Stationery Energy Storage System Using Repurposed Electric Vehicle Batteries

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As Electric Vehicle (EV) battery systems degrade, a point is reached that the battery is no longer suited to a vehicle application, yet they potentially still have remaining life. Typically after the storage capacity of the battery has degraded to approximately 80% state of charge (SOC) the battery is no longer suitable for electric vehicle use. Such used batteries potentially have a significant number of cycles remaining prior to end of life recycling. A multi-partner project [1A] sponsored by the Clean Energy Fund of Canada (CEF) investigated methodology for extending the useful life and thereby repurposing used electric vehicle battery systems into a utility grade stationery energy storage system. The project has successfully demonstrated a prototype system using custom built bi-directional dc-dc converters. Each dc-to-dc converter is connected to an individual battery system, forming a battery bank module. Multiple battery bank modules are connected in parallel together, forming a battery bank collection bus. This battery bank collection bus is connected to the ac grid using a dc-ac converter system.

Keywords: Repurposed batteries, stationary energy storage

INTRODUCTION

Degraded EV battery systems that are no longer suited to their original vehicle application potentially have many cycles remaining before end of life recycling is required. The development of a program to repurpose the EV battery systems to a new utility grade stationary storage application has challenging requirements: (i) EV battery technology will continue to change and develop as time proceeds; (ii) battery systems that become available either due to the degradation of energy storage capability or removal of the source vehicle from service for other reasons have little or no historical usage information; and (iii) There will be differences between battery vendors, vehicle vendors and from year to year, that impact the battery ratings and specifications for repurposing the batteries including:

- chemistries
- voltage rating
- storage capacities (kWhr)
- cycle life
- depth of discharge capability
- maximum current rating (short and long term)

The CEF project developed and demonstrated a stationery energy system using used electric vehicle [2] battery systems in an "as is" state. Each vehicle battery system consists of the vehicle battery modules and its battery management system (BMS). The project designed and implemented dc-dc converters that served as both isolation and a bi-directional energy flow interface for each battery module. The battery system and its dc-dc converter make up battery bank modules (BBM) and the battery side operating range of each of the individual dc-dc converters is specific to its battery voltage specifications (which can range from 300 Vdc to 700 Vdc). In order to allow the parallel connection and interfacing of many battery bank modules, each dc-dc converter ties to a common collection side dc bus. For the demonstration project a 900 Vdc rating was selected to facilitate the second stage dc-ac conversion to a three-phase 600 Vac. The Canadian standard voltage is 600 Vac while in the USA the secondary voltage is 480 Vac. A 480 Vac voltage would allow the dc bus voltage to be reduced.

The introduction of a dc-dc converter allows each re-proposed battery system to be operated within its required ratings independently of the other parallel BBMs. A Master Controller monitors and determines how each of the BBMs will be dispatched to suite power needs and ensures that they are operating within the battery systems specific ratings and capabilities. A dc-ac converter system connects the BBMs to the ac system. Within the project a scaled diesel generator was included in order to demonstrate the impacts and benefits of energy storage on diesel plant operation. The overall system configuration is shown in Figure 1. System description and preliminary test results are presented.

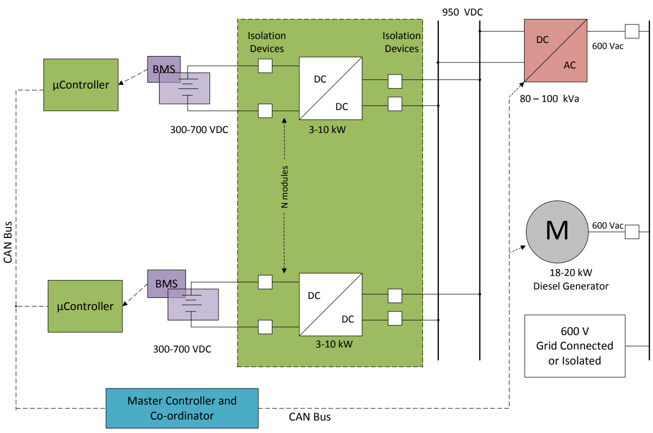

Figure 1 Repurposed Battery System

DESCRIPTION OF THE SYSTEM

The repurposed battery system concept was designed by integrating retired EV batteries (SOC ~ 70 - 80%) in an as-is state, which includes a BMS communication module, which in this case was CAN based. This external CAN bus interface, which transfers operational alarm and status information to the vehicle drive systems, was interfaced directly to the dedicated BBMs dc-dc converter. Typically the BMS transfers data including: battery capacity (state of charge); minimum, maximum and average cell voltages; current values; battery and/or coolant temperatures; alarm and trouble codes; etc. In order to ensure safe and efficient use of the battery system, the dc-dc converter requires basic information regarding the status and health of the battery; as a result the BMS protocol needs to be documented to permit decoding of the required operating parameters. This is required to allow the particular battery system to be used within a re-purposing system. A rack of four repurposed batteries is shown in Figure 2.

Figure 2: Four Battery packs, with BMS interfaces

In the demonstration system, the two stage buck-boost bi-directional dc-dc converter and high speed microcontroller based processing unit shown in Figure 1, were designed to accommodate a wide battery voltage range from 300 Vdc to 700 Vdc, while maintaining a constant dc bus collection voltage of 900 Vdc. The dc-dc converter was designed generically to include: local protection, fusing, isolation relays and voltage/current measurements.

A processing unit receives input the BMS information from the batteries and control orders/setpoints from the Master Controller (CANopen based protocol). The microcontroller controls current, voltage control loops and generates the required switching pulses for the power electronic switches. Isolation relays for start-up, stop and protective shutdown, are provided on both the battery connection and the collection bus connection. Pre-charge resistors are used to limit the converter inrush current during the start-up sequence. Through software configuration the dc-dc converters can be easily adapted to accept different battery voltages, and different BMS protocols.

Both 5 kW and 10 kW dc-dc converters were developed. The combination of a battery system and dc-dc converter can be considered one battery bank module (BBM). Many BBMs each with different ratings and characteristics can be operated in parallel on the 900 Vdc collection bus.

Figure 3 Dc –Dc converters

Used battery systems consisting of multiple 100V battery modules and a BMS for this project were supplied by Electrovaya [2A]. Multiples of three different battery systems with ratings of nominal 300 V (3 modules), 400 V (4 modules) and 600 V (6 modules) were supplied. All of the battery systems had similar amp-hour ratings. It is understood that batteries used in the vehicle had liquid cooling circuit and a packaging frame. The repurposed batteries are now air cooled. For this project, it was decided not to implement any short time current C rating that may be available.

The dc-dc converter is designed as two cascade buck/boost converters in order to obtain the required dc boost ratio of 3. The initial design was completed within the PSCAD simulation environment as shown in Figure 4. Multiple iterations of the design cycle were completed in simulation to optimize the selection of the switching frequency and sizing of various components including: IGBTs, pre-charge resistors and filter elements. Different control approaches were studied and verified before any hardware design and assembly was undertaken. Once the component sizing was optimized and the appropriate control algorithms were verified, PSCAD was successfully used for the preliminary tuning of the controllers and verification of the different operating modes. Final tuning was completed on the test system hardware.

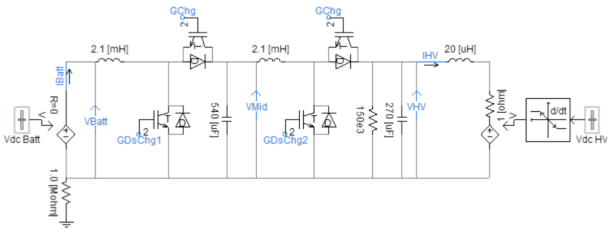

Figure 4 PSCAD Simulation

A server based Master Controller receives the operation and status inputs from each of the battery systems via the Master Controller CANopen based interface. The Master Controller performs the primary supervisory and control dispatch and has the ability to start, stop and monitor each dc-dc module independently. The Master Controller is tasked with setting the operational mode and target set-point for each BBM. Each BBM can be discharged in either power or current control when the battery system is designated to transfer energy into the ac system. The battery system can be charged by either current control or battery side dc voltage control. The Master Controller also interfaces to the main dc-ac 100 kW converter. A multi-page Graphical User Interface (GUI) has been developed to allow for operator interface to configure the system, select operating mode and set-point controls, these pages also include analog display and status/alarm monitoring. A sample of these displays is shown in Figure 5.

A bi-directional dc-ac voltage-sourced converter (VSC) is used to connect the parallel BBMs to the ac system. In this case a 100 kVA 600 volt three-phase converter allows the connection of multiple (10-15) parallel BBMs.

The VSC controls the dc collection bus voltage and as a result transfers and balances the power exchanged between the ac-system and the BBMs for either charge or discharge operation. The Master Controller has a system interface into the VSC to provide parameter monitoring and supervisory control, including dc-bus set-point and start/stop, through the GUI.

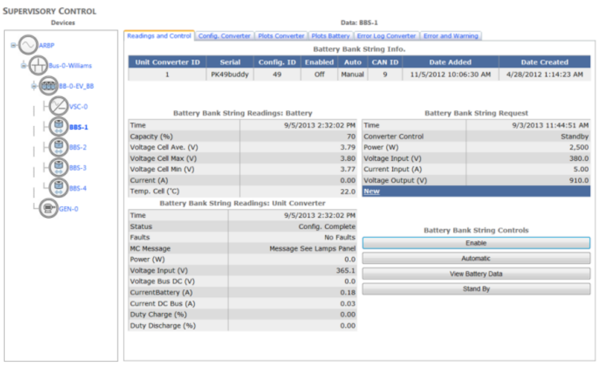

Figure 5: Sample Screen of Master Controller GUI

REPURPOSED BATTERY SYSTEM ISSUES

One of the important requirements when considering a battery for repurposing is determining the ratings to be used for the battery system's particular BBM. When the battery system was new it had typical ratings defined as [2]:

- Energy storage capacity (kWh) represents the amount of energy that the battery can store (i.e. 12.5 kWh battery).
- Maximum steady state current that should be drawn from the battery. As the current increases the length of time the battery can supply the current decreases. Typically described in terms of C, where a one C rating is the current in amps that will discharge the batter to its acceptable discharge limit in one hour. For example a nominal 400 V 12.5 kWh battery has a 1C rating of 31.25 amps.
- The 30 second maximum pulsed current rating, typically in C. In order to accommodate short term, high current demands such as acceleration in an electric vehicle. The same battery described above with a 5C pulse capability would be able to deliver 157.5 A for a defined short duration.

There are questions regarding how to determine the rating for a repurposed automobile based battery system. Factors include battery aging and subsequent reduction of energy storage capacity to at least 80%. The initial 12.5 kWh rating may now be 10 kWh or less. The second factor to consider is that the cooling system of the automotive battery may have been modified when configuring the modules for repurposing. This would impact the short time current rating. As a conservative approach, our demonstration project chooses to limit the maximum current to 0.5C value (for a 5 kW dc-dc) and 1 C (for a 10 kW dc-dc) and actively monitor the battery temperature through the BMS. The maximum battery allowable temperature for an individual cell is 45 C°.

PROTECTION REQUIREMENTS

The main BBM protections include hardware based protection including fusing at a margin above the selected maximum steady state C rating and software based monitoring of the following: over/under voltage of the overall battery pack; over/under voltage of the dc collection bus; temperature of the battery; overcurrent on both the battery and dc bus side; minimum and maximum cell voltages; and persistent communication errors will result in a shut down.

As a battery system ages, each cell is impacted differently and become weaker at different rates. A weaker cell will both charge and discharge more rapidly than healthy cells. The weakest link of the battery pack can be identified by the weakest cell. To ensure safe operating limits a conservative approach to selecting the charge and discharge limits of the battery have been recommended by the battery OEM as follows: (i) The discharge limit of the battery is determined by the minimum cell voltage within the battery pack reaching a threshold value as reported by the BMS; and (ii) the charge limit is determined by using the maximum cell voltage within the battery pack reaching a threshold as reported by the BMS. This will safeguard the individual cells from overcharging or under-discharging.

PRELIMINARY TEST RESULTS

Operational testing of the repurposed battery bank has been the operation of 3 BBMs in parallel operation. Both 300Vdc and 400Vdc battery systems modules have been utilized together in the charge and discharge operating modes. The throughput efficiency of the dc–dc converter and battery module has been measured at between 85 and 90% for discharge operation and 70 and 85% for charge operation as shown in Figure 6.

The new battery capacity was stated as 12.5 kw/hr. The repurposed battery capacity is approximately 80%

of new which is consistent with the expected capacity for a repurposed battery. Discharge testing showed the battery capacity based on the minimum cell voltage criteria is less than the 80% as shown in Figure 7, which is not an unexpected result given the conservative safety margins.

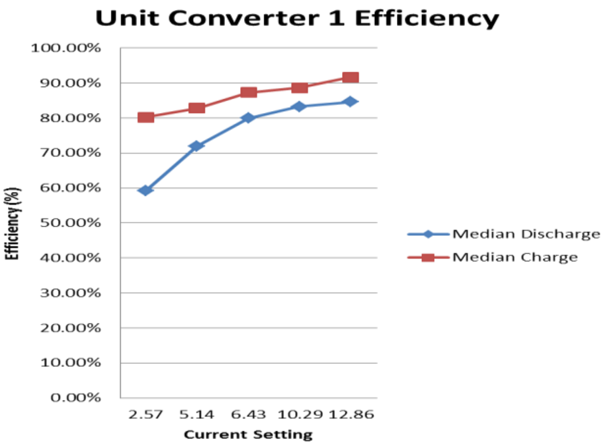

Figure 6 BBM efficiency charge and discharge cycles

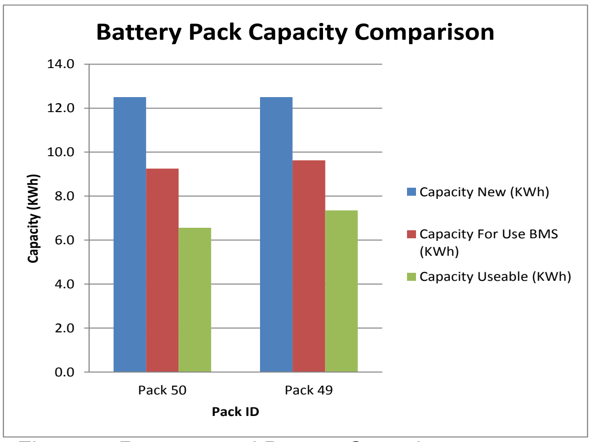

Figure 7: Re-purposed Battery Capacity

ISLANDED TEST SYSTEM FEATURE

A scaled 18 kW diesel was procured to form an experimental system suitable to evaluate the performance of diesel generator in parallel with a repurposed energy storage system. This test system comprises of an additional ac-ac power electronic converter configured to be a programmable load bank. This programmable load bank provides a realistic daily load kW cycle, allowing various battery/diesel configurations to meet load demand and maintain the frequency/voltage of an islanded community or micro-grid. The generator control requires governor control in order to adjust ac frequency and exciter reference voltage control in order to adjust the ac voltage. This experimental set-up is under development and should be operational in the next six months. Results of this effort will assist in the assessment and selection of battery energy storage requirements versus peak daily load and expected diesel and diesel emission savings that could be expected.

CONCLUSIONS AND FUTURE TESTING

A fundamental proof of concept for the topology and control for a stationary energy battery system suitable for repurposing various electric vehicle battery models has been demonstrated. The stationary energy storage system consists of 5 dc-dc converters and batteries modules of fundamentally different voltages and energy ratings operating together to form a larger energy rated system. For commercial applications, it is envisioned that the generic dc-dc converter is customized for a particular battery type. The customization consists of BMS serial communication protocol and a number of cascade buck-boost stages, based on battery voltage. When the battery module reaches end of life, that battery system would be transferred to the appropriate end of life recycling stage and a replacement repurposed battery would be paired with the dc-dc converter.

Continued enhancements and development as well as tuning of the dc-dc converters should see an increase in the overall efficiency and thus reduce the system losses. The intention in the future is to operate the battery system as part of an islanded diesel or micro-grid test facility.

ACKNOWLEDGMENTS

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[2A] Electrovaya Corp. Canada provided used lithium ion based battery system complete with the original battery management system (BMS) that had been utilized in an automotive application.

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RE-PURPOSE BATTERY PROJECT TEAM

The re-purposed battery team leader is Randy Wachal. Randy is a professional engineer for Manitoba Hydro with 32 years of HVDC experience. This project includes significant contributions from team members; JS Stoezel, Dexter Williams, Arash Darbandi, Farid Mosallat, Warren Erickson, Adam Chevrefils and Robert Yonza.