

AC Heating for EV/HEV Batteries

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ABSTRACT

Methods have been developed for internally heating EV/HEV batteries at cold temperatures using either low or high frequency AC currents. The performance of these batteries in cold climates is of major concern because they suffer a huge loss in capacity that drastically reduces both their charge and discharge capabilities.

Recent thermal analysis by the Department of Energy National Renewable Energy Laboratory (NREL) has shown that applying heat to the electrolyte will heat the battery faster than external heating techniques. Additional research at the University of Toledo Power Electronics Laboratory has shown that by circulating an AC current of sufficient amplitude through the battery, it is possible to apply heat directly to the battery electrolyte. Tests in the -20°C to -40°C range have shown that a 60 Hz current can revive inoperable lead acid batteries within 5-6 min. The concept of using high frequency heating for nickel metal hydride (NiMH) batteries also was verified by building and testing a 10-20 kHz heater. Tests show that at -20°C and -30°C , a 10 kHz current also can restore these batteries within 3-6 min.

The use of 60 Hz is economically attractive because it is relatively simple compared to higher frequency systems. However, the 60 Hz system is much larger and heavier. Therefore it would be a poor choice for on-board purposes and appears to be feasible only as an off-board heater. High frequency heaters appear feasible for on-board heating, but only for HEVs, where the DC input power for the heater can be supplied by the vehicle's generator.

I. INTRODUCTION

Hybrid electric vehicles (HEVs) and electric vehicles (EVs) use large packs of secondary batteries connected in series. Some of the popular batteries used in most of today's HEVs and EVs, include lead acid, nickel metal hydride and lithium-ion.

The performance of these batteries at cold temperatures is of major concern. This is because their capacity decreases

with a decrease in ambient temperature. The degree of the effect on the capacity also depends upon the type and quality of the electrolyte and the state of charge (SOC). This decrease in capacity at low temperatures occurs because the viscosity of the electrolyte increases, and in some cases the electrolyte can actually freeze. This limits the flow of current from one electrode to the other, and the battery resistance, R_B , increases. Therefore the electrolyte needs to be warmed at low ambient temperatures so that the vehicle will operate satisfactorily.

II. BATTERY HEATING METHODS

Batteries can be warmed up by applying heat either externally or internally. There are several methods that can be used for external heating, including,

1. Electrically heated thermal jackets.
2. A sealed enclosure with an internal heating element.

These methods have been used in some applications, but they add considerable weight and expense. If the pack is allowed to reach a very low temperature, all of these methods require a significant amount of time for warming the batteries since the external heat energy must penetrate the large mass of the pack.

It would therefore be more beneficial to heat the battery electrolyte directly rather than by making use of external heaters. At present there are at least two ways of doing this:

1. Resistive heating elements embedded within the batteries.
2. High AC currents that provide heat via internal I^2R losses.

Method 1 might be effective for rapid heating, but a literature search and discussions with battery manufacturers and other experts have not uncovered any applications of this technique. This indicates that the feasibility of this method is

unknown, and it also seems safe to predict that it would significantly increase the battery cost.

Method 2 has no effect on the cost of the pack itself, and it has been proven that it can heat a cold battery quite rapidly. There is, however, some expense for the equipment that applies the AC to the battery.

The use of DC currents for heating the electrolyte is extremely detrimental, especially for sealed batteries. This is because at very low temperatures, DC currents of even moderate amplitudes create excessive gassing long before significant heating occurs. The reason for this occurrence is explained in the next section.

III. BATTERY MODEL

Fig.1 shows a simplified model that can be used to explain why at cold temperatures (such as those below 0°C), battery charge and discharge become increasingly difficult.

The model consists of three parts:

1. An ideal voltage source, V_0 , that represents the charge storage mechanism.
2. A conventional coulomb resistance, R_c , that represents the ohmic voltage drop.
3. An equivalent resistance, R_{ov} , called the overvoltage resistance.

R_{ov} is not a resistance in the usual sense, but a component used to account for the extra energy that must be supplied to get charge into or out of V_0 [1, 2]. As the battery temperature drops, R_{ov} increases because more energy is required to either charge or discharge the battery. R_{ov} is highly nonlinear with respect to the state of charge (SOC) and the magnitude and direction of the current, I_B .

At a sufficiently low temperature and SOC, R_{ov} becomes so large that the battery is virtually unusable. Assuming V_0 remains fairly constant, the detrimental effect of a large R_{ov} on discharge is obvious once R_{ov} begins to approach or exceed the load resistance. A high R_{ov} seriously also limits

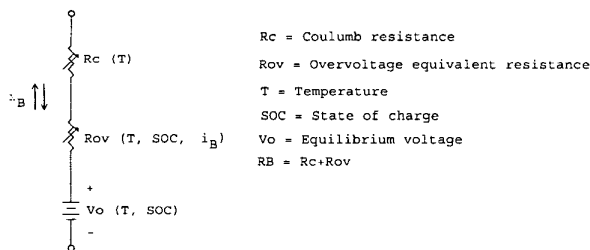


Fig.1. Battery Model

the charging ability because the energy level required to force a higher current through a high R_{ov} also creates excessive gassing. This leads to a loss of electrolyte, and for sealed batteries the internal pressure can exceed the capacity of the relief valves. When this happens, it is quite easy to rupture the battery case.

IV. AC BATTERY HEATING

The primary goals of AC heating are to permit faster charging and warm the batteries before usage. As mentioned earlier, AC can be circulated through the batteries at either a low frequency such as 60 Hz, or a higher frequency such as 10-20 kHz. The corresponding experimental set-ups for both techniques are explained below.

Fig.2 shows the block diagram of a system which uses a 60 Hz source to provide the AC current along with a charger that is represented by the current source, I_{DC} [3]. The 60 Hz heating current, I_{AC} , is supplied from the source, V_s , via the current transformer, T . L is selected so that $X_L \gg R_B$, so virtually all of I_{AC} will flow through the battery.

The control system uses the input measurements T_B , V_B , I_{DC} and I_{AC} , to regulate I_{AC} and either I_{DC} or V_B , depending on whether current or voltage regulation is required. The control system also ensures that no maximum limits are exceeded.

Fig.3 shows the 10-20 kHz circuit [4], where the pack is divided into two halves whose voltages are V_{B1} and V_{B2} . The circuit includes a pair of switches, Q_1 and Q_2 , connected in a half bridge configuration. The purpose of this circuit is to circulate an AC current between the two halves of the pack. Therefore, each half is alternately charged and discharged and thus heated by internal $I^2 R_B / 2$ losses. This circuit provides the advantage of much smaller reactive components, but it is more complex and expensive than the 60 Hz version in Fig.2 because of the power electronics equipment.

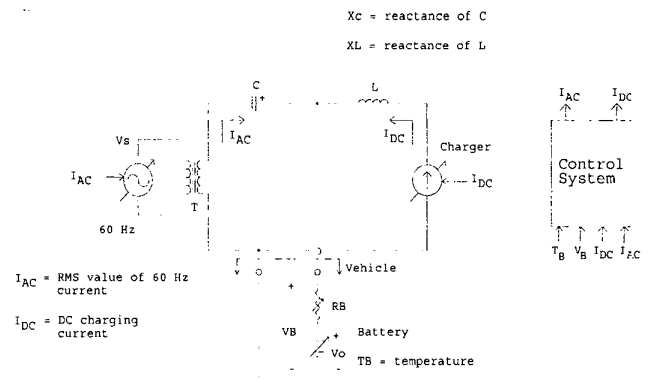


Fig.2. Battery charger with 60 Hz. AC heater

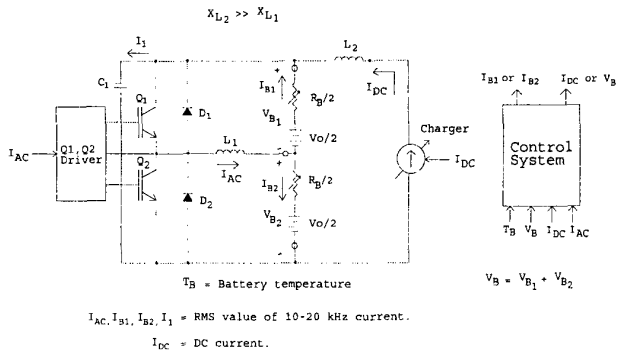


Fig.3. Battery charger with 10-20 kHz. AC heater

In Fig.3 a third connection is made to the center of the battery pack. Referring to the I_{AC} waveform in Fig. 4, Q_1 first turns on at $t = 0$ and then turns off at t_1 . Also at t_1 , I_{AC} commutates to D_2 and flows in the D_2, L_1, V_{B2} loop until it reached zero at t_2 . Thus for $0 \leq t \leq t_1$, energy is removed from V_{B1} and stored in L_1 . For $t_1 \leq t \leq t_2$, the energy in L_1 is transferred to V_{B2} . The operation is similar for the $Q_2 - D_1$ conduction cycle. This shows that energy is being cycled between the two halves of the pack, which means that the AC RMS battery current in either the $Q_1 - D_1$ or the $Q_2 - D_2$ branch is $I_{AC}/\sqrt{2}$.

L_2 is chosen so that $X_{L2} \gg X_{L1}$. This insures that I_{DC} remains essentially constant, and virtually no 10-20 kHz current flows through the charger. C_1 is used in Fig.3 to prevent excessive voltage transients across Q_1 and Q_2 when they turn off. While C_1 must be large enough to provide protection, it also should be as small as possible to minimize I_1 . This is because I_1 represents current that is siphoned away from I_{B1} and I_{B2} . To avoid overheating, a polypropylene capacitor was used for C_1 . If $C_1 = 0$, then $I_{B1} = I_{B2} = 0.707 I_{AC}$. However, the present C_1 value resulted in $I_{B1} = I_{B2} \cong 0.5 I_{AC}$. Therefore, the AC conduction losses in the pack are,

$$2 \left(\frac{I_{AC}}{2} \right)^2 \cdot \frac{R_B}{2} = \frac{I_{AC}^2 R_B}{4} \quad (1.)$$

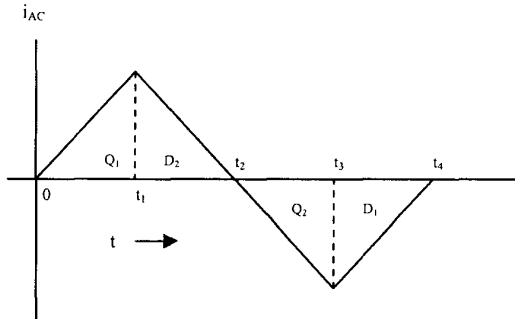


Fig.4. i_{AC} Waveform for the circuit in Fig.3.

Therefore, in order to achieve an effective 100 A.rms heating current, we need $I_{AC} \cong 200$ A.rms.

V. EXPERIMENTAL RESULTS

The 60 Hz. heating test circuit is shown in Fig.5. Tests were conducted on a 12V., VRLA (valve regulated lead acid) Hawker Odyssey PC1200 battery rated at 38 Ahr. The SOC was set to approximately 50%. A very low resistance load was applied across the battery during these tests by closing S_1 for slightly over 5 sec. This test simulates the initial starting current of an electric motor, and it allows the application of quite a few pulses without changing the SOC significantly.

S_1 was first closed for about 5 sec. at $25^\circ C$ while S_2 was open (no AC). The pulse amplitude at $t = 5$ sec. was observed to be 250 A (Fig.6). The battery was then soaked at $-40^\circ C$ for > 10 Hrs and re-tested without AC. Fig.7 shows that the amplitude at $t = 5$ sec. decreased to $\cong 45$ A. S_2 was then closed for 5 min. (S_1 open), and 100 A.rms/60 Hz was applied to the battery. S_2 was then opened and S_1 closed for > 5 sec. The result obtained is shown in Fig.8. The amplitude of the pulse discharge increased to $\cong 140$ A. These results indicate that 100 A.rms at $-40^\circ C$ was able to revive a virtually unusable battery within 5 min.

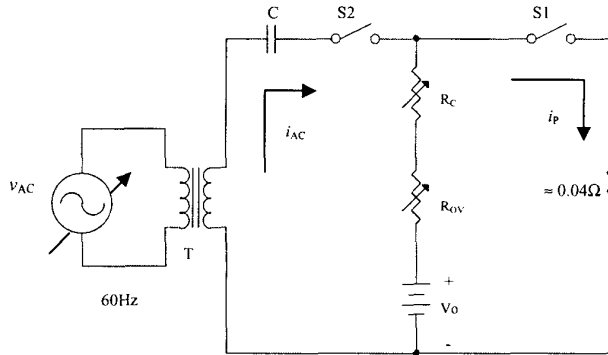


Fig.5. Pulse discharge test circuit

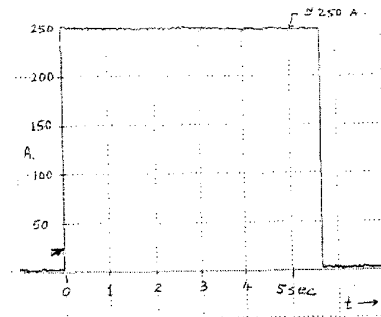


Fig.6. Pulse discharge current at $25^\circ C$, SOC $\cong 50\%$.

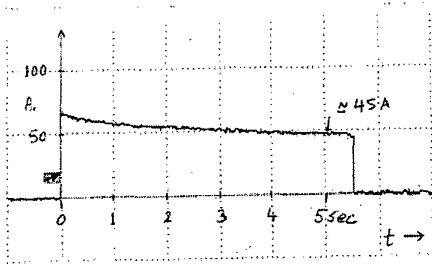


Fig.7. Pulse discharge current at -40°C , SOC \cong 50% before AC heating.

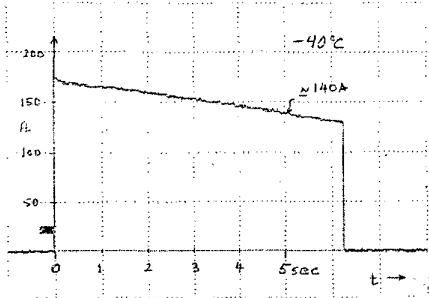


Fig.8. Pulse discharge current at -40°C , SOC \cong 50% after $I_{ac}=100$ Arms for 5min.

The 10-20 kHz heater was tested on a pack of 16 series connected Panasonic NiMH battery modules which were rated at 6.5 Ah. The nominal open circuit voltage was about 8 V./module at 25°C over most of the SOC range. The series battery resistance, R_B , was used to measure battery temperature during the 10-20 kHz heater tests described in Fig.3. A pulse waveform, I_0 , having amplitudes of 25A/2 sec. on both the discharge and charge cycles was applied in order to measure R_B . Fig.9 shows the pulse waveform. Measurements were made with the aid of an AeroVironment ABC-150 power processing system using its Remote Operating Software (ROS) and a personal computer. The data acquisition was carried out using a National Instruments PCI-6024E NI-DAQ card that interfaced with a 16 channel Analog Devices 5B Series signal conditioning module. Eight channels were used for measuring battery voltages and the remaining 8 were used to sense the module temperatures.

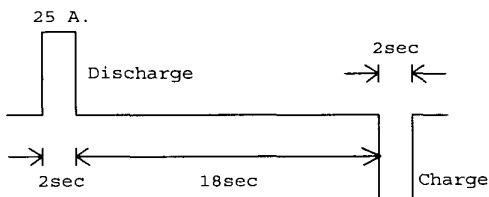


Fig.9. I_0 characterization profile

If $\Delta V_0 = V_0$ voltage drop (during the discharge cycle) when I_0 is applied, $R_B = \Delta V_0 / I_0$.

The pack was soaked at different temperatures in the range -30°C to 45°C for at least 5 hours to insure that the electrolyte temperature, T_{bat} , was the same as the ambient temperature. R_B was measured at each of these temperatures with pack SOCs set at 25%, 55% and 75%. A graph of R_B vs temperature (Fig.10) was plotted at each SOC value. In subsequent tests, measured values of R_B were used along with this graph to identify T_{bat} .

The charger in Fig.3 must supply the losses in both the battery pack and the AC heating circuit to prevent significant battery discharge. During the tests the charger was set in the voltage regulation mode in order to provide the necessary DC current to compensate for these losses.

Tests were conducted at three different SOCs viz. 25%, 55%, and 75%, and at temperatures of -20°C and -30°C . Before each test, the battery pack was soaked at the desired temperature for at least 5 hours. Various values of $I_{B1}(=I_{B2})$ were then used to heat the batteries.

Figs.11 and 12 show the results obtained after soaking the battery pack at -20°C with an SOC \cong 55%. Before applying the AC, $R_B \cong 1$ ohm and $T_{bat} \cong -20^{\circ}\text{C}$. However, T_{bat} increased to about 10°C and R_B decreased to about 0.33 ohm after 5 min. of 60 Arms AC circulation. When the amplitude of the AC was increased the heating process sped up. With 70 Arms, only 3 min. were needed to heat the pack to 10°C , and with 80 Arms, only 2 min were needed.

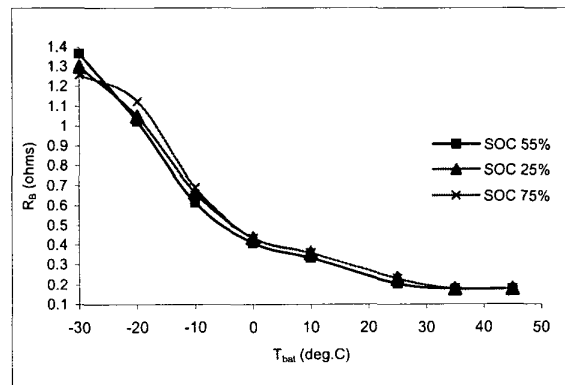


Fig.10. R_B v T_{bat} @ SOCs of 25%, 55% and 75%.

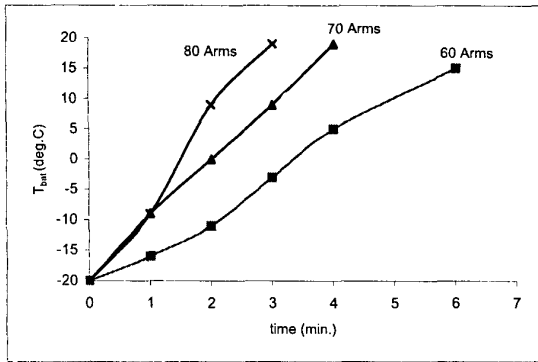


Fig.11. T_{bat} v time @ -20°C , $\text{SOC} \cong 55\%$.

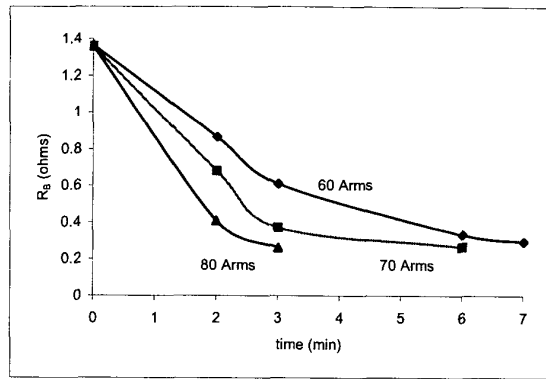


Fig.14. R_B v time @ -30°C , $\text{SOC} \cong 55\%$.

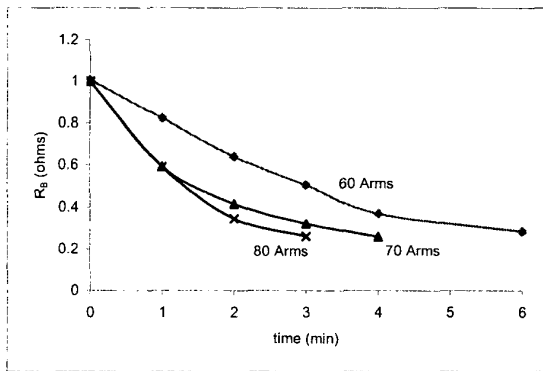


Fig.12. R_B v time @ -20°C , $\text{SOC} \cong 55\%$.

Figs.13 and 14 show the results obtained after soaking the battery pack at -30°C with an $\text{SOC} \cong 55\%$. Before applying AC, $R_B \cong 1.36$ ohm and $T_{bat} \cong -30^{\circ}\text{C}$. T_{bat} then increased to about 10°C and R_B decreased to about 0.33 ohm after 6 min. of 60 Arms AC. Once again as the amplitude of AC was increased, the heating process sped up. With 70 Arms, only about 3.5 min. were needed to heat the pack to 10°C , and with 80 Arms, only 2.5 min. were needed.

Figs.15 and 16 show the results obtained after soaking the pack at -30°C and circulating 60 Arms AC with pack SOC's of 25%, 55%, and 75%. 6 min. were needed to heat the pack to 15°C when the pack SOC was 75%. However, slightly more time was need when the SOC was lower, eg, 7 min. were needed with $\text{SOC} \cong 55\%$, and 8 min. were needed with $\text{SOC} \cong 25\%$.

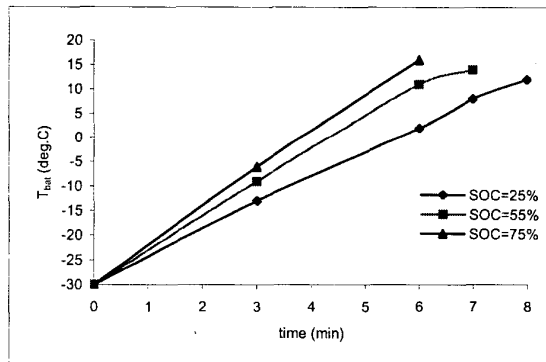


Fig.15. T_{bat} v time @ -30°C , 60 A.rms.

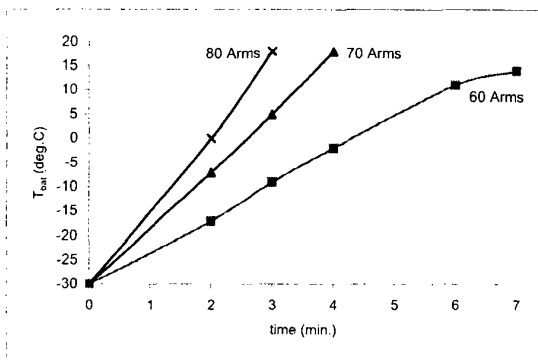


Fig.13. T_{bat} v time @ -30°C , $\text{SOC} \cong 55\%$.

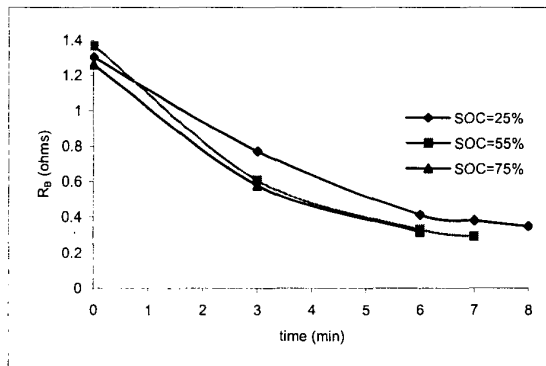


Fig.16. R_B v time @ -30°C , 60 A.rms.

VI. SUMMARY

Effective methods have been developed for internally heating lead acid and NiMH batteries at cold temperatures using either low or high frequency AC currents. Low frequency heaters, e.g., 60 Hz, are much larger and heavier, but because of their low cost, they are attractive for stationary charging applications. Because of their small size and lighter weight, high frequency heaters such as 10-20 kHz, are the only feasible choice for on-board heating applications.

Tests have shown that it is possible to heat both lead acid and NiMH batteries within a reasonable amount of time. Neither type of battery has shown any distinct signs of degradation, but long term effects were not studied. The test conditions for the 10-20 kHz heater were designed to simulate those on an HEV where a DC generator (charger) would be available to replace the energy lost in the heating process. These results appear to verify the feasibility of this technique, but the required heating times are still somewhat longer than desired. For example, 80 A.rms for 2 min. was required for the battery to reach 0°C for a -30°C ambient (Fig.13). Presumably, higher currents would decrease the required time even further.

ACKNOWLEDGMENT

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