2011

A high frequency alternating current battery heater for military vehicles

Aaron Paul Bloomfield
The University of Toledo

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A Thesis

entitled

A High Frequency Alternating Current Battery Heater for Military Vehicles

by

Aaron Paul Bloomfield

Submitted to the Graduate Faculty as partial fulfillment of the
requirements for the Master of Science Degree in Electrical Engineering

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May 2011
Energy storage devices such as electrochemical batteries typically do not perform well at low temperatures where energy density and peak power suffer. One battery chemistry that is particularly susceptible to this phenomenon is lead-acid which is used predominantly in automobile and truck applications for cranking internal combustion engines during starting. Several approaches have been implemented to aid in cold engine cranking which include external battery preheat techniques as well as using temperature-independent parallel energy storage devices such as ultracapacitors.

An alternative approach proposed in U.S. Patent No. 6,259,229 teaches the use of alternating currents for internal heating of the battery electrolyte. This approach was examined and its implementation was studied for 24-volt battery systems intended for cold cranking diesel engines in large military vehicles. Prototype high-frequency heaters were developed and tested for operation in extreme cold climates to -40°C with peak-to-peak currents up to 600 Amps in the frequency range of 5 kHz to 50 kHz.

Experimental results demonstrate significant improvement in pulse discharge performance (approaching that of room temperature) using large alternating currents to
heat small and medium size battery packs. The research suggests a scale factor that relates the magnitude of heating current to the ampere-hour rating of the battery. However, for large battery packs it is estimated that currents may approach or exceed 1000 Amps peak-to-peak making a compact, cost-effective solution impractical. Additionally, an alternative approach was tested on a large-size battery pack which combines efficient low-current external and internal heating.
To my lovely wife, Karen, for her unwearied support, and to my little boys, Collin and Ethan, for their encouraging smiles.
Acknowledgments

This thesis was made possible first and foremost because of the loving support and sacrifice of my wife of eight years, Karen. The broader educational pursuit of the Master of Science degree in Electrical Engineering was challenging but made easier by her encouragement and that of my parents and family.

I extend an earnest thank you to my advisor, Dr. Tom Stuart, for his thoughtful guidance, insight, and critique of the research, and to my committee members Dr. Mohsin Jamali and Dr. Richard Molyet. I also thank Tom Jacob for his help with laboratory supplies. Fellow graduate students, Casey Theman, and, especially, Wei Zhu, provided invaluable assistance and encouragement.

Additionally, I thank Hartsel Bryant of Northwest State Community College for the expertly machined parts and newfound friendship. And, lastly, I thank Anthony Palumbo, Associate Professor Emeritus of Bowling Green State University, for his mentorship, friendship, and interest in the subject.
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Chapter 1

Introduction

1.1 Background

Energy storage devices such as the electrochemical battery typically do not perform well at low temperatures where energy density and peak power suffer. One battery chemistry that is particularly susceptible to this phenomenon is the lead-acid used heavily in automobile and truck applications for cranking internal combustion engines during starting. Engine cranking in extreme cold climates to -40 °C requires additional power and energy that a cold battery may not provide.

Methods have been implemented to improve battery performance in cold engine cranking that include preheat techniques as well as using temperature-independent parallel energy storage devices such as the ultracapacitor [1]. Strategies for battery preheating using electric current have been demonstrated over several decades and include external and internal heating methods. Previous techniques employed heavy and expensive equipment not suitable for on-vehicle use or less effective external resistive heating elements.
A primary objective of preheating a cold battery using the method proposed in this study is to render it serviceable in engine cranking when exposed to subzero environments. Additionally, the method can maintain the internal core temperature of the battery to allow proper charging and continued serviceability. Algorithms implemented in control logic can provide for this and other advanced functionality. Strategies using a parallel ultracapacitor for assisting engine cranking in cold climates do not have this potential.

The work presented here improves on previous core heating techniques in the development of a high-frequency alternating current device for on-vehicle use. The method circulates alternating current through the battery terminals to warm the electrolyte within, and utilizes waste heat from the process to provide some external heating. Lead-acid battery packs of various types and ampere-hour (Ah) sizes, namely 7.5 Ah, 24 Ah, and 50 Ah, were tested and evaluated for improvement in pulse discharge current when subjected to a cold environment. Figure 1-1 depicts a large military vehicle representative of one that might be deployed in the extreme cold and require battery heating.

Figure 1-1: Large military vehicle representative of the target application [2]
1.2 Objectives

A key focus of the research was on maximizing the pulse current capability of lead-acid batteries in cold climates down to -40 °C. The objective was to get the performance close to that at room temperature using a high frequency alternating current through the battery terminals. A desired outcome of the research was the development of a prototype integrated heating device suitable for conditioning 24-volt battery systems on military vehicles deployed in the extreme cold. The following were specific objectives of the study.

- Develop a prototype alternating current battery heater with integrated control and power electronics to be close-coupled to batteries under test in ambient temperatures to -40 °C.

- Provide a means of programmable feedback control to allow automatic operation of the heater using process variables such as: battery voltage, case and ambient temperatures, internal resistance, and inductor current.

- Design a self-contained heating system to enable 24-volt battery packs to deliver maximum rated current in a -32 °C environment with up to 90 minutes of conditioning.

- Evaluate pulse discharge performance improvement in three sizes of lead-acid battery in the range 7 Ah to 50 Ah.

- Investigate whether a fully charged battery at -40 °C can self-power the heater and still provide rated discharge current once heated, without being simultaneously charged.

- Identify a relationship between the magnitude of peak inductor current and battery heating time relevant to ampere-hour rating and ambient temperature. This is the designated Peak Current Factor.
Chapter 2

Background and Previous Work

2.1 Lead-Acid Battery

Lead-acid batteries are the oldest type of rechargeable battery, invented by a French physicist Gaston Planté in 1859. [3] This battery chemistry offers high surge current capability for high power-to-weight ratio but suffers low energy density. The low cost and high power makes the lead-acid battery attractive in motor vehicle applications to supply current to the starter motor during engine cranking. A typical lead-acid cell has an electrical potential of around 2.0 volts. A nominal 12-volt automotive battery then is comprised of six cells in series.

Each lead-acid cell contains electrodes of lead metal (Pb) and lead (IV) dioxide (PbO₂) in an electrolyte of sulfuric acid (H₂SO₄) in the charged state. [3] When discharged, both electrodes of the cell turn into lead (II) sulfate (PbSO₄) and the electrolyte becomes primarily water with the loss of dissolved sulfuric acid. As such, the electrolyte is more likely to freeze as the battery discharges and the concentration of sulfuric acid decreases. About 60% of an automotive lead-acid battery by weight is lead
Various types of lead-acid batteries exist and are broadly separated into two categories, deep-cycle and SLI (Starting, Lighting, and Ignition). Deep-cycle batteries are constructed such that repeated full discharges, 80% to 100% depth-of-discharge (DOD), do not significantly reduce expected service life. The SLI batteries in contrast are designed for higher power at shallow DOD. Repeated full discharges of such non deep-cycle batteries severely hamper the longevity of the battery. Typical applications of deep-cycle batteries include stand-by or stationary use as in electrical backup systems or as traction batteries in vehicles. SLI batteries are primarily used for engine cranking in automotive applications and to support auxiliary low-power electrical loads.

Lead-acid batteries are available primarily in one of two formats that being the flooded or “vented” wet-cell (shown in Figure 2-1 above) and the valve regulated lead acid (VRLA), also known as the “sealed” lead-acid (SLA). The flooded wet-cell battery has liquid electrolyte that covers all internal components and removable vent caps to
allow the escape of gasses and the periodic addition of water that is lost during the charging process. In addition to requiring periodic service, the electrolyte can leak and spill posing a physical hazard. The so-called maintenance free VRLA, in contrast, utilizes a dilute sulfuric acid electrolyte that is immobilized so as to eliminate leakage and spillage and to facilitate an oxygen recombination cycle. [5] The oxygen recombination cycle minimizes gassing and eliminates the need to add water to the electrolyte which makes vent caps unnecessary. As a fail-safe measure, non-serviceable pressure relief valves are present to prevent excessive build-up of gasses.

The VRLA battery is further classified by the particular “starved-electrolyte” design, gel or absorbed glass mat (AGM). The gel cell battery has a sulfuric acid electrolyte turned gelatinous by the addition of silica fume to render it immobile. The AGM battery on the other hand uses a finely woven fiberglass mat to trap the liquid electrolyte. The mat does not absorb the electrolyte but only serves to immobilize it and bring it in contact with the cell plates. [6] The VRLA battery construction has many advantages over the traditional wet-cell design and as such is used in many high performance power applications. Figure 2-2 below illustrates VRLA batteries of the AGM type. Shown on the left is a typical 12-volt 7.5 Ah SLA used in uninterruptable power supply (UPS) applications. Shown in the center and right, respectively, is the 50 Ah Optima Red Top 34R SLI and the 55 Ah Optima Yellow Top D34/78 dual deep-cycle/SLI, both of spiral-wound construction [7].
A common measure of relative battery size is the ampere-hour (amp-hour, Ah) rating which refers to a battery’s electrical storage capacity. The ampere-hour is a unit of electric charge, equivalent to 3600 coulombs (C), transferred by one amp of current flowing for one hour [8]. The amp-hour rating of a battery by convention is given for a 20-hour discharge to 100% depth-of-discharge. [9] For example, a 20 amp-hour battery could supply 1 amp of current continuously for 20 hours before full discharge. The parameters of the rating may vary depending on the application and manufacturer with a DOD in the range of 80% to 100% and hours less than and greater than 20. [10]

The capacity of the lead-acid battery will vary with temperature and rate of discharge yielding an effective capacity that can be more or less than its amp-hour rating. Higher discharge currents and lower temperatures work to lower this effective capacity. The Peukert Equation is an empirical relation discovered in 1897 that describes the diminished capacity of a particular battery with increasing current. [11, 12] Figure 2-3 and Figure 2-4 below illustrate the effective amp-hour capacity of typical lead-acid batteries across various discharge rates and temperatures, respectively.
Specific to engine cranking batteries is the Cold Cranking Amps (CCA) rating. This identifies the maximum continuous amperage that can be supplied by the battery for 30 seconds at 0 °F while maintaining useful voltage. The CCA is generally unrelated to amp-hour capacity and may indicate a measure of internal resistance of the battery design. The reserve capacity is another useful rating of lead-acid batteries and is industry defined as the time to reach 1.75 V per cell at a 25 A discharge. [7]
Two factors that have particular impact on battery capacity and service life are charging and maintenance. According to [10], the most common cause of premature loss of capacity in deep-cycle batteries is over- and undercharging. In a flooded battery overcharging can evaporate the electrolyte causing the lead plates to become dry. If the maximum charge voltage is exceeded with an AGM or gel type battery gas pockets can form around the plates causing permanent damage. Undercharging can cause lead sulfate to form on the plates and prevent or slow necessary chemical reactions.

Figure 2-5 below is a simplified equivalent model of a typical lead-acid battery suggested by [13] that can be used for electrical analysis.

\[ \text{Figure 2-5: Simplified lead-acid battery model [13]} \]

### 2.2 Principles of Alternating Current Heating

The lead-acid battery can be electrically modeled as an ideal voltage source in series with a variable resistor as shown in Figure 2-5. The resistance is comprised of two elements representing the coulomb resistance and overvoltage equivalent resistance. The electrical resistance results from the chemical reaction between the electrolyte and electrodes. At cold temperatures the chemical reactions slow and effectively increase the
resistance. Conversely, warmer temperatures allow faster chemical reactions and decrease internal resistance. In addition to temperature the internal resistance of the battery is affected by the battery state-of-charge (SOC), generally increasing with lower SOC. The increased resistance of a cold battery hampers discharge and charge currents from those at room temperature. At extremely low temperatures the voltage drop across the internal resistance, according to Ohm’s Law, may be significantly high so that only a fraction of open circuit voltage (OCV) can be applied to external circuits. Also, during charging at low temperature, even relatively low direct current (DC) can cause an overvoltage condition that may lead to gassing of the electrolyte and permanent damage. With valve-regulated or sealed batteries the case may rupture under excess pressure. [13]

According to Ohm’s Law, electric current flowing through a resistor will dissipate energy in the form of heat. The power dissipated is a function of resistance and the square of current. This fact, along with the inherent resistance of the lead-acid battery, can be exploited as an internal heat source. Direct current through the battery for heating has been shown not to be useful and may be harmful to the battery [13]. Alternating current (AC), however, is well accepted by the battery and does not pose immediate risk. The root-mean-square (RMS or rms) value of the alternating current is the equivalent direct current used to calculate the resistive heat loss. The alternating current, which both charges and discharges the battery in each cycle, can be supplied externally or generated by the battery itself. However, an external energy source is typically used to maintain a desired SOC during internal battery heating.

In the proposed AC heater, the heating current is generated by a pair of batteries using a half-bridge switching converter at relatively high frequency together with an
external DC source. Referring to the simplified half-bridge switching circuit of Figure 2-6, semiconductor switches Q1 and Q2 are gated on and off in opposition to cause current to flow in and out of each battery B1 and B2. An inductor L1 provides nearly lossless temporary storage of energy that is transferred from one battery to the other on each half cycle. Diodes D1 and D2 (which mirror the inherent body diode of the MOSFET switches Q1 and Q2) provide paths for inductor current at switch turn-off. An explanation in detail of this energy flow is found in [14].

Figure 2-6: Simplified half-bridge switching circuit as in proposed AC heater

Figure 2-7 below is a representative oscilloscope plot of inductor heating current with the conducting device highlighted.

Figure 2-7: Scope plot of inductor current showing conducting device
Heating power is determined by the internal resistance of the battery and also the RMS value of the circulating current squared. The battery current can be approximated following that of the inductor which is triangular having an RMS value as in (1.). The battery current is sawtooth with a duty factor of 0.5 having an approximate RMS value as in (2.). [15]

Approximation of RMS inductor current:

$$I_{L \text{rms}} = \frac{I_{L \text{peak}}}{\sqrt{3}} \quad (1.)$$

Approximation of RMS battery current:

$$I_{B \text{rms}} = \frac{I_{L \text{peak}}}{\sqrt{3}} \cdot \sqrt{D} \quad (2.)$$

where $D = \text{duty cycle}$

The size of the inductor is application dependent and is correlated to the desired peak current and operating frequency. (3.) estimates peak inductor current based on the value of the inductance. Sample values of current at various frequencies are calculated in Table 2.1.

$$v_L = L \frac{di}{dt}$$

$$v_L = v_{batt}$$

$$\frac{di}{dt} = \frac{I_{L \text{peak}}}{\left(\frac{1}{4} f_L\right)} = \frac{I_{L \text{peak}}}{\left(\frac{1}{4 f_L}\right)}$$

$$L = \frac{v_L}{\frac{di}{dt}} = \frac{v_{batt}}{4 f_L I_{L \text{peak}}}$$
Approximation of Peak inductor current:

\[ I_{\text{peak}} = \frac{V_{\text{batt}}}{4f_L L} \]  

Table 2.1: Sample calculated current and frequency for \( V_{\text{batt}} = 14 \text{V}, L = 2.5 \mu \text{H} \)

<table>
<thead>
<tr>
<th>( f_L ) (kHz)</th>
<th>( I_L ) pk (A)</th>
<th>( I_L ) rms (A)</th>
<th>( I_B ) rms (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>28.0</td>
<td>16.2</td>
<td>11.4</td>
</tr>
<tr>
<td>40</td>
<td>35.0</td>
<td>20.2</td>
<td>14.3</td>
</tr>
<tr>
<td>30</td>
<td>46.7</td>
<td>26.9</td>
<td>19.1</td>
</tr>
<tr>
<td>20</td>
<td>70.0</td>
<td>40.4</td>
<td>28.6</td>
</tr>
<tr>
<td>10</td>
<td>140.0</td>
<td>80.8</td>
<td>57.2</td>
</tr>
<tr>
<td>5</td>
<td>280.0</td>
<td>161.7</td>
<td>114.3</td>
</tr>
</tbody>
</table>

2.3 Review of Previous Work

The poor performance of the typical electrochemical battery at extreme low temperatures has long been known. Strategies for battery preheating using electric current have been demonstrated spanning several decades and include external and internal heating methods. A search of early U.S. patents issued for methods of battery heating using electric current reveals several patents. [16, 17] For example, Patent 2,442,380 filed by J.P. Schrodt et al in 1942, entitled “Method and system for warming dry batteries,” details several techniques for internal core heating using alternating currents. Patent 2,710,937, filed in 1952 by Godshalk and Lowry, describes an internal battery-heating scheme where the battery itself is the source of alternating heating currents and is targeted to military vehicles in the field.

Another patent filed in 1993 by Vanderslice, Jr. et al, 5,362,942 entitled “Battery heating system using internal battery resistance,” alludes to a closed loop temperature
control circuit that provides for DC charging and AC heating of batteries in cold climates. More recent patents by Ashtiani and Stuart, 5,990,661 and 6,259,229, jointly held by the University of Toledo (UT) and Chrysler Corporation, disclose modern techniques modeled after these older concepts.

In 2002, A. Hande of the University of Toledo presented work based on the above mentioned patents by Ashtiani and Stuart in his Ph.D. dissertation [13]. Hande successfully demonstrated the internal core heating of lead-acid and nickel metal-hydride batteries using alternating current, sourced from the 60Hz utility line and also from a higher frequency switching converter. Results showed that low frequency utility current was effective at warming batteries. The equipment however was heavy and expensive and not suitable for on-vehicle implementation. A high frequency version was also investigated for use with higher voltage nickel metal-hydride battery packs.

The subject of battery heating has also been the focus of many studies by entities such as the National Renewable Energy Lab (NREL). The development of electric and hybrid-electric vehicles using battery technology has necessitated the need for thermal management including active heating in some climates. A paper written in 2002 by Pesaran of NREL and Vlahinos of Advanced Engineering Solutions investigates preheating methods using thermal models of a battery pack [18]. Finite element modeling was used to study four strategies including internal core heating, external and internal jacket heating using electric heaters, and internal fluid heating using hot air or liquid. Results of the thermal modeling suggest that the most efficient method of battery heating is internal core heating using alternating currents through the terminals, with early work by Stuart and Hande cited. A follow up study in 2003 entitled “Cooling and
Preheating of Batteries in Hybrid Electric Vehicles,” authored by Pesaran, Vlahinos, and Stuart, further investigates internal core heating and includes results of laboratory testing at UT [19].
Chapter 3

Test Method and Apparatus

3.1 Test Method and Evaluation

An important aspect of this study was the evaluation of pulse discharge performance of battery packs at extreme cold temperature and the improvement resulting from battery heating. An environmental chamber was used to soak a 24-volt battery pack, consisting of two 12-volt batteries in series, at the desired test temperatures of -40 and -32 °C. Once the battery core temperature stabilized at the set point, usually after twelve or more hours, a baseline discharge test was performed using a resistor load to simulate the high currents associated with engine cranking. The resistor load bank was selected such that the discharge current could meet or exceed the cold cranking amp (CCA) rating of the battery. During a 5-second pulse discharge test, pack voltage and current were measured and recorded using an HP 54600-series dual-channel digital oscilloscope. A plot image and raw data from the oscilloscope were then transferred to a personal computer (PC) for characterization and analysis using spreadsheet software. Prior to exposing the battery pack to the extreme cold temperature, a pulse test was executed to establish a baseline of room temperature performance.
After establishing the low temperature baseline, the battery pack was subjected to heating before undergoing another pulse test at elevated core temperature. The environmental chamber maintained the ambient temperature to the desired low set point. Again, data captured by the oscilloscope was transferred to the PC and saved to file. The heat-then-discharge cycle continued on the pack until the maximum core temperature was reached, or room temperature performance was achieved, or the maximum heating time elapsed. Heating time thresholds of 20, 40, 60, and 90 minutes were typical after which a pulse discharge was performed.

It is important to note that the battery state-of-charge was held to nearly 100% during the low temperature soak and subsequent heating cycles. The battery SOC affects the internal resistance and therefore the current delivered under resistive load as indicated in Chapter 2. Maintaining maximum SOC across all battery tests eliminated a variable and provided more comparable results. An external DC power supply served to charge the battery pack at an approximate float voltage of 28 V while under test, excluding the pulse discharge phase. This is consistent with the target application in which a battery charger would be operated in tandem with the heating device.

The charger replenishes energy lost to heating the battery core and in the heater itself. For the 24 Ah battery pack, the charger provided up to 30 A of charge current in order to maintain a full state-of-charge during high current heating. In some instances, the charger was found to be undersized during testing such that the SOC of the pack fell below 100%. And, in one heating test, the charger was purposefully disconnected from the pack to evaluate pulse performance at a charge state well below maximum.
The experimental heater test system consisted of four main components: an environmental chamber in which to cool the battery pack under test, an inverter to supply the alternating current for heating, a pulse discharge resistor, and an external battery charger to maintain SOC near 100%. Early testing on the 7.5 Ah and 24 Ah battery packs utilized an inverter decoupled from the pack and outside the chamber as in Figure 3-1. Later testing utilized an inverter close-coupled to the 24 Ah and 50 Ah packs inside the chamber. Additional selected photographs of the various experimental setups appear in Appendix II.

![Laboratory setup for preliminary testing of 7.5 Ah batteries](image)

Figure 3-1: Laboratory setup for preliminary testing of 7.5 Ah batteries

The block diagram of Figure 3-2 shows a simplified view of the early heating system and test apparatus with the inverter outside the chamber. The red rectangle to the left illustrates the half-bridge power circuit and the gate drive logic (without the feedback circuits shown). The blue rectangle in the center shows the battery pack under test in the environmental chamber. The green rectangle on the right is the external charger that maintains the battery pack near 100% SOC with a relatively large inductor in series to
block the high frequency alternating current. The dotted oval illustrates the discharge load used to provide current pulses as in engine cranking. Fuses offer protection from excessive currents during heating in each battery circuit as well as the charging circuit. The load and L1 inductor are selected to match the battery pack rating.

A procedure for testing and evaluating heating effectiveness and resulting battery performance was followed. A representative nine-step procedure appears below.

1. Charge battery pack to 100% SOC at room temperature.
2. Perform 5-second pulse discharge test and record current and voltage profile.
3. Chill batteries in environmental chamber to -40 °C for at least 12 hours, and maintain 100% SOC.
4. Perform 5-second pulse discharge test and record baseline current and voltage profile.
5. Begin heating cycle and adjust frequency for desired test current.
6. Stop heat at time interval and perform 5-second pulse test as above.
7. Resume heating cycle and adjust frequency for desired test current.

Figure 3-2: Simplified diagram of early heater system and test apparatus
8. Repeat steps 6 and 7 until room temperature performance is reached, or battery temperature limit is exceeded, or maximum heating time has elapsed.

9. Plot discharge curves.

Several measurements were taken at periodic intervals throughout testing activities and are indicated as test points on the diagram of Figure 3-2. Note that not all test points appear on the diagram but do so in Table 3.1. Data was recorded in test logs of which a sample is shown in Figure 3-3 for 50Ah battery testing.

Table 3.1: Test points monitored during heating cycles

<table>
<thead>
<tr>
<th>Test Point</th>
<th>Description</th>
<th>Test Point</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP1</td>
<td>Voltage, Q2 drain</td>
<td>TP7</td>
<td>Current, charger</td>
</tr>
<tr>
<td>TP2</td>
<td>Voltage, Q1 drain</td>
<td>TP8</td>
<td>Voltage, charger</td>
</tr>
<tr>
<td>TP3</td>
<td>Current, L1 inductor</td>
<td>TP9</td>
<td>Temperature, battery case</td>
</tr>
<tr>
<td>TP4</td>
<td>Voltage, B1 positive</td>
<td>TP10</td>
<td>Temperature, chamber</td>
</tr>
<tr>
<td>TP5</td>
<td>Voltage, B2 positive</td>
<td>TP11</td>
<td>Frequency, inverter/heater</td>
</tr>
<tr>
<td>TP6</td>
<td>Current, load resistor</td>
<td>TP12</td>
<td>Temperature, inv. heatsink</td>
</tr>
</tbody>
</table>

Figure 3-3: Sample data log for 50 Ah battery pack testing
3.2 Environmental Chamber

To subject the battery pack to the extreme cold environment of the target application a temperature chamber was used. Initial testing on the small and medium-size battery packs used a Tenney Jr. chamber with about a 1 cubic foot temperature-controlled workspace measuring approximately 15” W x 11” H x 10” D. The chamber is pictured in Figure 3-4. It was just powerful enough to maintain the chamber at -40 °C throughout the heating cycles with the small and medium-size packs. Figure 3-5 shows, respectively, the 7.5 Ah SLA (Transcontinental SL1275) and 24 Ah wet-cell (Dynalite UIL-250) battery packs ready for testing in the chamber.

Figure 3-4: Small environmental chamber used in early testing, the Tenney Jr.

Figure 3-5: 24 Ah and 7.5 Ah battery packs ready for testing in the chamber
A second environmental chamber, a Test Equity 1027C with a 27 cubic foot workspace measuring 40” W x 32” H x 36.5” D, pictured in Figure 3-6, was used for testing the large 50 Ah Optima Red Top 34R battery pack. The temperature range of the chamber was roughly -70 °C to +175 °C and had plenty of cooling power for maintaining test temperature. Figure 3-6 also shows the 50 Ah battery pack ready for testing in the chamber.

Figure 3-6: Large environmental chamber, the Test Equity 1027C, and 50 Ah pack

3.3 Resistor Load Bank

The resistor load bank pictured in Figure 3-7 below was constructed to provide a means to pulse discharge the small-size battery packs. A single 200 W-rated 0.1 Ohm resistor was sufficient for the 7.5 Ah pack to draw test currents up to 160 A for a 5-
second pulse. At room temperature, the 24-volt 7.5 Ah pack delivered an impressive peak power of 2.8 kilowatts. This current magnitude may have exceeded the designed capacity but was used for consistency with an earlier test by another researcher at UT, Casey Theman.

The rated cold cranking amps of the 24 Ah pack dictated a nominal resistance of about 0.05 Ohms. Eight 240 W-rated 0.1 Ohm resistors in series-parallel accomplished this and provided for currents up to 350 A. Peak power from the 24 Ah pack was nearly 7.0 kilowatts. In each configuration a contactor was used to control the pulse current which was measured using a LEM current transformer with output scaling of 2.5 A/mV.

Figure 3-7: Discharge resistor bank used with 7.5 Ah pack, 0.1 Ω

The CCA rating of the 50 Ah Optima pack exceeds 800 A for extremely high peak power. As such, a robust discharge load bank was constructed using two large resistors made by General Electric for use in locomotive dynamic braking applications. The high current discharge apparatus is shown below in Figure 3-8. Strips of aluminum sheet metal were fabricated to segment each resistor into three parts. The parallel configuration of four segments from the two resistors yielded a total resistance of about 0.015 Ohms.
and easily handled pulse currents up to 1000 A for a 5-second discharge. Peak power of the 24-volt pack at room temperature was a remarkable 18 kilowatts.

The load bank was switch-configurable for two levels of resistance such that a step change in current could be achieved. The step change enabled the accurate calculation of internal battery resistance using Ohm’s Law. Contactors selected a single resistor or two in parallel for a two-stage load of 0.030 Ohms and 0.015 Ohms, respectively.

Figure 3-8: Two-stage high power resistor bank used with 50 Ah pack, 0.015/0.030 Ω

Battery pack voltage and current measurements were taken during a pulse discharge test. Current was measured using a Nana/LEM Hall-effect current transformer, HEC-06A, with output scaling of 4V/600A. The resulting time-based plot revealed the power profile of the discharge event. Figure 3-9 below is a representative screen print captured from the oscilloscope used to record the 50 Ah room temperature discharge. Channel 1 is pack voltage at 5 V/div and Channel 2 is pack current at 300 A/div. Notice the step change in current that was used to quantify actual internal resistance of the batteries.
3.4 High Frequency Heater

Significant research effort was devoted to the design and development of the inverter/heater device. Several iterations of the heater were developed and tested from low current versions using external benchtop controls to high current integrated devices ready for the -40 °C environment. Hardware development and testing concentrated on two focus areas: high current “internal” heating and low current “external/internal” heating, using resistors in one version and iron-core inductors in another.

3.4.1 High Current “Internal” Heater

The initial testing of the high frequency alternating current heater began on the small 7.5 Ah battery pack. The previous researcher at UT developed a half-bridge inverter to circulate current through the batteries up to 80 A peak-to-peak. The gate logic was executed in hardware (suggested by [13]) requiring an external power supply and a frequency generator to provide clock pulses. The MOSFET power section was separate.
from the logic and gate driver board and was connected to the battery pack via a relatively long cable run.

Early results of testing indicated the need to increase the magnitude of circulating current. The author of this study upgraded the power section and inductor such that high current occurred at frequencies above 5 kHz as opposed to the previous 1 kHz. Adjustments were made to the control via trim pots to change the deadband and minimum frequency. The power leads to the batteries in the chamber were shortened and made heavier gauge to accommodate heating currents up to 200 A peak-to-peak. Figure 3-10 shows the inverter MOSFET switches and gate logic/driver board during early bench testing.

Figure 3-10: Early inverter for currents up to 200 Ap-p with 7.5 Ah pack

The larger 24 Ah battery pack required necessarily higher circulating current to increase its core temperature at the same rate as the 7.5 Ah pack. A new inverter was constructed to provide currents up to 550 A peak-to-peak, and at higher frequency, that the previous inverter could not. It was desirable to build a more integrated device and one that could be tested in the chamber along with the batteries. This would allow
shorter power leads and better overall efficiency. Figure 3-11 shows the prototype inverter, on the left, with paralleled MOSFETs and onboard gate driver circuit visible with the heatsink removed. Mounted to the board was a stout air-core inductor, passive snubber circuits to protect the switches, and fuses in each battery leg. Frequency (and current) adjustment was provided by the external gate logic circuit from the previous 200 Ap-p controller.

![Figure 3-11: Higher current inverter for heating 24 Ah pack (heatsink removed)](image)

Figure 3-11 also shows the inverter as tested, on the right, modified for high current with increased DC bus capacitance and paralleled power inductors (of about 1.25 μH combined inductance), less MOSFET heatsink. Notice the muffin style cooling fan in the background necessary to keep the inverter components from overheating at maximum current. The polypropylene bus capacitor and copper board traces became especially hot during operation with the cooling fan off.

To handle the extremely high heating currents required of the 50 Ah Optima pack an improved low-profile and high current half-bridge controller was constructed. A single stand-alone package provided integrated control and power electronics and better
thermal management, measuring approximately 6”W x 8”D x 2”H including the power inductor. An attempt was made to capture waste heat from the inverter and direct it to the battery pack to supplement the high-current internal heating. The controller was designed as a low-profile “hotplate” on which the battery pack could rest. The power inductor and MOSFET heatsink were fabricated in such a way to create a warming plate between the controller and the bottom of the batteries. The inductor-heatsink, machined out of ½-inch aluminum plate, made an effective heatsink and yielded an inductance of less than 1.0 µH. Figure 3-12 and Figure 3-13 show the bottom and top, respectively, of the controller prior to testing in the chamber.

![Figure 3-12: Bottom side of low-profile inverter for 900 Ap-p heating](image1)

![Figure 3-13: Top side of low-profile inverter forming inductor-heatsink “hotplate”](image2)
3.4.2 Low Current “External/Internal” Heater

The hotplate concept following earlier experimentation by the researcher seemed a viable solution to providing external heat using low battery currents. The primary difference from traditional electric hotplates was the use of high frequency alternating current sourced from the battery pack itself. An original test of this notion utilized a low value power resistor (1 Ohm or less), attached to an aluminum plate, in series with an air-core inductor as the controller load. Battery current (on the order of Amps) through the resistor generated significant heat to bring the surface temperature of the plate to near 100°C. The inductor provided slower changes in current (di/dt) and served as an energy store between the batteries. A previously constructed controller was modified for low current operation and fitted with an aluminum plate on which the batteries sat, and this is pictured in Figure 3-14.

![Figure 3-14: Inverter configured as 150 W “hotplate” with 24 Ah pack on top](image)

In preliminary testing, the 24 Ah batteries warmed sufficiently to improve performance in pulse discharges. Hotplate temperature fell short of the 65°C target but managed nearly 45°C in the -40°C environment of the test chamber. Efforts to increase the hotplate temperature in the test chamber were taken. Various combinations of
resistors and inductors were evaluated to increase the power dissipated due to resistive loss. One concept that was pursued was a single inductor/resistor element using a coil of small gauge wire sandwiched between two thin aluminum plates. Fabrication of this element was not easy. In the end no combination of resistor value and size (wattage) was found to yield significantly higher hotplate temperature in the application.

A resulting observation was that the “lossless” air-core inductor was anything but. Despite attempts to optimize the wire size and inductance there was considerable heat generated by the inductor. Means to capture and/or redirect this waste heat to the hotplate were attempted with marginal results.

As an alternative, it occurred to the researcher to eliminate the resistors from the circuit and use only an iron-core inductor. Without resistors, the maximum current through the inductor could increase significantly and ultimately deliver higher heating power from the battery. Heat generated in the iron core primarily due to induction [20] could be transferred to the battery pack in addition to internal heating from circulating currents. In initial tests, a cylindrical steel rod was inserted in an air-core inductor which heated up quickly. Surface temperature of the rod reached greater than 100°C and actually melted part of the plastic bobbin. Various core materials and sizes were tested. Common cold-rolled steel provided a good balance of machinability and heat generation due to magnetic hysteresis and eddy currents.

Alternating currents of 15 to 20 A-rms at frequencies up to 50 kHz worked well at heating steel rods. The challenge was to transfer the heat to the battery in an efficient and cost-effective manner. An early attempt used magnet wire wound on a threaded steel bolt to form the inductor with threads left exposed to screw into a flat aluminum plate. This
transferred the heat well but created a vertical profile too tall as a hotplate. A second attempt used an aluminum plate with a half-round groove machined to accept a steel rod. The steel rod was turned in the center to a smaller diameter so that the coil of magnet wire was flush with the diameter of the ends. The steel-rod inductor was then held against the groove with a mechanical strap. This allowed for a flat profile with decent heat transfer to the aluminum plate.

These techniques provided a solution to the problem but neither was ideal. Both techniques relied on a hotplate platform on which to set the batteries that would replace or add to the standard battery mounting system. Insulation around the perimeter of the hotplate-battery interface would be advisable as the edges of the hotplate may be exposed. Also, the plastic case that surrounds the cells of the lead-acid battery is typically thicker at the bottom than the sides, making heat transfer through the bottom less efficient.

A better coupling technique was found in the spiral-cell construction of the Optima Red Top battery, a target of the study. The battery construction creates two cavities in the plastic case on the underside of the battery where adjoining cylindrical cells meet. The cavities run nearly the full height of the battery and expose the inner sidewall of each cell. The cells form a natural insulating barrier to keep the inner cavities isolated from the cold environment. Heater rods of the previous design were shortened to fit the length of the cavity (with one rod in each). Except for a small externally mounted controller, the heating system was concealed by the battery itself.
Several methods of conducting heat from the rods to the battery cells were attempted. The first method pressed a heater rod against the lengthwise crease between two inner cells. The heated steel rod was in direct contact with the polypropylene case with a chemical odor apparent after a short time, presumably from the case. A second method placed the heater rod lengthwise in the center of the cavity equidistant from each cell wall with an air gap separator. Air as the heat transfer medium necessitated a high rod temperature, 100 °C or higher, and provided slow heat transfer. The chemical odor did vanish however. The third method replaced air with vegetable oil in the cavity surrounding the heater rod. There was marked improvement in thermal transfer and lower rod temperature but making a liquid (oil) tight seal presented a challenge. The test was conducted with the battery upside down.

The fourth, and lab tested, method used an aluminum block to transfer heat from the steel rods to the cells. A block of aluminum the height of the cavity was machined to the profile of the cavity with a hole bored down the center. An inductive heater rod was then inserted into the tight fitting hole and the assembly pressed into the cavity. The aluminum block provided good thermal transfer without excessive rod temperature and was relatively lightweight and low cost. Variations using a thermally conductive casting material to replace the aluminum insert may reduce cost and complexity. Heater blocks (without core) are shown installed in the Optima Red Top battery in Figure 3-15 on the following page.
Two types of heater cores were tested with the aluminum blocks including the iron-core inductor and a commercially available resistive cartridge heater. The iron-core inductor was fabricated using a 6-inch long ½-inch steel rod and approximately 6 feet of 22 AWG magnet wire. The wire was wound around the center of the rod which had been turned so that the wire was flush with the outside rod diameter, with grooves machined lengthwise down the rod. Each hand-wound inductor measured approximately 4.3 \( \mu \)H of inductance at 10 kHz using a Wayne-Kerr LCR meter. For testing, two inductors were wired in series as a pair and the two pairs wired in parallel for a combined inductance of about 4.3 \( \mu \)H.

For comparison purposes a purely resistive heater core was tested at the same input power levels as for the inductor tests. Attempts at fabricating a suitable resistor in the lab of the proper wattage, resistance, and form factor proved troublesome. Using Nichrome wire (22 AWG) around the same iron core was difficult to provide the right combination of resistance and power handling without the wire glowing red hot or surface temperature becoming too high. There was also difficulty maintaining proper electrical isolation. In the end, commercially available industrial heater cartridges were procured. A 300 Watt
½-inch diameter by 5-1/2-inch long cartridge designed for 120V AC was selected. A DC power supply with voltages up to 60 V generated the target 50 W to 100 W per cartridge. Figure 3-16 and Figure 3-17 show the inductor and resistive heater cores, respectively.

Figure 3-16: Inductor heater cartridges installed in Optima Red Top

Figure 3-17: Resistor heater cartridges installed in Optima Red Top

A compact, integrated half-bridge controller was designed and developed to drive the low current “external/external” induction heater. The custom controller used a Microchip PIC-based logic section and MOSFET power section comprised of International Rectifier IRFP3306 HEXFET series switches. The controller was
programmable and had configurable inputs and outputs to enable automatic control of heating. However, for testing, the controller was programmed for manual control of switching frequency over a range of 5 to 50 kHz with a fixed duty cycle of 50%. Peak-to-peak currents of 70 A were typical at the float voltage of 28 V in the -40 °C environment. Figure 3-18 below is a picture of the hand-fabricated controller as tested on the 50 Ah battery pack.

![Custom half-bridge controller for low current AC heating](image)

Figure 3-18: Custom half-bridge controller for low current AC heating

Low current external/internal heating tests were conducted with and without an insulation wrap around the Optima pack to evaluate its effectiveness. The insulation used was 2-inch thick fiberglass duct insulation with foil back, Thermwell product SP55/6, with an R-value of 6. Figure 3-19 shows the insulated pack in the chamber.

![50 Ah Optima pack as tested with insulation wrap](image)

Figure 3-19: 50 Ah Optima pack as tested with insulation wrap
Chapter 4

Experimental Results

The following is a presentation of results of testing and is divided into results for each battery pack tested. Plots are presented that show the current profile in the 5-second pulse current test.

4.1 7.5 Ah SLA, SL1275

Initial testing of the AC battery heater began on a battery pack consisting of a pair of 12-volt 7.5Ah SLA batteries (Transcontinental Battery SL1275). Heating currents on the order of 90 A-peak (shown as 180 A-peak-to-peak) provided significant improvement in pulse performance after 20 minutes in a -40 °C environment at 100% SOC. Room temperature performance was nearly restored in the pack after approximately 40 minutes of heating at the same current level, as is shown in Figure 4-1 on the following page.
Two lower-current heating tests were conducted by the previous researcher at UT and are shown for comparison in Figure 4-2 on the next page. Circulating currents of 40 A-peak (shown as 80 A-peak-to-peak) improved performance after 30 minutes but well below that of the higher current heating after just 20 minutes. Heating was applied for an additional 30 minutes without an appreciable increase in performance indicating thermal equilibrium at that heating power.
Internal heating power can be approximated by multiplying the square of battery current, as in (2.), by the internal resistance of the battery. Figure 4-3 on the following page illustrates observed internal resistance versus case temperature calculated from pulse discharge measurements. Using a resistance of 55 mΩ and a peak inductor current of 90 A, the heating power was approximately 75 watts per battery. For the lower current test at 40 A peak inductor current, heating power was about 15 watts per battery.
4.2 24 Ah Wet-cell, U1L-250

Testing continued on a larger battery pack consisting of a pair of 12-volt 24 Ah wet-cell batteries (Dynalite U1L-250). The pack was heated using high-and low-level internal currents in -40 °C and -32 °C temperatures at 100% SOC. Tests were conducted with an insulation wrap of 1-inch fiberglass duct board, Type 475-FRK, having an R-value of 4.3. Figure 4-4 on the following page shows results of heating at high peak inductor currents of 265 A (shown as 530 A-peak-to-peak) at -40 °C. Significant improvement in pulse performance was achieved after nearly 30 minutes of heating, and almost room temperature performance was reached after 60 minutes.
Low-current heating of about 125 A-peak (shown as 250 A-peak-to-peak) versus 265 A-peak was carried out on the pack chilled to both -40 °C and -32 °C. Results are indicated in Figure 4-5 and 4-6, respectively. In both cases, approximately one hour of low-current heating resulted in pulse performance equal to that of the high-current heating after only 30 minutes. Low-current heating was applied again for an additional 30 minutes but did not significantly improve pulse performance indicating thermal equilibrium.
Figure 4-5: 24 Ah Wet-cell, low current internal heating at -40°C thermal soak

Figure 4-6: 24 Ah Wet-cell, low current internal heating at -32°C thermal soak

Figure 4-9 illustrates observed battery resistance versus case temperature calculated from pulse discharge measurements on the 24 Ah pack. Using a resistance of 15 mΩ and
an inductor current of 158 Arms, the heating power was approximately 185 watts per battery. For the lower current test at 85 Arms inductor current, heating power was about 55 watts per battery.

Results similar to the low-current internal heating tests were observed for the external/internal heating test in which a 150-watt hotplate was placed directly under the batteries. Figure 4-7 shows sizable improvement in pulse performance after 60 and 120 minutes of heating in the -40 °C environment. Figure 4-8 compares the performance enhancement of the low current internal heating, with inductor currents of 85 Arms, versus the external heating with inductor currents of about 12 Arms. It is noteworthy that for similar pulse performance the low current internal heating required about twice the charging power to maintain the pack at 100% SOC, indicated in Table 4.1 and Table 4.2.

Figure 4-7: 24 Ah Wet-cell, low current external heating at -40°C thermal soak
Figure 4-8: 24 Ah Wet-cell, internal vs. external low current heating at -40°C

Figure 4-9: 24Ah Wet-cell, battery characteristics vs. case temperature, ~100% SOC
4.3 50 Ah AGM, Optima Red Top 34R

A target battery of the study was the high performance Optima Red Top Group 34 engine cranking battery. The 12-volt Optima Red Top delivers exceptional cold cranking amps, in excess of 800 A, due in large part because of its extremely low internal resistance. The published internal resistance is 3 mΩ and as tested measured 3.5 mΩ at room temperature, as shown in Figure 4-17. For sufficient internal heating this means the magnitude of circulating current must be significantly high. As such, the improved low-profile high current inverter was constructed to heat the 50 Ah pack as discussed in Chapter 3.

Bench testing of the new controller was successful with peak currents up to 400A and roughly 200A constant using a primarily resistive load. Tests were conducted at and above room temperature with higher current capacity expected at subzero temperatures in the chamber. The circulating current heating test connected to the Optima pack did not go well however. The batteries, controller, and instrumentation were readied in the environmental chamber at room temperature. Initial tests were conducted successfully at moderate circulating current levels. However, just prior to beginning the low temperature soak the controller failed unexpectedly.

The half-bridge driver IC failed in a manner that allowed a short across one battery. Fusing from the battery terminal was not fast enough to break the excess current, likely in the 1000A range. The MOSFETs in the conducting leg overheated and self-destructed with flames resulting. The flames were extinguished immediately without incident and the remaining battery leads disconnected. Figure 4-10 that follows is a photograph of the failed controller after the flames were extinguished.
The International Rectifier IR2110 gate driver IC used here was troublesome from the beginning of the research. The gate drive behavior was suspect even with the original low current controller hand-built by the previous UT researcher. A replacement IC in the socket would clear any trouble. Subsequent gate driver boards using the IC were built using both the DIP and surface mount packages. In a few distinct cases the drive exhibited peculiar behavior prior to MOSFET failure, with normal circuit operation resuming after the blown switches and driver IC were replaced. The exact cause of the failures was not identified but the lack of confidence in the IC forced the use of an alternate gate driver, the Allegro A4940.

The Allegro gate driver seemed to be highly reliable in the subsequent low current external/internal heating tests. In an initial test, the pack was heated using low-level circulating currents in a -40 °C environment at 100% SOC. Figure 4-11 on the following page shows results of heating at peak inductor currents of 35 A (shown as 70 A-peak-to-peak), with notable improvement in pulse performance after 40, 60, and 90 minutes of
heating. Room temperature performance was not achieved but approached 94% thereof. About 200 watts of charging power was supplied to the pack during the test.

An interesting note about Figure 4-11 is that two curves for room temperature performance are indicated. The second curve from the top (star marker) is the room temperature performance recorded for the Optima battery pack when new. The top curve (dot marker) is the recorded room temperature baseline post high-frequency testing after the pack sat dormant in the lab for one year. Pulse discharge current appears noticeably higher for the post test result and is used for comparison in all subsequent figures.

Figure 4-11: 50 Ah Optima, low current external/internal heating at -40°C thermal soak

Figure 4-12 on the following page shows performance enhancement after 90 minutes of continuous heating in the 40 °C environment, but at slightly lower current of 65 Ap-p, and with the initial core temperature of the battery at -34 °C.
The test was repeated at -40 °C but with an insulation wrap around the battery pack described in Chapter 3. Results are shown in Figure 4-13 for heat treatment of 60 and 90 minutes at 70 Ap-p with improvement over those of the non-insulated test, nearing room temperature performance. Heat was applied for an additional 15 minutes but at a reduced inductor current of 25 Ap-p, requiring about 65 watts of charger power. This level of heating is representative of what might be required for maintaining elevated core temperature at equilibrium. The battery core temperature continued to rise slowly, with slight improvement in pulse performance, signifying a lower equilibrium current.
The temperature set point in the chamber was raised to $-32 \, ^\circ\text{C}$ and the heating tests were repeated for the pack with and without insulation. Again, pulse performance increased after heating with almost room temperature results as shown in Figure 4-14.
The baseline discharge curve for the pack without heating yields nearly the rated cold cranking amps. Figure 4-15 shows the additional performance increase afforded by the pack insulation was less significant than when at a chamber temperature of -40 °C.

Figure 4-15: 50 Ah Optima, external/internal heating at -32°C, with insulation

Figure 4-16: 50 Ah Optima, external/internal heating at -32°C, no charger
A heating test was conducted at -32°C on the insulated pack without the battery charger connected so the battery SOC fell below 100%. Figure 4-16 on the preceding page demonstrates that the battery was self-heated for about 90 minutes and still provided higher pulse current than without heating. The current magnitude was lower than previous tests in part because of reduced battery voltage without the charger.

Figure 4-17 shows battery resistance and median pulse current versus case temperature. Resistance calculations seemed consistent with published internal resistance values from Optima Battery.

Alternating current external/internal heating using inductor cores was successful at warming the Optima battery pack and improving pulse performance. For comparison, an alternative core was tested using resistor cartridge heaters as discussed in Chapter 3. A direct current source was used to match the power profile of the charger during previous
inductor-core tests. Results of heating the Optima pack at -40 °C and -32 °C without insulation yielded very similar discharge performance, but with battery case temperature slightly lower. Heating and discharge cycles were not repeated for the pack with insulation as the results would have likely shown the same result, that is, that the resistive heating and inductive heating yields practically the same discharge performance.

A third test however was carried out on the pack at -40 °C to determine the effect of increased heating power. The resistor cores delivered up to 600 W to the heater blocks with the surface temperature quickly approaching a limit of 65 °C. Careful regulation of the power was required with a maximum continuous power of about 250 W based on observed thermal limitations. As a result the heating time was not significantly less than with the 200-watt inductor cores.

4.4 Summary

Table 4.1 on the following page is a summary of pulse discharge tests and the improvement resulting from high and low current internal heating of the 7 Ah and 24 Ah battery packs. Table 4.2 summarizes improvement in pulse discharge of the 24 Ah and 50 Ah battery packs as a result of heating tests using the external/internal technique. In both tables heating times are shown as accumulated minutes at each test current. The results of tests conducted on the Optima pack using the resistor heater cores are not shown.
Table 4.1: Summary of pulse discharge performance with internal heating

<table>
<thead>
<tr>
<th>Inductor Current</th>
<th>Heat Time</th>
<th>Charge Power</th>
<th>Pulse Performance</th>
<th>Case Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap-p Arms kHz Min.* W % Increase % Rm.Temp °C</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>— — — — — — — 0 43 -37</td>
<td></td>
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<tr>
<td>180 52 7 20 380 104 87.8 0</td>
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<td>80 23 13 30 — 52.2 65.5 —</td>
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<td>60 — 60.9 69.6 —</td>
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<tr>
<td>60 18 19.4 30 — 37.2 59 —</td>
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<tr>
<td>60 — 46.5 63 —</td>
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</tbody>
</table>

* Accumulated heating time in minutes.

Table 4.2: Summary of pulse discharge performance with external/internal heating

<table>
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<tr>
<th>Inductor Current</th>
<th>Heat Time</th>
<th>Charge Power</th>
<th>Pulse Performance</th>
<th>Case Temp</th>
</tr>
</thead>
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<td>— — — — — — — 0 43 -37</td>
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<tr>
<td>24Ah U1L-250 Insulated 180 52 7 20 380 104 87.8 0</td>
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<tr>
<td>80 23 13 30 — 52.2 65.5 —</td>
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<td>60 — 46.5 63 —</td>
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</table>

* Accumulated heating time in minutes.
Chapter 5

Conclusion

5.1 Summary

Battery heating using high frequency alternating current was studied to preheat 24-volt lead-acid battery packs in extreme cold temperatures to -40 °C prior to pulse discharge testing. A selection of high frequency AC battery heaters were constructed and tested to render cold batteries serviceable in high current pulse discharge events, as in engine cranking. The battery packs under test (of various size and type) were charged during heating to maintain a state-of-charge near 100%. Experimental results demonstrate significant improvement in pulse discharge performance using large circulating currents through the battery terminals of small- and medium-size battery packs. For example, a 7.5 Ah SLA battery pack delivered near room-temperature pulse current after approximately 40 minutes of heating with peak inductor currents of 90 A (180 A peak-to-peak). A 24 Ah wet-cell pack achieved nearly room-temperature performance after less than 60 minutes of inductor heating current of 265 A peak (530 A peak-to-peak).
Heating of the battery electrolyte results from the current that flows through the battery having an equivalent series resistance (ESR). This resistive loss is proportional to the square of current, with higher current yielding increased heating power and faster warm-up. However, for larger amp-hour batteries with low internal resistance, high frequency AC heating through the terminals may be practically limited for the following reasons.

1. Lower internal resistance requires exceedingly high current for adequate heating. As an example, the high performance 50 Ah Optima Red Top requires hundreds of Amps of circulating current for both peak and RMS values.

2. High current necessitates the use of heavy conductors and a stout half-bridge controller power section with a substantial power inductor.

3. Fast-acting fuses must be utilized to guard against excessive battery currents in case of circuit failure. A low cost automotive style fuse for high current (250+ amps) is typically a delay-type fuse that does not adequately protect MOSFET switches. Instead, a costly semiconductor-type fuse must be used.

4. Significant heat is generated by losses in the power electronics (e.g. resistive, switching) even with a high efficiency system. The heat escapes to the environment and does not warm the battery pack without means to capture it.

5. The dollar cost and equipment size of the high-current heater may be prohibitive for some battery systems.

An alternate method of battery heating was tested that used an external heating element to supplement internal heating from the high frequency circulating current. In
one implementation a “hotplate” was created using power resistors in the inductor leg of the circuit fastened to an aluminum plate used to mount the 24 Ah battery pack. Tests of the external/internal heating on the pack using an approximately 150-watt hotplate revealed that room temperature pulse performance was not achieved, but the pulse performance did increase significantly. After about 60 minutes of heating in the -40 °C chamber the pulse current was above 82% of the room temperature baseline. After 120 minutes of heating the pulse current was at 89% of the baseline.

A second implementation of the external/internal heating method used high frequency induction heating to warm the batteries. Hand-wound inductors were fitted in specially machined aluminum blocks made to fill the voids in the underside of the Optima Red Top battery case. A custom low-current half-bridge controller generated alternating current at frequencies in the range 50 kHz to 5 kHz that passed through the induction heater cores. The method was effective at transferring heat through the battery side walls to warm the electrolyte within. Results of tests on the large 50 Ah Optima pack were impressive using the external/internal method that consumed about 200 W of charger power. After 60 minutes of heating at a peak inductor current of 35 A (70 A peak-to-peak), pulse discharge performance was about 87% of that at room temperature in the -40 °C chamber, and over 93% after 90 minutes. With a modest insulation wrap around the pack, about 92% of the baseline was achieved after 60 minutes of heating and 96% after 90 minutes.

Results of testing the external/internal heating method revealed the following.

1. The electronic controller for low current operation can be made smaller, have lower cost, and likely with higher efficiency.
2. Charging power during heating to maintain 100% SOC is significantly lower than with high-current internal heating and even low-current internal heating of similar effectiveness.

3. Low-current heating can allow a charged battery to heat itself sufficiently to deliver pulse current at least once without external charging. As noted previously, the effective energy capacity of a battery increases as load current decreases. Heating with a nominally low current then may provide sufficient reserve.

An additional test was conducted on the Optima battery pack using the external/internal heating method with the aluminum heater blocks. A commercially available resistor cartridge heater was inserted in the heater block in place of the hand-wound inductor core. Under similar conditions, tests were repeated on the 50 Ah battery pack with a DC power supply as the sole heating source providing an identical input power profile. Results of the initial tests indicated that the DC resistive heating was not significantly better or worse than the AC inductive heating in terms of warming the battery to improve pulse performance. This stands to reason as the internal power dissipation due to the rather low circulating current is practically negligible. However, with higher inductor currents, the resulting increase in heating power can warm the battery pack faster. This extra heating effectiveness is worthy of future study as an alternative to exceptionally high current through the battery terminals.
5.2 Discussion of “Peak Current Factor”

Early in this study a relationship was recognized between the magnitude of peak internal heating current and the time required to warm a battery of a given size such that room temperature pulse performance was achieved. An objective of the study became the identification of a scaling factor, designated the Peak Current Factor, to predict peak inductor current relative to battery ampere-hour rating, ambient temperature, and desired heating time or pulse performance improvement. The simple ratio of peak inductor current to amp-hour rating for the 7.5 Ah and 24 Ah packs as tested in the -40 °C chamber yields approximately 12:1 and 11:1, respectively. The heating time of the 7.5 Ah pack to near room-temperature was about 40 minutes, and for the 24 Ah pack it was just short of 60 minutes. A scaling factor of 11:1 for the 50 Ah Optima pack indicated a peak inductor current of about 550 A (1100 A peak-to-peak).

The pulse performance of a battery is dictated in large part by the state-of-charge of the battery and its ESR, which is closely tied to the battery core temperature as discussed in Chapter 2. The time required to raise the internal temperature of a battery a given amount depends on its thermal conductivity, the power of the heat source, and the ambient temperature. The power of the internal heat source is determined by the RMS battery current that passes through the terminals squared times the battery resistance. The thermal conductivity of the battery and time constant of heat transfer depends on its mass and the type and spatial arrangement of material. Commercially manufactured lead-acid batteries have similar construction and materials so the thermal characteristics are likely to be consistent, even across different varieties. Assuming a consistent thermal model,
the standard amp-hour rating (usually at a 20-hour rate) of lead-acid batteries can become a proportional measure of battery mass and internal resistance.

It is observed that as the amp-hour rating of a battery increases there is a relative increase in the mass and decrease in the internal resistance. The increased battery mass requires additional heating power to raise the core temperature by a given amount in a fixed time. The increase in heating power goes by the square of current but is reduced proportionately by the drop in internal resistance, yielding perhaps a nearly linear relationship between power and current. Consider two nearly identical batteries except the amp-hour rating of one is twice the other. The larger battery may likely have twice the mass requiring two times the heating power, but at half the resistance. For instance, the smaller battery may take one (1) unit of heating current while the larger takes two (2) units (2 x 2 x 0.5). As the pack size is increased four-fold or more, assuming a proportional decrease in resistance, the relationship becomes less linear. However, as seen by experimental data in Chapter 4, the resistance falls disproportionately with increase in amp-hour rating so the linearity may be preserved.

Since power dissipated in the battery is a function of its resistance, having an accurate measure of internal resistance is important. It is known that internal resistance of the battery changes with core temperature and state-of-charge. The core temperature of the battery is difficult to measure as recognized by [13], but temperature of the battery case is readily accessible. This study recorded case temperature periodically during heating cycles (with known heating power) and correlated it with pulse discharge performance in which a calculated measure of internal resistance was found. Holding the battery steady at 100% SOC reduced the variation of resistance due to state-of-charge.
It is possible then with an accurate thermal and resistive model of the battery to predict the required peak heating current to raise the core temperature a given amount in a set time; or to determine the heating time required to raise internal core temperature in an environment given a peak circulating current; or to predict the pulse performance based on heating time at a particular current level.

Also, as the battery warms the internal resistance decreases so the heating power at a particular peak current diminishes. The point source of heat is then variable and requires perhaps non-linear adjustment of the thermal modeling. Of course, it is conceivable that a computer program could be written to solve and accurately predict this behavior. A thermal model for each major type and construction of lead-acid battery could be generated to further increase accuracy of the relationship. The exercise could also be extended to other battery chemistries. Taken together this could yield an accurate scaling factor of battery heating current to ampere-hour rating for a given pulse performance with a particular heating time and ambient temperature, referred to as Peak Current Factor. The detail analysis of this scaling factor was outside the scope of this research and is reserved for future study.
References


Appendix A

AC Heating Waveforms

Shown below are selected oscilloscope plots of inductor current for the 7.5 Ah Transcontinental Battery SL1275 during internal heating. At high current insufficient DC bus capacitance and parasitic effects resulted in non-ideal current waveforms.
Selected oscilloscope plots of inductor current appear below for the 24 Ah Dynalite U1L-250 during internal and external/internal heating.

Chnl 1: Switch Voltage (Vds) 20V/div
Chnl 2: Inductor Current 530 App, 8.5 kHz

Chnl 1: Pack Voltage 20V/div
Chnl 2: Inductor Current 250 App, 16 kHz

Chnl 1: Pack Voltage 2V/div
Chnl 2: Inductor Current 20 App, 50 kHz

Chnl 1: Pack Voltage 2V/div
Chnl 2: Inductor Current 9 Arms, 20 kHz

Chnl 1: Pack Voltage 2V/div
Chnl 2: Inductor Current 10 Arms, 14 kHz
Selected oscilloscope plots of external/internal heating current for the 50 Ah Optima Red Top Group 34 appear below. Notice the clipped current waveform of the 70App plot due to limitations of the current sensor measurement range. The maximum measurable peak-to-peak current of the sensor was approximately 30 A.
Appendix B

Additional Photographs

Selected photographs of the experimental setups throughout various stages of the research appear below.

Photograph of laboratory setup during early testing on 7.5 Ah SLA showing meters, oscilloscope, function generator, power supplies, temperature chamber, and inverter.
Photograph of high current inverter with external gate logic used to heat the 24 Ah pack.

Experimental setup for testing the 50 Ah Optima pack using low-current external resistive heating. The large power supply to the far right supplied heating power while the other maintained the pack SOC at 100% in the -40 °C chamber.
Optima Red Top battery pack ready for testing in the environmental chamber with resistive heater blocks installed. Thermocouple probes measured heater block surface temperature along with inner sidewall case temperature.

Another view of the experimental setup for testing the Optima pack showing pulse discharge control switches, multi-channel temperature switch and display, analog meters, and oscilloscope. Power and signal leads exit the temperature chamber on the left.