Battery Energy Storage for Grid Support Applications

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INTRODUCTION

Recent demonstration projects have validated the use of energy storage for grid support, as well as peak power shaving, with the use of a mobile Advanced Battery Energy Storage System (ABESS). The ABESS team, which consisted of Satcon, ZBB, Detroit Edison, and Sandia, designed the entire system to be housed on a 40-by-8-foot trailer, making it possible for one battery system to be used in multiple applications and locations. The ABESS zinc bromine flow battery has advantages for utility energy storage applications in that it provides two to three times the energy storage capacity compared to lead-acid batteries. Other battery advantages are low cost materials, plus deep discharge and rapid recharge capabilities. When connected to an electric power circuit known to have daily, seasonal, customer peak demands, ABESS reduces peaks in the electrical load by supplementing energy on the circuit at predetermined conditions or times. When the peak use period passes, the system is recharged using energy from the power grid during low-cost energy periods.

In the first demonstration test (Akron site), the power conversion system (PCS) controlled the charge and discharge of the battery to provide voltage stability at the end of a soft utility line during periods of heavy line loading. VAR and real power was injected into the line for line voltage regulation. The PCS adjusted the reactive power on the line per the line voltage requirement or kVA demand signal, through a communication link with the utility as an option.

The second demonstration test monitored the power (VA) output of a seasonally overloaded 800kW substation to provide the overload difference during peak loading periods (Lum site). For this test, the PCS was capable of peak power shaving through feedback current transducers (CT) from the point of common coupling with the utility through a communication port.

EQUIPMENT DESCRIPTION

The ABESS system, mounted on a 40-foot trailer, is composed primarily of three components: the zinc/bromine battery for energy storage housed in a 20 foot shipping container; the PCS that interfaces the battery with the AC line; and the isolating transformer, connected to the output of the PCS and providing voltage matching to the existing line. The following sections describe each of these components.

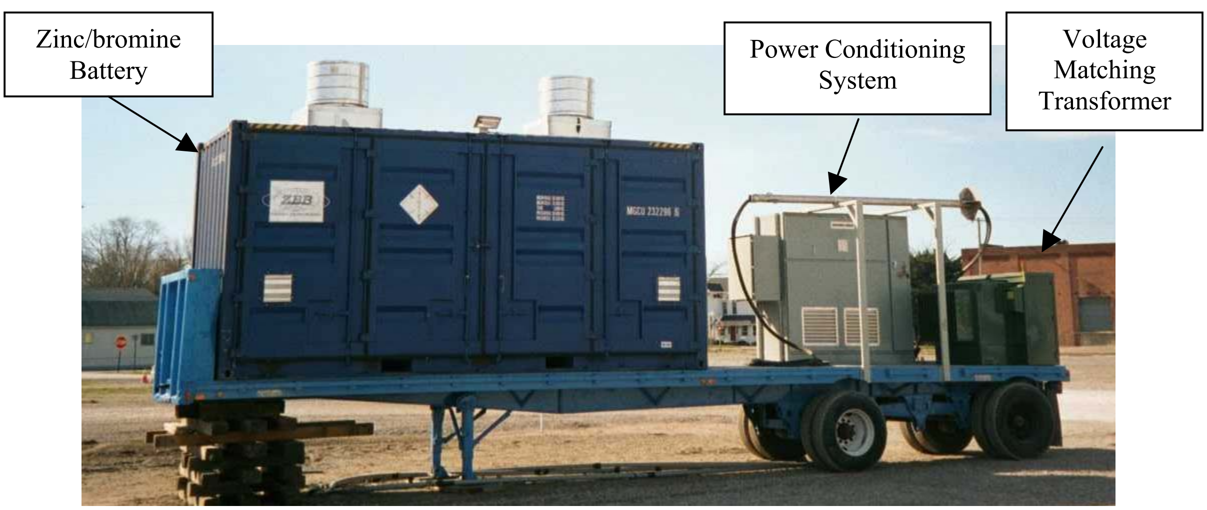

Figure 1 ABESS Trailer

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Zinc/bromine Battery

The zinc/bromine battery uses a circulation system to continuously feed reactants to the battery cell stacks. The flowing electrolyte insures uniform zinc plating, separates the reactive polybromide from the electroplated zinc (contained in the battery stack), and improves the thermal management of the system. The battery consists of electrochemical cell stacks, electrolyte storage reservoirs and an electrolyte circulation system. A schematic of the zinc/bromine battery is shown in Figure 2.

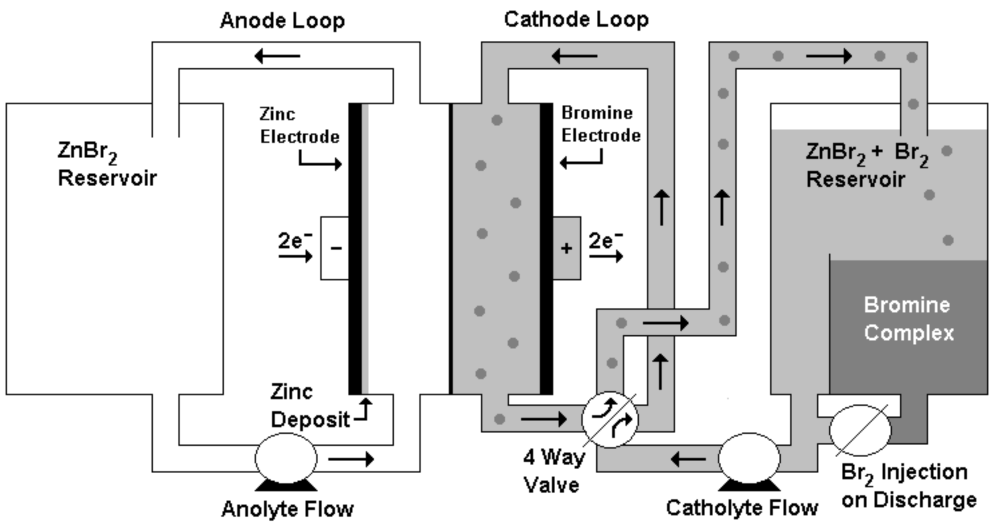

Figure 2. Schematic of Zinc/bromine Battery

The electrolyte is an aqueous solution of zinc bromide salt, which dissociates into zinc ions and bromide ions in water. During charge, the zinc ions are reduced, causing pure zinc to be electroplated on the anode, and bromide ions are oxidized causing bromine to be evolved at the cathode. A quaternary salt in the electrolyte forms a polybromide complex with the bromine, which reduces the reactivity and vapor pressure of the elemental bromine. Complexation of the bromine minimizes the self-discharge of the battery and significantly improves the safety of the system. The complexed bromine is removed from the stacks with the flowing electrolyte and is stored in an external reservoir. On discharge, the complexed bromine is returned to the battery stacks, where zinc is oxidized to zinc ions, and bromine is reduced to bromide ions. The electrochemical reactions during charge are given as follows:

Overall:	$ZnBr_2 \rightarrow Zn + Br_2$
Anode:	$Zn^{2+} + 2e^- \rightarrow Zn$
Cathode:	$2Br^- \rightarrow Br_2 + 2e^-$
Bromine Complex:	$QBr^- + nBr_2 \rightarrow Q(Br_2)nBr^-$

The building block for large zinc/bromine energy storage systems is a 50 kWh battery module. Each module consists of three cell stacks, two electrolyte storage tanks, pumps and plumbing to circulate electrolyte, and a control system. The control system monitors all battery parameters and shuts down the entire system if any safety hazard exists.

A 400 kWh battery system is comprised of eight individual 50 kWh zinc/bromine battery modules, each containing three battery cell stacks connected electrically in parallel. These eight modules are configured in two separate strings of four modules connected in series, with an open circuit voltage of 432 Volts (see Figure 3). Two controlled inputs to PCS are connected directly to each of these battery strings and can operate them simultaneously or independently. The two battery strings can be operated as two separate batteries or as a single battery, giving the entire energy storage system a great degree of charge/discharge flexibility. The battery system has a rating of 400 kWh at the two-hour discharge rate.

Power Conversion System (PCS)

A 200-kW/250-kVA PCS, supplied by SatCon Power Systems, was designed to interface with the dc power from the battery output to the utility power line, or to an isolated load. The two-stage unit, comprised of buck/boost choppers and inverter/converter, enables the bi-directional flow of power from the zinc/bromine battery to the AC power line.

The buck/boost (step-up/down) choppers (DC-DC converters) boost the voltage from each zinc bromine battery string to the DC voltage required by the inverter and for bucking (stepping down) the voltage from the rectified bus to each battery string for charging. The amount of current flow in either direction is controlled by pulse width modulation (PWM). Two choppers were used for individual control of each battery string as shown in Figure 3.

String 1	**Module**
432 V O/C	108 V O/C
150 amp nom.	150 amp nom.
300 amp cont.	300 amp cont.
String 2	**Total**
432 V O/C	432 V O/C
150 amp nom.	300 amp nom.
300 amp cont.	600 amp cont.

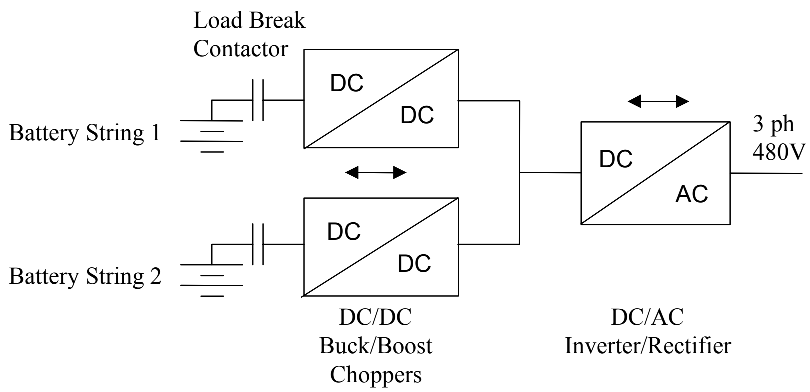

Figure 3. Battery and PCS Block Diagram

The inverter/converter is a voltage source inverter utilizing IGBTs with a high degree of voltage margin. The inverter converts the DC voltage from the step-up chopper to the required AC output voltage as well as converts the AC voltage back to DC for the step down chopper. The AC output voltage is controlled by pulse width modulating (PWM) the IGBTs. The pulse width modulation for both the chopper and inverter is done at a frequency that minimizes switching losses and provides the required performance. The PCS utilizes fiber optic gating isolation and includes protection circuitry for over-current and over-temperature protection and indication on a panel display. The inverter has been designed for three-phase output connection of 480VAC, 60Hz operation or an output voltage of 400V at 50/60Hz.

In the grid-connected mode, the PCS operates as a current controlled voltage source inverter. The inverter is synchronized with the phase of the line voltage automatically through controlling the current reference signal, which is synchronized with the line. This allows the control of power factor. VAR and real power control for line voltage regulation is injected in to the line. The PCS adjusts the reactive power to the line as per the line voltage requirement. The PCS unit has functions of VAR power control and limiting real power, in order to prevent the line voltage from increasing. If the VAR control is not sufficient to prevent the line voltage from increasing, and when the line voltage exceeds a set value, the PCS limits the real power depending on the available power form the Zinc bromine Battery.

The following summarizes the PCS control actions for line voltage support:

<u>Line under-voltage compensation — PCS and Battery:</u> PCS injects required amount of real power from the battery and reactive power at (VAR) leading power factor to the line in order to maintain constant voltage.

<u>Line over-voltage compensation — PCS and Battery:</u> PCS draws real power and reactive power (at lagging power factor) from the line in order to prevent the line voltage from increasing. During this mode of operation, the real power drawn from the line is used to charge the battery.

<u>Line under-voltage compensation — PCS-only in VAR Compensation:</u> When the battery is not available, the PCS functions as a VAR compensator. The PCS generates VARs by injecting reactive current in leading power factor to the line in order to prevent the line voltage from decreasing.

Line over-voltage compensation — PCS-only in VAR Compensation: The PCS draws reactive current from the line in lagging power factor to prevent the line voltage from increasing.

Transformer

A 300-kVA pad-mounted, three-phase, dual voltage (4800V x 13200V) transformer was supplied by The Detroit Edison Company for use on this project. A dual-voltage transformer was chosen so that the same components could be used at a number of potential site locations.

AKRON SITE GRID SUPPORT CASE

Testing of the ABESS during the fall of 2000 was performed at the Cooperative Elevator Company, a grain drying facility in Akron, Michigan (approximately 100 miles north of Detroit). The drying season typically runs from mid-September to early December. The grain dryer uses three 75 horsepower motors, which cause power quality sag issues for the other customers in the area. The facility uses an additional five 75 Hp fan motors which can also cause line voltage variations. Four to six major disturbances can be encountered per day. No prior voltage profile was available from this site, but data from a similar site indicated that a 200 kWh ABESS should be sufficient to handle the load. Initial testing of the ABESS found that the startup of the grain dryer draws greater than 800kVA from the line for about 3-5 seconds, causing a sag in the line voltage. This was much higher than anticipated when designing the size of the ABESS. Stopping the grain dryer motors was found to cause an overvoltage due to a slow voltage regulator response time of 60 seconds.

For the power quality application at this site, the battery was partially charged to enable compensation for both the under-and-over voltages associated with the facility. The battery was charged and discharged when needed by the PCS to reduce the voltage variations on the utility line. It was also used to reduce the large voltage depressions and overshoots encountered when starting and stopping the grain dryer motors. During the operation of the PCS with the battery in a voltage compensation mode, the battery needed to be available to be charged and discharged. For the tests at the grain dryer site, the battery was only charged to 50% in order to allow the battery to accept charge during line over-voltage compensation.

The battery system was located relatively close to the grain dryers, which was expected to minimize the flicker observed on the rest of the circuit. A photograph of the ABESS at the site is shown in Figure 1. Figure 4 shows the electrical connection of the ABESS to the 4.8-kV line at the Akron site.

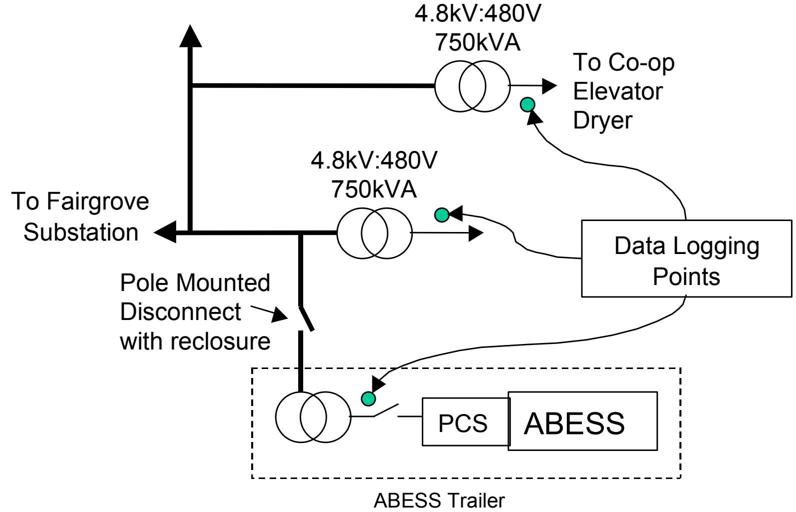

Figure 4. Electrical Connection of ABESS to 4.8 kV Overhead Line at Akron Site

Akron Test Results

The majority of the data was measured at the low voltage side (480V) of the 300-kVA transformer as shown in Figure 5. Data was collected using a PowerPro power quality analyzer from Candura Instruments (www.candura.com). The PowerPro samples data on each channel 128 times per cycle and updates all RMS-based calculations every 1/2 cycle.

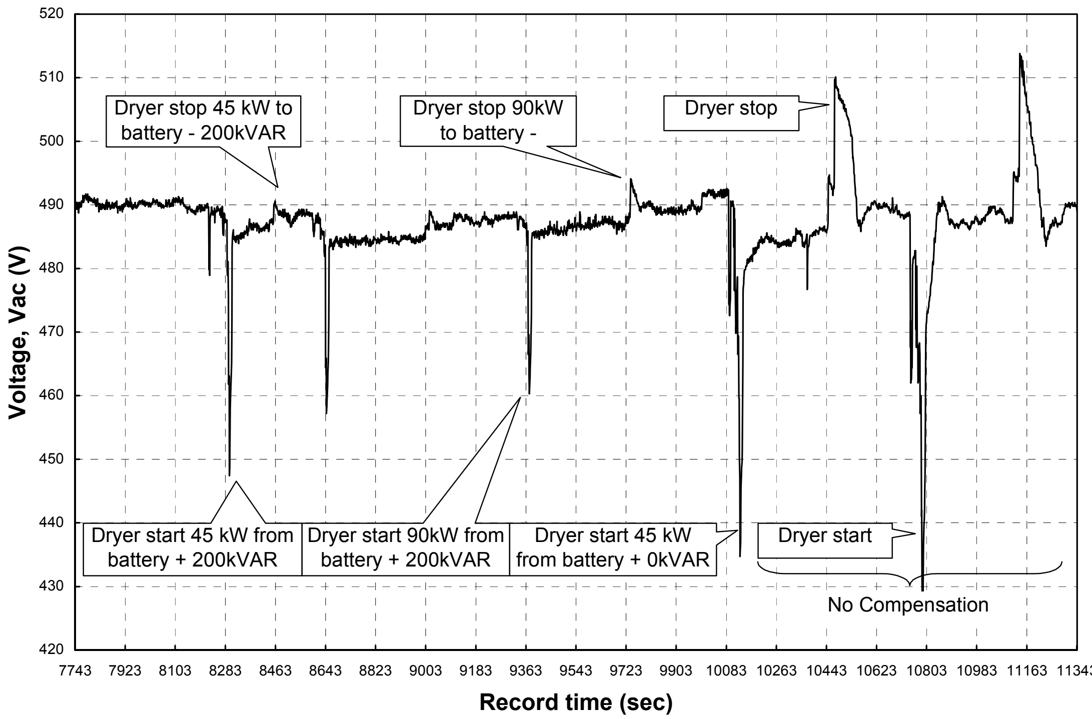

Figure 5. Line Voltage Profile During Startup and Shut-Down of Grain Dryer

A series of tests were performed by starting and shutting down the grain dryer using various combinations of real and reactive power compensation. Figure 5 shows the line voltage measured during these tests. The end of the recorded waveform was uncompensated. Voltage compensation from the ABESS not only reduced the peak excursions, but also significantly smoothed the voltage profile of the overhead line.

Both the battery and the PCS individually were able to reduce the voltage depression caused by the start up of the grain dryer. By compensating with both real and reactive power, the voltage drop was reduced even more. This voltage drop could be eliminated completely with a larger ABESS. The peak voltage caused by shutting down the grain dryer was nearly eliminated by compensating the line with real and reactive power.

LUM SITE PEAK POWER SHAVING CASE

Testing of the system during the late summer of 2001 was performed at a Detroit Edison sub-station, located in the town of Lum, Michigan. The sub-station contains three 250kVA pole-mounted transformers, for a combined rating of 800 kVA capacity. Summer air conditioning loads cause the transformer combination to exceed their rating typically by 200kVA making this site an ideal location for the ABESS trailer rating with its peak power shaving ability. The ABESS trailer was located close to the sub-station transformers. Figure 6 shows the electrical connections at the Lum site.

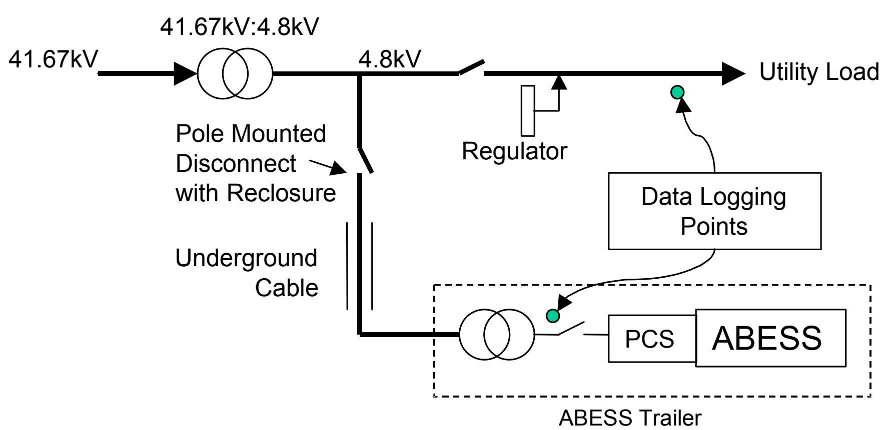

Figure 6. Electrical Connection of ABESS to 4.8 kV Overhead Line at Lum Site

For the power quality application at this site, the battery was to be fully charged during evening, low-power demand periods, and discharged when required for peak power shaving of the substation. The charge and discharge levels are adjustable at the PCS. The feed-back as monitored by power transducers (PT) and CT's at the utility load line (data logging point) trigger the charge and discharge events.

Lum Test Results

Testing of the ABESS commenced in late summer, August 24, and ended October 10, 2001. As a result of this late start, loading at the Lum sub-station barely exceeded 500kVA. However, the ABESS trailer was exercised by the charge and discharge of the battery at various power levels, as shown in Figure 7.

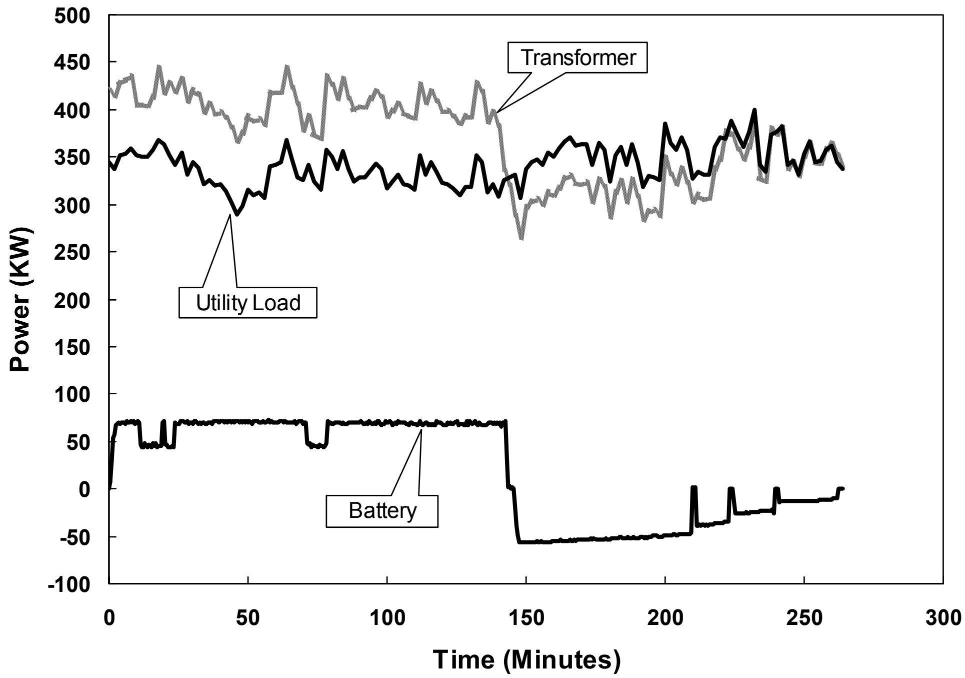

Figure 7. Power Profiles of Lum Sub-station and ABESS

Automatic control of the ABESS for peak shaving application was demonstrated for lower power level trigger points. The ABESS trailer was left on site for full-power testing in the summer of 2002.

CONCLUSIONS

Because the ABESS was undersized for this particular location, the voltage drop on the line due to the startup of the Akron grain dryer was not completely eliminated. Based on data from a similar site, it was believed that the 200-kVA ABESS would be sufficient for this application, but it was later discovered that the grain dryer caused an 800-kVA drain on the circuit. The power output of the ABESS was limited to 200 kVA, the size of the PCS.

Overall, these two projects successfully demonstrated the use of the zinc/bromine ABESS for power quality applications. By utilizing real and reactive power, the ABESS effectively compensated for voltage variations on both the PCS and grain dryer sides of the electrical system. Even though line droop voltage regulation for motor starts can be economically accomplished by VAR compensation capacitor banks, the PCS and battery can also compensate for line voltage surges from motor stops. Also, the combination of VAR compensation and peak power shaving capabilities make ABESS a versatile tool for utilities with localized power quality issues. The mobility of the ABESS trailer makes it ideal for seasonal power quality applications.

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