Systematic Characterization and Evaluation of Grid-connected Flow Battery Systems

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ABSTRACT

This paper provides an overview of flow technologies and how the ESRC's research and test center of excellence supports the evaluation and validation of various grid-scale flow battery technologies, with systematic characterization and evaluation including: factory acceptance testing, baseline functional and performance characterization, and advanced testing and modeling, including stacked services testing also informed by the duty cycle tests developed by Sandia and Pacific Northwest National Laboratories

The ESRC includes a software-hardware infrastructure that enables economic evaluation as well as support modeling of aging and performance over time for a range of technologies. A Factory Acceptance Test (FAT) has been done on an Avalon Flow battery system:

1. Visual inspection of all system components
2. Basic DC testing of 3 of 9 of the batteries
3. AC testing of a 3 battery string
4. Post-DC and AC testing visual inspection

Keywords: vanadium redox flow battery, energy storage testing, grid-connected, evaluation, stacked services

1 BACKGROUND AND INTRODUCTION

Energy storage deployments in the United States have continually increased over the past several years, and are projected to grow exponentially in the future. As deployments become more widespread, and a wider range of technologies are employed, understanding and evaluating system performance and capabilities will be essential to support continued energy storage growth,. Flow batteries came up later as they could not benefit from developments for computer applications and other smaller size. The form an emerging technology in the grid storage space and are well-suited to a number of support applications while characteristically they have long cycle life and projected operational lifetime. Significant work has been done at the Energy Storage Research Center to contribute to ESIC's Energy Storage Test Manual.

Flow batteries rely on "chemical reduction and oxidation reactions…to store energy in liquid electrolyte solutions which flow through a battery of electrochemical cells during charge and discharge [1]" as shown in Figure 1.

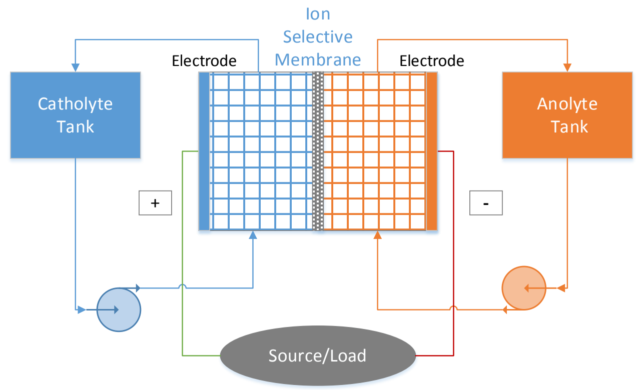

Figure 1: Basic flow battery schematic [2].

While the deployment of flow batteries for grid-scale applications is relatively new, the technology itself has been around significantly longer [3], [4]. Recent efforts by Pacific Northwest National Laboratories, among others, have increased the performance of a range of flow battery chemistries, especially vanadium redox flow batteries [5]–[10]. Other important flow battery chemistries include include iron-chromium and zinc-bromine.

Recent developments in flow battery technologies have enabled their deployment to the grid by improving energy density and reducing cost. They are known for their long cycle life and slow degradation, as well as their high safety level. Flow batteries are particularly appealing due to their relatively simple construction with limited moving parts, do not require high temperatures, and there are "no morphological changes that limit cycle life and depth of discharge [4]." Recent concerns regarding leakage have also been addressed.

In terms of applications, flow batteries are most competitve in applications where the power to energy ratio of the system is relatively low, and especially for instances where the energy storage application has a longer duration, particularly more than four hours [11]. Understanding how the energy storage system will be used is critical to support the economic deployment of these batteries.

Future developments related to flow batteries, particularly improvements to separator and electrode materials that enable better efficiencies, will make the technology more attractive for a wider range of stakeholders. As demand for flow batteries increases, the scale up of production will drive costs downs further increasing the competitiveness of these energy storage systems [12].

The evaluation of flow batteries, particularly related to their ability to perform particular applications and perform mutliple services (i.e. value stacking) will be critical to support the development and adoption of flow batteries as a competitive option for grid-scale energy storage.

2 TEST APPROACH

The Energy Storage Research Center at Southern Research (ESRC) is a research and test facility designed to accommodate the evaluation of grid-scale flow battery energy storage systems.

A number of types of testing are addressed in this paper and are critical to the systematic characterization and evaluation of flow battery energy storage systems. These testing types include factory acceptance testing, baseline functional and performance characterization, and advanced testing and modeling, including stacked services testing (see Figure 2).

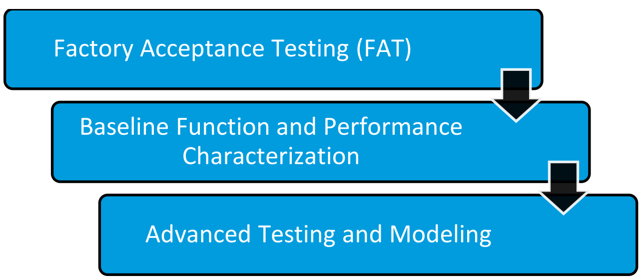

Figure 2: Overview of Systematic Characterization and Evaluation of Grid-connected Flow Battery Systems.

2.1 Factory Acceptance Testing

Factory Acceptance Testing (FAT) is completed by the vendor before the energy storage system is sent to the customer and is intended to “ensure that the system meets the customer requirements [13].” FAT is one step in the process towards ensuring that a safe an reliable system is installed; as a part of the FAT, there must be a review of the system “sequence of operations” used to develop the required factory acceptance test plan [14]. This testing relies on cooperation between the customer and vendor and other key stakeholders.

2.2 Baseline Functional and Performance Characterization

Significant work has been done at the Energy Storage Research Center to contribute to the Energy Storage Test Manual published by the Energy Storage Integration Council of EPRI [15]. The procedures and testing approach outlined in this manual will guide the development of a test program for a flow battery to be installed at the ESRC for testing. In addition to the test procedures in this document, peformance characterization tests will also be informed by the duty cycle tests that have been developed by Sandia and Pacific Northwest Natioanl Laboratories in their Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems [16], [17] (see Figure 3).

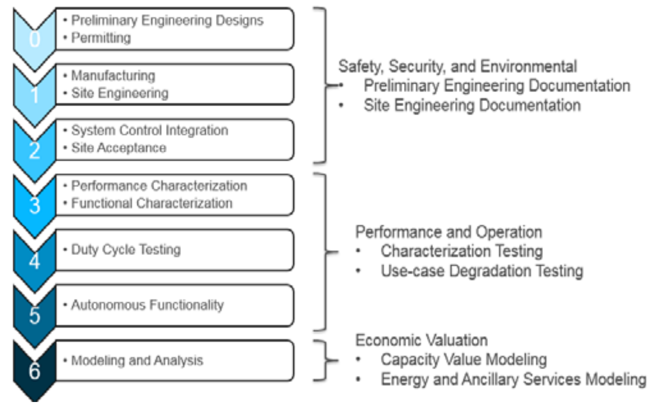

Figure 3: Overview of ESRC Function and Performance Testing Approach.

2.3 Advanced testing: Stacked services and Modeling

In addition to the functional and performance testing detailed by documents from EPRI and Sandia and Pacific Northwest National Laboratories [15]–[17], understanding a system’s ability to perform multiple functions within a single day or even simultaneously, is critical to the evaluation of a system’s economic feasibility. The ESRC, in collaboration with Acelerex, a software and consulting firm, includes a software-hardware infrastructure that can enable this kind of testing as well as support modeling of aging and performance over time for a range of technologies including grid-scale flow batteries (Figure 4).

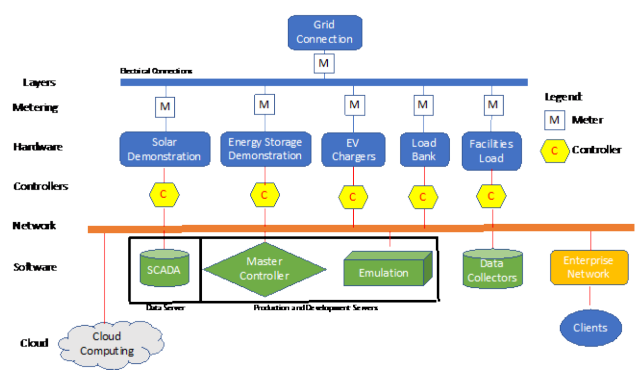

Figure 4: ESRC Architecture to enable advanced energy storage testing.

3 INITIAL RESULTS AND FUTURE ACTIVITIES

The ESRC is currently beginning its testing program for an Avalon vanadium redox flow battery. The system to be installed onsite for testing includes 9 batteries in an array of the Avalon AFB2.10 for a total power of 90 kW and a nominal capacity of 270 kWh [18], with an standard operating temperature range of -5°C to 45°C.

Factory acceptance testing was conducted on this battery energy system on April 4 and 5, 2019 in Vancouver, Canada. The factory acceptance test plan was developed in conjunction with the Electric Power Research Institute.

The Factory Acceptance Test (FAT) for the Avalon Flow battery system included the following components of testing:

1. Visual inspection of all system components including inspection of:
    a. Residual electrolyte and
    b. Any discoloration indicative of overheating within the enclosure
2. Basic 10 kW DC testing of 3 of 9 of the batteries involved in the system, including one time charging, sustaining and one time discharging and sustaining, observing temperature limits and SOC range; basic functioning of the BMS, temperature sensors, pumps, and fans are evaluated, while there is a short demonstration of charge and discharge at full rated power. Attention is focused on the beginning and end of discharging.
3. AC testing of a 3 battery string including one time charging, sustaining and one time discharging and sustaining; this functional test confirms the interaction of the inverter/PCS, DC batteries and EMS.
4. Post-DC and AC testing visual inspection to ensure there are no changes in the battery status or cleanliness (of particular concern would be any electrolyte residue that was not previously present).

Upon completion of the FAT, all units were delivered to ESRC at SR's Birmingham site and riggers unloaded the units onto the ESRC's test pad. Figure 5 shows the unit at the site. The remaining work with respect to its grid connection and other electrical work is currently progressing through planning and licensing.

Figure 5: Avalon ESS onsite at the ESRC (a) and during its delivery to the ESRC (b).

4 CONCLUSIONS

Energy storage has been more widely adopted over the past several years in the United States, and according to leading industry organizations, this growth is expected to accelerate in the future [19]. As deployments become more widespread, and a wider range of technologies are employed, including a number of flow battery chemistries, understanding and evaluating system performance and capabilities will be essential to support continued energy storage growth, especially as systems are integrated into mission-critical portions of our energy infrastructure.

Due to their long cycle life and projected operational lifetime, flow batteries are expected to be well-suited to a number of grid support applications. Southern Research, in collaboration with Oak Ridge National Labs, the Electric Power Research Institute and Southern Company Services have established the Energy Storage Research Center (ESRC) in Birmingham, Alabama to address this need for testing and research, particularly for flow batteries.

The facility has been designed to test the function and performance of grid-connected energy storage systems, supporting many technologies including flow batteries. The facility is capable of characterizing the function and performance of flow batteries, and other energy storage systems, at the grid scale, and including stacked services evaluation.

This paper has provided an overview of flow technologies and how the ESRC's test beds support the evaluation and validation of various grid-scale flow battery technologies, including preliminary results from the Factory Acceptance testing conducted for the first system to be evaluated at the ESRC, a flow battery energy storage system from Avalon Battery.

5 ACKNOWLEDGMENTS

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REFERENCES

[1] Energy Storage Association, "Redox Flow Batteries," 2019. [Online]. Available: http://energystorage.org/energy-storage/technologies/redox-flow-batteries. [Accessed: 07-Apr-2019].

[2] L. Li, S. Kim, G. Xia, W. Wang, and Z. G. Yang, "Milestone Report for the DOE-OE Energy Storage Systems Program," Pacific Northwest National Laboratory, Richland, Washington, PNNL Report PNNL-21174, Feb. 2012.

[3] M. Bartolozzi, "Development of redox flow batteries. A historical bibliography," *J. Power Sources*, vol. 27, no. 3, pp. 219–234, 1989.

[4] M. Skyllas-Kazacos, M. Chakrrabarti, S. Hajimolana, F. Mjalli, and M. Saleem, "Progress in Flow Battery Research and Development," *J. Electrochem. Soc. Crit. Rev. Electrochem. Solid-State Sci. Technol.*, vol. 158, no. 8, pp. R55–R79, Feb. 2011.

[5] Energy Storage Association, "Zinc-Bromine (ZNBR) Flow Batteries | Energy Storage Association," 2017. [Online]. Available: http://energystorage.org/energy-

storage/technologies/zinc-bromine-znbr-flow-batteries. [Accessed: 25-Jul-2017].
[6] K. Gong *et al.*, “A zinc–iron redox-flow battery under \$100 per kW h of system capital cost,” *Energy Environ. Sci.*, vol. 8, no. 10, pp. 2941–2945, 2015.
[7] L. Li *et al.*, “A Stable Vanadium Redox-Flow Battery with High Energy Density for Large-Scale Energy Storage,” *Adv. Energy Mater.*, vol. 1, no. 3, pp. 394–400, May 2011.
[8] T. Liu, X. Wei, Z. Nie, V. Sprenkle, and W. Wang, “A Total Organic Aqueous Redox Flow Battery Employing a Low Cost and Sustainable Methyl Viologen Anolyte and 4-HO-TEMPO Catholyte,” *Adv. Energy Mater.*, vol. 6, no. 3, p. 1501449, Feb. 2016.
[9] P. Maloney, “Despite technological advances, flow batteries struggle against market giant lithium-ion,” *Utility Dive*, 14-Mar-2017. [Online]. Available: http://www.utilitydive.com/news/despite-technological-advances-flow-batteries-struggle-against-market-gian/437399/. [Accessed: 14-Mar-2017].
[10] A. Z. Weber, M. M. Mench, J. P. Meyers, P. N. Ross, J. T. Gostick, and Q. Liu, “Redox flow batteries: a review,” *J. Appl. Electrochem.*, vol. 41, no. 10, p. 1137, 2011.
[11] I. McClenny, “Flow Batteries Under Fire: What’s happening?,” *Navigant Research*, 05-Apr-2018. [Online]. Available: https://www.navigantresearch.com/news-and-views/flow-batteries-under-fire-whats-happening. [Accessed: 10-Apr-2019].
[12] A. Colthorpe, “Flow in flux: Long duration batteries in fight to commercialise,” *Energy Storage News*, 29-Mar-2018. [Online]. Available: https://www.energy-storage.news/blogs/flow-in-flux-life-on-the-frontier-of-commercialising-long-duration-batterie. [Accessed: 10-Apr-2019].
[13] M. Wilson, “Chapter 6 - Specification Preparation,” in *Implementation of Robot Systems*, M. Wilson, Ed. Oxford: Butterworth-Heinemann, 2015, pp. 133–146.
[14] T. Olinsky-Paul, I. Gyuk, and D. Borneo, “Energy Storage Technology Advancement Partnership (ESTAP) Webinar: Commissioning Energy Storage,” presented at the Energy Storage Technology Advancement Partnership, Clean Energy States Alliance, 20-May-2014.
[15] EPRI, “Energy Storage Integration Council (ESIC) Energy Storage Test Manual,” ELECTRIC POWER RESEARCH INSTITUTE, Palo Alto, CA, Technical Update 3002011739, Dec. 2017.
[16] S. R. Ferreira *et al.*, “Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems,” Sandia National Lab, Pacific Northwest National Lab, Albuquerque, NM and Livermore, CA, Sandia Report SAND2013-7084, Aug. 2013.
[17] D. Conover *et al.*, “Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems,” Sandia National Lab, Pacific Northwest National Lab, Albuquerque, NM and Livermore, CA, Sandia Report PNNL-22010 Rev 2/SAND 2016-3078 R, Apr. 2016.
[18] Avalon Battery, “Avalon Battery | Storage For Power Management And Renewable Energy,” *Avalon Battery*, 2019. [Online]. Available: https://www.avalonbattery.com/. [Accessed: 12-Apr-2019].
[19] P. Maloney, “2019 Storage Outlook: Utility procurement will drive deployments, analysts say,” *Utility Dive*, 08-Jan-2019. [Online]. Available: https://www.utilitydive.com/news/2019-storage-outlook-utility-procurement-will-drive-deployments-analysts/545448/. [Accessed: 12-Apr-2019].