REDFLOW ZBM USA OPERATIONAL EXPERIENCE

Steven Hickey[1]

[1]RedFlow LLC, Albuquerque, New Mexico

RedFlow developed the R510 (Residential, 5kW, 10kWh) Energy Storage System (ESS) to meet the requirements of a utility smart-grid distributed storage project[1] in Australia. The R510 includes one Zinc Bromine Module (ZBM) and an SMA Sunny Island 5kW inverter in a weather proof enclosure. In May 2012 several variants modified for the USA (R510US) were commissioned. This paper reviews the operational experience gained and some analysis of the results.

Installations typically employed cellular data links for remote control and data logging via host server in Brisbane Australia. Data logging at 15 second resolution for more than 100 points of ZBM and SMA operation provide a rich and accurate resource for system analysis. The R510US control software allows the operator to conduct a wide range of energy storage experiments including conventional peak-shifting and renewable firming. All sites are grid connected and the FGCU and Sprint sites have load-side AC coupled PV supplies. The SNL device was subjected to a wide range of characterization tests including the emerging ESS protocol.

Keywords: battery, zinc bromine, energy storage, grid, solar, inverter

R510 DESIGN AND FUNCTION

The R510 was designed to fulfill the requirements of the smart-grid project[1] as a residential distributed energy storage device under remote control by the utility. The steel enclosure was constructed to meet IP45 rating and stand against a house wall as an "under-eves" unit (figure 1). Respecting domestic amenity, particular attention was given to ensuring acceptably low acoustic noise levels. Segregating ventilation between the lower battery room and upper electrical section prevents potential for explosive gas ignition.

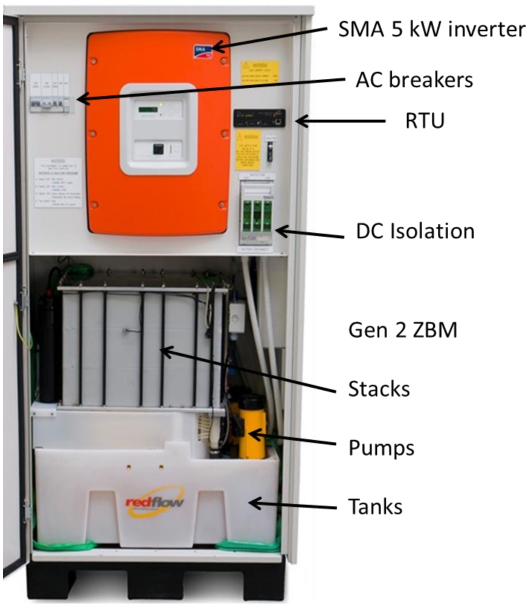
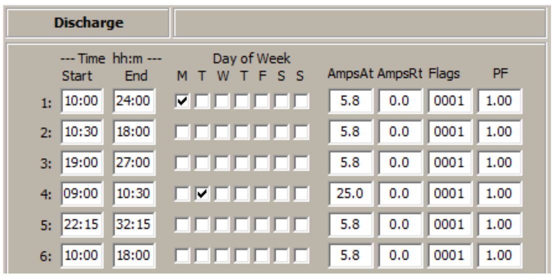


Figure 1 R510 unit showing main components

RedFlow's investment in custom SMA firmware allowed the standard Battery Management System (BMS) to be disabled, thereby allowing the inverter to operate with ZBM voltages instead of those normally required of lead-acid batteries. This modification allowed the inverter to charge the ZBM at a maximum of 62.5 V and discharge it down to 40 V. A small (nom 36 V) lead-acid battery and power supply allow the inverter to operate whilst the ZBM is discharged (stripping is the process were the ZBM is discharged to zero volts in order to refresh electrodes).

The Remote Terminal Unit (RTU) coordinates actions via RS-485 serial links to the ZBM battery controller, the SMA inverter, and cellular phone modem. The RTU also logs system data points (typically at 15s intervals) and maintains scheduled operations during communication outages. An internet protocol links each RTU to a central server (Host). PC-based client software allows operators to connect via the Host to a remote R510 and edit settings.



Discharge

	--- Time hh:m --- Start	End	Day of Week M	T	W	T	F	S	S	AmpsAt	AmpsRt	Flags	PF
1:	10:00	24:00	☑	☐	☐	☐	☐	☐	☐	5.8	0.0	0001	1.00
2:	10:30	18:00	☐	☐	☐	☐	☐	☐	☐	5.8	0.0	0001	1.00
3:	19:00	27:00	☐	☐	☐	☐	☐	☐	☐	5.8	0.0	0001	1.00
4:	09:00	10:30	☐	☑	☐	☐	☐	☐	☐	25.0	0.0	0001	1.00
5:	22:15	32:15	☐	☐	☐	☐	☐	☐	☐	5.8	0.0	0001	1.00
6:	10:00	18:00	☐	☐	☐	☐	☐	☐	☐	5.8	0.0	0001	1.00

Figure 2 Power Control Screen

"Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000."

The essential function of the R510 is to charge the ZBM from the AC supply and to then subsequently discharge the stored energy back into AC. Figure 2 shows a portion of the user software displaying a power control schedule. Start and end times for six sessions can be selected on a day of week basis along with the desired AC current (active and reactive). Charge and discharge sessions are presented similarly, with parsing to prevent overlaps.

R510 US version

Electrolyte circulation in the ZBM is powered by magnetically coupled, single phase, induction motor pumps. While these motors are rated for 50 Hz and 60 Hz operation, the pressure-flow characteristic varies considerably with shaft RPM. As a result the ZBMs destined for the USA were customized to account for this difference.

A further challenge for Australian electrical Engineers is the variety of AC mains connections available in the USA (and the confusion surrounding *neutral* and *earth*). Initially 5 kW isolation transformers were used to create a (European/Australian) earthed neutral on the R510 side. Lately this has been replaced with dual-pole breakers for grid and load L1 & L2 connections.

R510US OPERATIONS

Calibration

As a grid connected energy storage system the R510 great scope for experimentation, and a key issue is the performance of the ZBM itself. The idea of calibration is to perform a standardized charge-discharge cycle that can be repeated regularly so as to track the DC efficiency of the ZBM as proxy for its state of health. Figure 3 shows such a chart recorded from an R510US. Cycle capacity, duration, charge/discharge current, and temperature all affect the DC efficiency. Standardizing the capacity, duration and current normalizes these effects, and temperature variation can be compensated to some extent. In addition to the energy efficiency (Ee, typically 75%), the analysis can determine internal resistance (Ri, typically 0.12 ohms), Coulombic efficiency (Ec, typically 88%), and Voltaic efficiency (Ev, typically 86%).

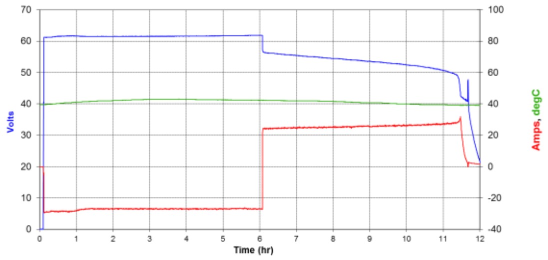


Figure 3 ZBM Calibration Cycle Chart

The product of Coulombic and Voltaic efficiencies equals the energy efficiency. The Voltaic losses are entirely due to the "I squared R" loss through the ZBM internal resistance. The Coulombic loss is entirely due to self-discharge effects (mainly aqueous bromine diffusion). Interestingly, these two metrics move in opposition with temperature. Ionic conduction (the major component of internal resistance) increases with temperature as does the diffusion rate.

Testing at Sandia National Laboratories [2] has provided a data set that has allowed the development of a mechanistic model describing ZBM columbic losses. These tests were parameterized with charge current, discharge current, and temperature. This approach allows a distinction to be made between losses occurring during the charge phase and those occurring during the discharge phase. It has been suggested that the majority of bromine in the electrolyte aqueous phase exists as polybromide ions (Br_3^-, Br_5^-).This implies that the dissolved bromine may be affected by both diffusion and migration. Diffusion would be expected to occur throughout the whole charge/discharge cycle, as do shunt currents. Migration would be expected to contribute during discharge only. These loss currents are influenced by charge capacity (Ahc Amp hrs), discharge current (Id Amps), and the number of stacks in the ZBM (some data is available for both 2 and 3 stack batteries) according to the following functions:

Ishuntcurrent = f(deg K, Ahc, #stacks)

Imigration = f(deg K, Ahc, Id)

Idiffusion = f(deg K, Ahc, #stacks)

The chart of figure 4 indicates the fit between measured and modeled coulombic efficiency across the parameter space.

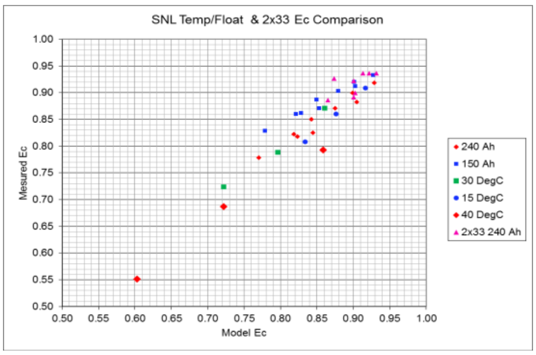


Figure 4 Measured vs Modeled Coulombic Efficiency

"Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000."

Renewable Integration

As a grid connected energy storage system the R510 offers great scope for experimentation. Peak shifting and arbitrage with off-peak charging are readily implemented. It also has the ability to accept load side (AC) sources and sinks. Figure 5 shows a daily energy flow balance for a system with load-side PV array (red arrows for DC and blue for AC energy flows). The researcher can choose to control the grid current or the inverter current. If the grid current is fixed, fluctuations in the PV load are accommodated by adjusting the ZBM current. In this way smoothing or firming of the solar resource can be achieved. PV current surplus to the grid set-point will be stored in the battery. Any PV deficit (perhaps from cloud cover) will be compensated by discharging the ZBM.

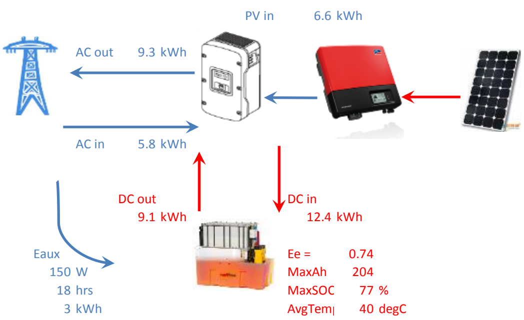


Figure 5 Energy flow balance with load-side PV

Figure 6 shows a cycle chart where the battery has been charged to capacity and then this state of charge has been maintained with a "float" trickle charge before the deferred discharge occurs.

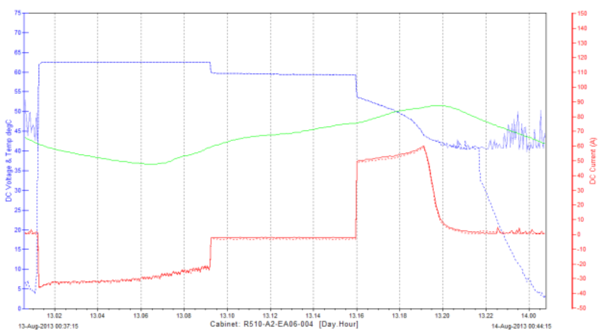


Figure 6 Charge/Float/Discharge Cycle

Storage Experiments

As described above, self-discharge due to aqueous bromine transport through the separator has a significant impact on ZBM efficiency. If electrolyte circulation maintains a high bromine concentration in the stack, a fully charged ZBM may self-discharge completely in approximately 48 hours. However, if flow is halted in the bromine circuit when charging is completed, so that no fresh bromine is brought into the stack, then the maximum loss is limited to the residual (~10%). Zinc circuit flow has no effect on self-discharge. So this can be maintained or reduced to a low duty cycle (e.g. 1 min on in every 30 mins).

Several R510US systems have been employed to conduct experiments with the ZBM as a storage battery. The procedure is to charge the ZBM to a desired state-of-charge (SOC) and then stop the bromine pump whilst duty-cycling the zinc pump. After some interval both pumps are fully activated and the ZBM is discharged onto the grid so that the energy retained can be measured.

Figure 7 shows the ZBM terminal voltage (blue) and current (red) during an 11 day storage test. As self-discharge progresses, consuming residual bromine in the stack, the terminal voltage falls. But after 11 days when the bromine pump restarts, the stack voltage recovers within seconds and the battery delivers rated power to the grid.

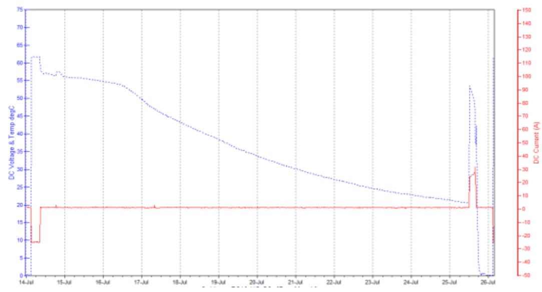


Figure 7 11 day ZBM Storage Test Chart

Under most conditions, when discharged immediately after charging, a ZBM will deliver a (DC) energy efficiency of approximately 75%. Figure 8 charts the energy efficiency achieved in storage tests with two R510US systems. After about 3 or 4 days the efficiency appears to asymptote to approximately 60%. This could be interpreted as the potential self-discharge being limited to the bromine remaining in the stack.

Clearly, it would be desirable to extend these storage experiments to longer durations, but some applications are apparent. In a UPS the ZBM could provide ~ 8kWh of long duration storage. In a multi-module ESS, efficiency could be improved by reducing auxiliary power consumption by putting some units into storage mode. A sophisticated control scheme could discharge the residual stack energy to the load instead of simply allowing it to self-discharge.

"Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000."

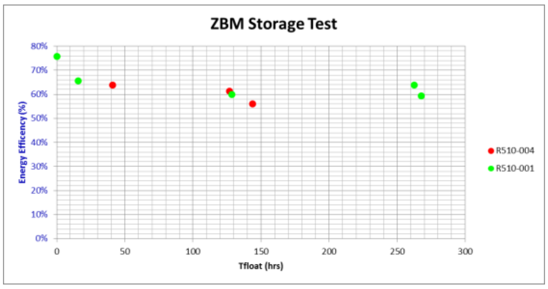


Figure 8 ZBM energy efficiency under storage tests

Conclusion

The R510US has proven a very effective vehicle for demonstrating and exercising the ZBM. Its SCADA system has greatly facilitated remote operation and data logging. The ability to connect load-side sources has allowed renewable integration studies. The ZBM storage experiments performed with the R510US have potential to improve operating efficiency and expand the range of applications for this technology.

References

[1] "*Utility-Owned Smart Grid Smart Grid, Smart Cities Trial*", *www.RedFlow.com*, July 2012.

[2] Rose D M, Ferreira S R, "*Initial Test Results from the RedFlow 5 kW, 10 kWh Zinc-Bromide Module, Phase 1*" Sandia National Laboratories Report **2012-1352**, February 2012.

[3] Rose D M, Ferreira S R "*Performance Testing of Zinc-Bromine Flow Batteries for Remote Telecom Sites*" Sandia National Laboratories publications **SAND2013-2818C**, May 2013.

ABOUT THE AUTHOR

Steven Hickey

Steve began his work with RedFlow in 2008, under the tutelage of Alex Winter where he developed control and testing systems and methodologies rom the time of the first ZBM construction. His initial focus was in the R&D test laboratory where he gained experience with the electrochemistry of the zinc-bromine system, hydrodynamics, failure analysis, performance analysis, and modelling techniques.

Steve developed the first PLC-based battery management system, and (latter) designs based on the RedFlow (microprocessor) Battery Controller. He designed and developed the innovative hybrid ZBM-Lead Acid Remote Area Power System for the successful ESV project.

Intimate knowledge of the battery and systems has enabled Steve to commission ZBMs, conduct training, and specify test programs in Australia, UK, and the U.S.A.

Prior to joining RedFlow, Steve was a founding director of Blastronics, a leading instrumentation and consulting company in the global mining industry. There he designed and developed systems for vibration, acoustics, structural monitoring, and explosive testing, with 15 years' experience in North and South America, and Australasia. He was awarded a Bachelor of Engineering (Electrical) from University of Queensland in 1981.

"Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000."