMS) is one of the key components for management and control of the battery system. The BMS is not only responsible for balancing of the battery cells within a system, but also often supports many protection mechanisms and safety checks, and data collection and provisioning through various communication means.

There are two guiding options regarding the BMS for a secondary use system: 1) utilize the existing original equipment manufacturer (OEM) BMS or automotive BMS or 2) apply a new BMS from aftermarket vendors or one that is COTS. Each option presents certain benefits and challenges as presented in Table 1.

When utilizing a OEM BMS proprietary datasets and algorithms may need to be protected as trade secrets and require a non-disclosure agreements (NDA). This ultimately may lead to a higher initial cost of development but lower long term costs as a COTS system may not be needed. However, vehicle based BMS system protection mechanisms may not be compatiable for electric grid based systems. Hence additional hardware may still be needed.

	Advantage	Challenge
OEM[1] BMS	Specifically calibrated to the battery technology	Often proprietary datasets and communications
	Usually already available from the EV.	Potentially only available on non-graded systems or new systems
		Safety mechanisms may be vehicle integrated and not grid ready or follow grid standard product codes
COTS[2] BMS	Vendor support for interfacing with open communications protocols.	BMS characteristic data must be entered.
		Adds cost to the system.

[1]OEM – original equipment manufacturer

[2]COTS – commercially off the shelf

Table 1: Options and Considerations for BMS.

3.2 Battery Module Stacking and Grading

During the drive cycle of an electric vehicle, single cells within a battery pack or system are thermally impacted uniquely based on their location and cooling methodologies applied to the vehicle. This often creates non-uniform aging of the cells within the electric vehicle battery pack that lead to a distribution of unique cell capacities and corresponding impedance values within the system.

The impedance value of the cell is a direct function of the health of the cells. An example survey of a manufacturer electric vehicle packs state of health versus resistance is shown in Figure 1. As the battery ages or as the state of health decreases, the battery module resistance increases. Within a electric vehicle pack (where all the battery cells are in series), a higher resistance incurs additional heating compared to neighboring cells leading to faster life degredation.

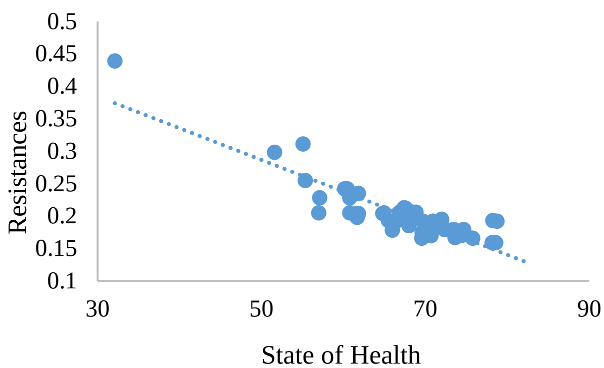

Figure 2. Example State of Health Versus Resistance for Electric Vehicle Packs.

An example experimental analysis of an electric vehicle pack remaining state of health (SOH) and capacity is provided in Figure 1. As shown, the SOH and remaining capacity range from 70% to 61% and 35.7 to 30.

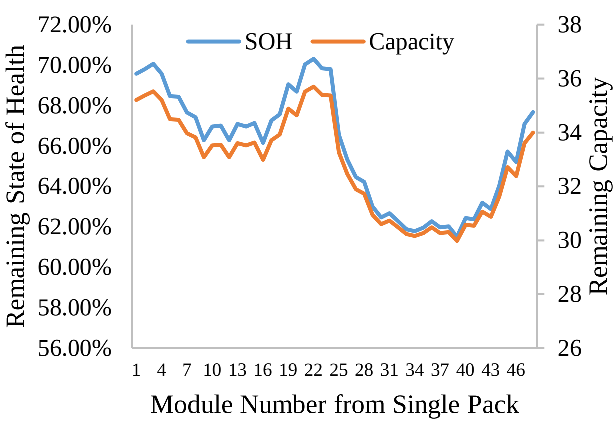

Figure 3. State of Health versus Module in a Single Pack Example.

Since many of battery modules and cells are placed in series, the lowest capacity battery within the system will create a bottleneck and limit the full capacity of the cells within the system. In the above case, this is approximately a 9% immediate loss in capacity of the system.

One method of reducing this impact is to deconstruct a vehicle battery pack and reconstruct with commonly aged cells of similar capacities and impedances. The process for identifying and sorting these batteries is known as 'grading.' Table 2 compares the advantages and disadvantages of the approaches.

In between these two approaches is the pack-level grading approach under development at Southern Research. It overcomes some of the performance limitations under the no-grading scenario and the higher costs associated with the grading approach. The pack-level grading approach involves the development and use of an online battery pack monitor, a pack observer and an algorithm to define pack grading; this setup is shown in Figure 4 below.

	Advantage	Challenge
No Grading	Simple implementation.	Battery available capacity is limited
		Battery system lifetime can be reduced more quickly with further operations.
Pack-Level Grading	Lower repurposing cost	No hardware accessibility to interior of pack
		Requires decryption of BMS data from CAN bus
	Automated pack-level grading to improve battery lifetime above 'no grading' scenario	Battery available capacity is limited (no replacement of aged hardware, software inside pack)
		Requires evelopment of online battery pack monitor and pack-level grading algorithm
Grading	Maximized pack life and capacity	Requires man-hours and resources increasing cost.

Table 2: Options and Considerations for Grading.

Figure 4 demonstrates the necessary observer design fed by data from the EV battery packs through the pack's internal BMS which is pulled by an online battery pack monitor using a CAN bus communication protocol. The data extracted from the pack level battery monitor is then used to design a pack observer which allows for the identification of all relevant pack internal parameters at all times. The application of an online battery pack observer warrants pack internal situational awareness necessary to control and diagnose it in compliance with energy storage safety and performance requirements.

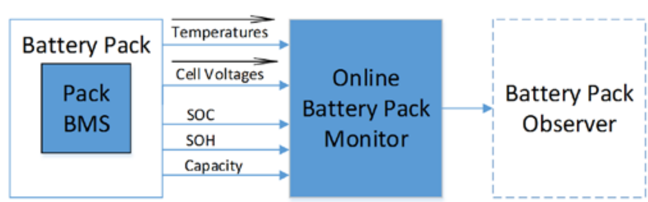

Figure 4. Schematic of system under development at Southern Research for pack-level grading.

3.3 Full System Integration and Management

The last stage of developing a secondary use system is the integration of a power conditioning system and communication interface to a main operating system. One approach is to utilize a centralized system that performs all of the decision making on a single computation node. This could be a single digital signal processor that performs the closed loop control and issues the signals to the gate drivers of the power conditioning system, reads data from the BMS, controls the appropriate safety contactors, and communication interface to the outside for dispatch by a utility. This creates a tightly coupled system that hosts all of the decision making at a single location leading to much simpler overall design. Another approach is to distribute the communication and decision making into separate subsystems as previously described. In this case the PECS could be responsible for controlling a requested power flow and fault isolation while the battery system can protect the battery modules. An overall system can support driving the system to perform in a particular way. The comparison is provided in Table 3.

	Advantage	Challenge
Central-ized	Single host of all the decision making.	Tightly coupled and changes are difficult.
De-central-ized	Provides a quick mechanism to interconnect different vendor products	More sophisticated.
		Can lead to higher initial development time.

Table 3: Options and Considerations for BMS

4 REVIEWS OF EXAMPLE PROTOTYPES

There are several deployment projects underway for evaluating and deploying secondary use energy storage systems. In this section, a discussion on several example prototypes and methods utilized are discussed.

An 25kW, 50kWh initial prototype was developed in partnership with General Motors and ABB utilizing Chevy Volt systems [6]-[7]. These were near-new battery systems that had not seen significant utilization before conversion to a stationary system. The system utilized the OEM or General Motors developed BMS and was tightly coupled with the ABB system in terms of communications and controls.

A second example is the 10kW, 16kWh system that has been developed utilizing Nissan Leaf batteries in a partnership between Spiers New Techologies and Oak Ridge National Laboratory. In this system, the batteries were collected, graded, and sorted from a number of EVs. The system utilizes an COTS-based BMS that self-protects the system. An agent based architecture was developed [8].

A third example is a prototype currently under test at Southern Research which also utilizes used Nissan Leaf batteries. With this system, Southern Research is developing a methodology and ranking approach that does not involve the disassembly of the battery pack in order to evaluate modules for repurposing individually. The hope is that this technique will prove to lower the cost of the system thereby reducing the economic barriers to system adoption.

5 CONCLUSIONS

This paper discusses the construction of energy storage systems from secondary use electric vehicle batteries in general in terms of architecture and presents the different options and considerations for secondary use systems. Options for consideration include the utilization of existing BMS, the grading of battery modules and compilation into a single system, and the utilization of distributed versus centralized control architectures. Each of these features provides cost differences and expected system life considerations and should be considered as part of the system design.

6 ACKNOWLEDGMENTS

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REFERENCES

[1] R. Byrne, “Energy Storage Overview.”

[2] D. Bender, R. Byrne, and D. Borneo, “ARRA Energy Storage Demonstration Projects: Lessons Learned and Recommendations,” Sandia National Laboratories, Albuquerque, NM, SANDIA REPORT SAND2015-5242, Jun. 2015.

[3] R. H. Bryne, M. K. Donnelly, V. W. Loose, and D. J. Trudnowski, “Methodology to Determine the Technical Performance and Value Proposition for Grid-Scale Energy Storage Systems,” Sandia National Lab, Albuquerque, NM, SANDIA REPORT SAND2012-10639, Sep. 2012.

[4] EPRI, “Functional Requirements for Electric Energy Storage Applications on the Power System Grid,” ELECTRIC POWER RESEARCH INSTITUTE, Palo Alto, CA, Technical Update 1022544, May 2011.

[5] R. Schainker and B. Kaun, “EPRI Energy Storage Testing and Demonstrations: EPRI Renewable Council Meeting,” Knoxville, TN, 05-Apr-2011.

[6] M. Starke *et al.*, “Community Energy Storage with Secondary Use EV / PHEV Batteries,” *TechConnect*, vol. 3, pp. 485–488, 2014.

[7] P. Irminger *et al.*, “Demand charge reduction, power factor control, and other functions using secondary-use batteries,” *Adv. Automot. Battery Technol. Appl. Mark. AABTAM 2015*, pp. 1–11, 2015.

[8] M. Starke *et al.*, “A Multi-Agent System Concept for Rapid Energy Storage Development,” in *2016 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2019*, 2019.