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Development of a High-Voltage, High-Power Thermal Battery

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Abstract

The power requirements for an inverter application were specified to be 500 V at 360 A, or 180 kW per each of six 1-s pulses delivered over a period of 10 minutes. Conventional high-power sources (e.g., flywheels) could not meet these requirements and the use of a thermal battery was considered. The final design involved four, 125-cell, 50-kW modules connected in series. A module using the $LiSi/CoS_2$ couple and all-Li (LiCl-LiBr-LiF minimum-melting) electrolyte was successfully developed and tested. A power level of over 40 kW was delivered during a 0.5-s pulse. This translates into a specific power level of over 9 kW/kg or 19.2 kW/L delivered from a module. The module was still able to deliver over 30 kW during a 1-s pulse after 10 minutes.

Introduction

Working with an outside customer, we initiated an effort to design and develop a thermal battery that was beyond the limits for this technology. The battery was required to deliver multiple 360-A pulses of between one and five seconds each at a working voltage of 500 V—a power delivery of 180 kW—over an operating time of 5-10 minutes. A specific power of at least 7 kW/kg was targeted.

This paper describes the development and testing of a 125-cell, high-power (>40 kW) thermal-battery module to be used to build the first 180-kW thermal battery. The resolution of challenging electrochemical as well as mechanical issues, including testing are discussed.

Experimental

Test Procedure – Since the necessary 50-kW electronic load was not available for testing of the 125-cell battery, a fixed-resistance load was used instead. The experimental setup is shown schematically in Figure 1. A nominal 0.6-ohm load bank (Avtron) was connected across the battery through a 500-A/400-V power relay (Kilovac Corp.). The relay, in turn, was controlled by a power supply across the coil leads.

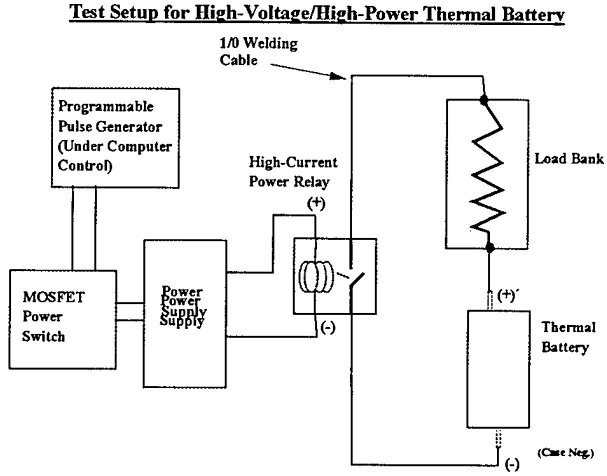

Figure 1. Schematic of Experimental Setup Used to Test 125-Cell High-Power Thermal Battery.

The duration of the applied pulse was determined by the width of the pulse supplied by an HP8116A pulse generator to turn on a MOSFET switch circuit to the power supply. The battery was connected to the load bank using 1/0 welding cable and copper collets connected to the copper feedthroughs in the header. (See Materials section for details.)

The battery was activated under open-circuit conditions and a 1-s pulse was applied to the load every 60 s to determine the battery's power capability. (The first two pulses were 0.5 s.) This also allowed calculation of the internal resistance, including the resistance of the 16 feet of connecting cables.

The physical arrangement of the load setup is shown in Figure 2. The power relay is at the upper right corner on the load bank. The MOSFET switching box and the control power supply are on the opposite side. The battery was tested under ambient conditions.

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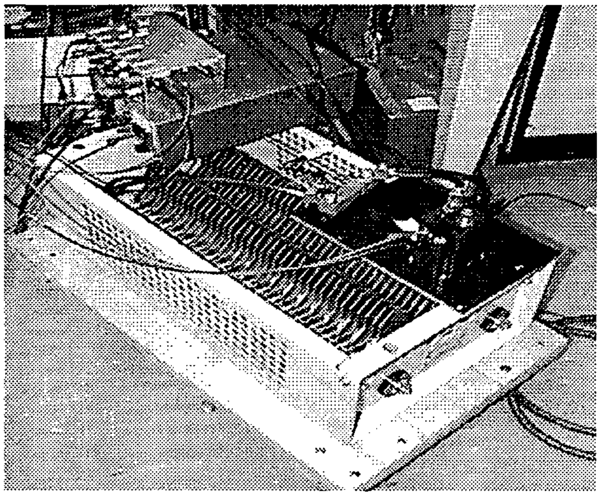

Figure 2. Photograph of Experimental Setup Used to Test 125-Cell High-Power Thermal-Battery Module.

Materials – For this application, the all-Li LiCl-LiBr-LiF electrolyte was selected because of its intrinsic high Li^+ conductivity. The anode contained 44% Li/56% Si alloy with 25% electrolyte and was 0.375 mm thick and weighed 1.95 g. The catholyte contained 73.5% CoS_2/25% separator/1.5% Li_2O and was 0.550 mm thick (with Grafoil backing) and weighed 6.6 g. CoS_2 was selected because of its high-rate capability. The separator contained 35% MgO and was 0.382 mm thick and weighed 4.1 g.

The stack diameter was 76.2 mm (3 in.) and was insulated with a 10-mm thick Min-K TE1400 sleeve. The heat pellets used were 84% Fe/16% $KClO_4$ and weighed 8.3 g. This corresponds to a heat balance of 108 cal/g ot total cell mass. The battery was ignited using three fuse strips of heat paper spaced 120 degrees apart along the length of the stack.

Results and Discussion

Design Issues – For the inverter application, the original design involved connecting four battery modules in series. Based on earlier rate-capability tests, it was determined that a stack diameter of 76.2 mm would be adequate for the intended application.[1] Since it was not practical to build a single battery that could deliver the requisite power, it was decided to use a modular approach. Four modules, each containing 125 cells, would be connected electrically in series. This design resulted in a 45-kW battery module at a load current of 360 A and a nominal voltage under load of 1 V/cell. The battery was instrumented with an internal thermocouple in the cell farthest removed from the header end.

Since there were no adequate electrical feedthroughs available commercially, it was necessary to design our own for test purposes. Ultimately, this issue will also have to be addressed, to allow commercialization of this design. A polyimide insert epoxied into a machined conventional header served as the header for the battery. The insert held tapered copper rods that served as the electrical feedthroughs. The rods tapered from 6.4 mm, at the end internal to the battery, to 4.8 mm, where connection was made to a copper collet attached to the welding cable.

Electrical connection from the stack to the feedthroughs was made via 0.254-mm-thick copper current collectors and 12.5 mm-wide copper braid. The braid was attached to the feedthroughs and current collectors by high-temperature silver solder. Figure 3 shows a picture of the parts before assembly into the battery.

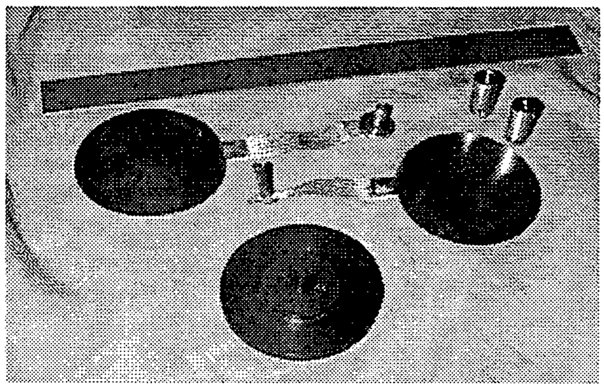

Figure 3. Copper Current Collectors, Braid, Collets, and Feedthroughs Used with Polyimide Header Insert. (A One-Ft. Ruler Is Also Shown.)

Figure 4 shows a full-length view of the battery and Figure 5 shows a close-up view of the header end. The battery was 279.5 mm (11 in.) in length, 101.2 mm (4 in.) in diameter, weighed 4.792 kg, and had a volume of 2.265 L. The negative end of the stack was connected directly to the case through a copper plug, to minimize voltage losses in the internal leads.

Electrical Performance – On activation, the battery reached 238 V in about 1.4 s. The steady-state voltage during pulsing of the battery is

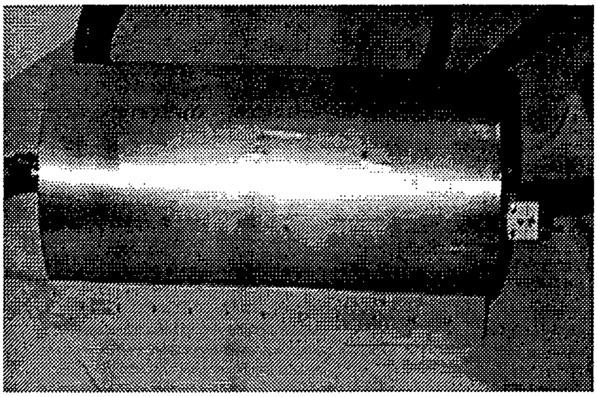

Figure 4. Lengthwise View of High-Power Thermal- Battery Module.

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Figure 5. Clasp View of Header End of High-Power Thermal-Battery Module, Showing Header Detail and Thermocouple.

shown in Figure 6. The voltage drop at ~360 s is a result of the phase transition in the Li-Si anode.

The maximum current measured across the load during pulsing is shown in Figure 7. (The first two pulses were 0.5 s and the remaining pulses were 1.0 s.) Currents of >260 A were obtained for the first six pulses during the first six minutes of discharge. This corresponds to a current density of 5.7 A/cm^2. This is well below the value of over 15 A/cm^2 measured during rate-capability testing with 31.8-mm diameter stacks.[1] (In earlier related tests, currents of 400 A, or 8.8 A/cm^2, were realized with a 10-cell stack 76.2 mm in diameter.)

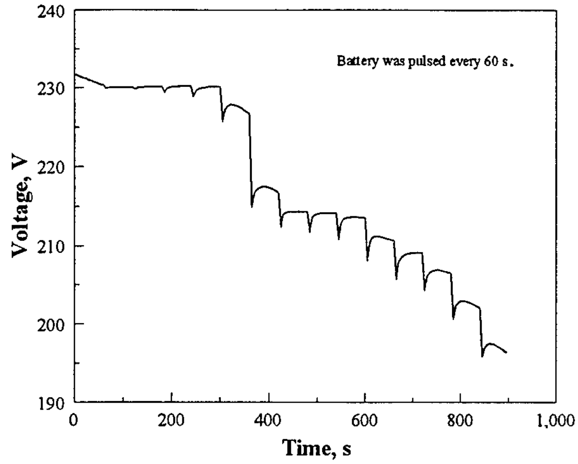

Figure 6. Steady-State Voltage of High-Power Thermal-Battery Module During Pulse Discharge Across Nominal 0.6-Ohm Load.

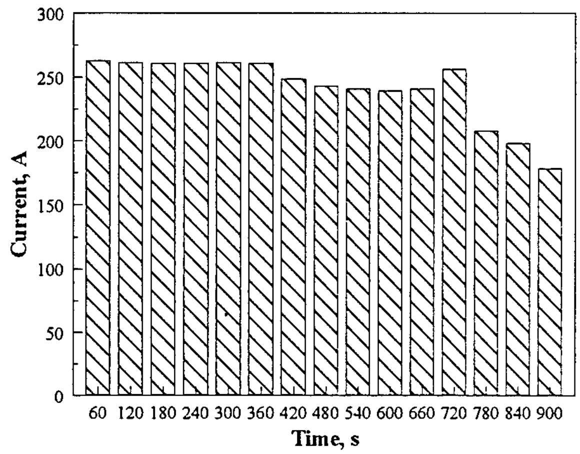

Figure 7. Pulse Currents During Testing of High-Power Thermal Battery Module.

The corresponding power and specific power delivered by the battery module are shown in Figure 8. During the first pulse, 43.6 kW was delivered which corresponds to a specific power of 9.09 kW/kg and a power density of 19.2 kW/L (955 W/cm^2). This is well below the maximum power capabilities of this system.

The internal resistance of the battery module during discharge is shown in Figure 9. The increase in resistance near 660 min is most likely due to the higher resistance of the first discharge phase that forms, Co_3S_4. This behavior has also been seen with FeS_2, where $Li_3Fe_2S_4$ forms as the first discharge phase in that system.[2]

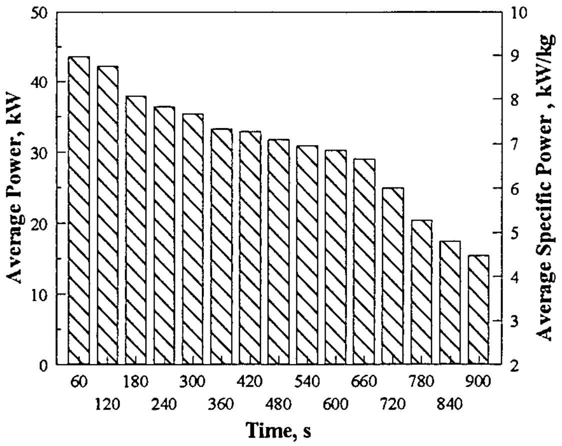

Figure 8. Power and Power Density of the High-Power Thermal-Battery Module.

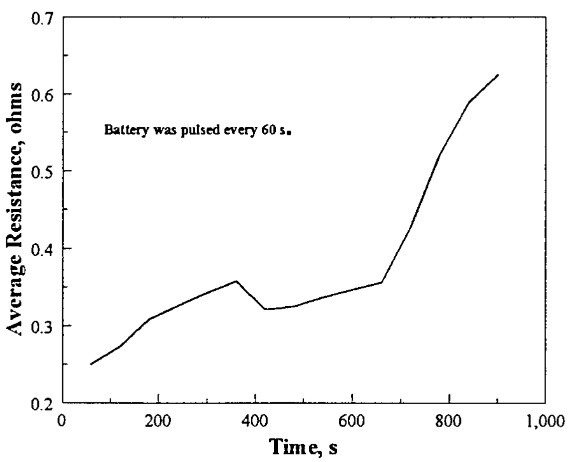

Figure 9. Internal Resistance of Battery Module (Including Connections and Leads) During Discharge.

The increase in resistance later in life is related to exhaustion of the capacity of the first discharge phase, and is not related to thermal effects, since the stack temperature actually increased during discharge due to Joule heating, as seen in Figure 10. The case temperature, however, remained relatively unchanged for the first 20 minutes.

Conclusions

A prototype, 125-cell, high-power thermal-battery module developed with the LiSi/LiCl-LiBr-LiF/CoS_2 system was capable of delivering over 43 kW during the first two 0.5-s pulses and over 30 kW during 1-s pulses after 10 minutes. The battery demonstrated a specific power of 9.09 kW/kg and

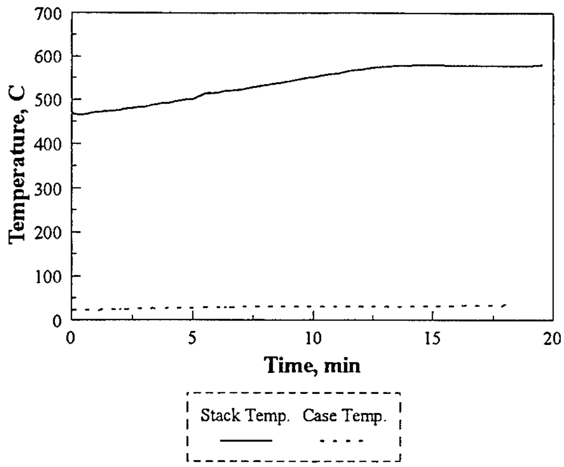

Figure 10. Internal and Case Temperatures of High-Power Thermal-Battery Module During Discharge.

a power density of 19.2 kW/L. To our knowledge, no one has previously reported power levels of this magnitude for this duration for a thermal battery.

Based on earlier related work, this system is capable of delivering even greater power in a smaller volume and with less weight. Tests are scheduled to realize the maximum power density that the battery module can deliver. Tests are also planned with multiple modules connected in series to deliver the full power of the battery pack as originally envisioned. Testing at these increased high voltages and power levels will require even more ingenuity and care than for a single module.

Acknowledgments

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