Direct Battery Electrolyte Heating and Temperature Maintenance at Low Temperatures

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Abstract

In this paper, the development of a novel technology for direct and rapid heating of battery electrolyte at low temperatures and maintaining the battery temperature at its optimal performance level is presented. The technology has been extensively tested on a wide range of primary and secondary batteries at temperatures as low as -60°C without causing any damage to the batteries and without interfering with the operation of chargers and existing electronic controls such as the Battery Management System (BMS). The technology is applicable to almost all primary and secondary batteries, such as Lithium-ion, Lithium-polymer, NiMH and lead-acid batteries. The technology is also applicable to super-capacitors and has been used to rapidly charge and heat super-capacitors at temperatures as low as -54°C without any damage.

Keywords

Rechargeable Battery Heating; Lead Acid Battery Heating; Lithium-Ion Battery Heating; Lithium-Polymer Battery Heating; Supercapacitor Heating; Battery Low Temperature Performance Enhancement; Low Temperature Charging of Batteries.

Introduction

The performance of batteries is significantly reduced at low temperatures. This is the case for both primary and rechargeable batteries. In addition, current lithium-ion and Lithium-polymer battery technology does not allow battery charging at temperatures below 0°C and charging at temperatures below their optimal level has been shown to reduce battery life.

Current solutions that try to address cold weather effects on batteries include heating the exterior of the battery by integrating “heaters” into the battery compartment or using heating blankets or pads, or recently by embedding heating elements inside batteries.

Omnitek has developed a novel patented technology [1] for direct and rapid heating of battery electrolyte at low temperatures and maintaining the battery temperature at its optimal performance level. The technology has been extensively tested on a wide range of primary and secondary batteries at temperatures as low as -60°C without causing any damage to the batteries and without interfering with the operation of chargers and existing electronic controls such as the Battery Management System (BMS). The technology is applicable to almost all primary and secondary batteries, such as Lithium-ion, Lithium-polymer, NiMH and lead-acid batteries. The technology is also applicable to super-capacitors and has been used to rapidly heat and charge super-capacitors.

The developed highly innovative technology is based on in-depth studies that were carried out by our scientists of the highly nonlinear dynamic behavior of the battery electrolyte components when subjected to a high-frequency electric field. Based on the results of these studies, a patented technology has been developed that uses high-frequency AC (symmetric with no DC component) current to heat any battery electrolyte directly and uniformly at temperatures that are as low as -60°C. In this direct electrolyte heating technology, the applied high-frequency currents are in general in the range of 50-120 KHz for Lithium-ion and Lithium-Polymer and 20-60 KHz for Lead-Acid batteries, and 1-2 MHz for super-capacitors.

The developed electrolyte heating unit is externally powered at very low temperatures at which the battery is unable to provide a significant amount of power. Once the battery can provide enough power, the battery temperature may be raised to its optimal level and maintained at that level by power from the battery itself. The battery may be fully charged or discharged. The battery may be charged while being heated.

The developed electrolyte heating units are inherently highly efficient and safe and do not interfere with battery safety and protection circuits (e.g., various BMS used in Li-ion battery packs). The following are some of the main characteristics of the developed technology:

- It requires no modification to the battery and super-capacitor.
- The basic physics of the process and extensive tests clearly show no damage to the battery and super-capacitor and their safety and protection circuits.
- The battery pack protection electronic units, such as those for Lithium-ion and Lithium-polymer batteries, can be modified to ensure self-powered continuous high-performance operation at low temperatures.
- The battery electrolyte and super-capacitor is directly and uniformly heated, therefore bringing a very cold battery to its optimal operating temperature very rapidly and minimizing heat loss from the battery.
- Direct electrolyte heating requires significantly less electrical energy than external heating.
- Standard sized Lithium-ion or polymer batteries can be used instead of thin and flat battery stack packaging that are used to accelerate external heating via heating blankets or the like.
- Unlike heating elements provided inside the battery, no local hot spots are generated inside the battery while heating at low environmental temperatures.
- By ensuring battery charging and usage at their optimal temperatures, the battery life cycle can be significantly increased.
- The technology is simple to implement and low-cost.

High-Frequency Battery Electrolyte Heating

The basic operation of a battery may be approximately modeled with the equivalent (lumped) circuit shown in Fig. 1. The temperature and frequency dependence of the elements used to model the battery electrolyte component of the battery is critical for describing high-frequency AC current electrolyte heating technology. In this model, the resistor R_e represents the electrical resistance against electrons from freely moving in conductive materials, i.e., electrodes, and wirings, etc. The equivalent resistor R_i and L_i represent the temperature and frequency (f) dependent resistance to free movement of ions and their resistance to acceleration due to their mass, charge interactions, etc. The capacitor C_s is the surface capacitance, which can store electric field energy between electrodes. The resistor R_c and capacitor C_c represent the electrical-chemical mechanism of the battery in which C_c is intended to indicate the electrical energy that is stored as chemical energy during the battery charging and that can be discharged during battery discharging, and R_c indicates the equivalent resistance to discharging current.

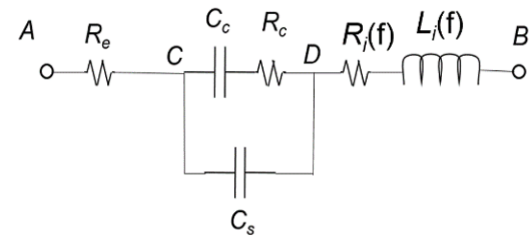

Figure 1: Equivalent lumped circuit model of a battery.

As an example, the operation of a Li-ion battery, as modeled in Fig. 1, may then be described as follows. If an AC current with high enough frequency is applied to the battery, due to the low impedance of the capacitor C_s, there will be no significant voltage drop across the capacitor and the circuit effectively behaves as if the capacitor C_s were shorted and the applied high-frequency AC current essentially passes through the resistors R_e and R_i and inductor L_i. Any residual current passing through the R_c and C_c branch would not damage the battery due to its high-frequency and zero DC component.

The resistance R_e is usually very small in batteries and would generate negligible amount of heat. However, at any given temperature, the frequency dependent R_i(f), which is shown below to increase rapidly with increased frequency of the applied current, generates heat in the battery electrolyte at a rate that is proportional to the square of the applied RMS current. It is also noted that since the electrical-chemical components of the battery are effectively bypassed, the applied high AC current and related voltage can be higher than those rated for the battery without causing any damage.

High-Frequency Circuit Model for Direct Battery Electrolyte Heating

A first order electric circuit model must include a frequency dependent "resistive" heating element and an inductive component accounting for the phase shift between the driving AC voltage applied to the battery terminals and the AC current flowing through the electrolyte. One such electric circuit model is illustrated in Fig. 2. The model includes a non-frequency dependent resistor R_o, and a frequency dependent inductive reactance X(f) and a frequency dependent resistor R(f). The battery impedance Z(f) is therefore given by

$$Z(f) = R(f) + j\,X(f) \qquad (1)$$

Using the first order approximation, R(f) and X(f) is expressed as,

$$R(f) = [P_0 + P_1 f\,] \;\text{ and }\; X(f) = P_2 f \qquad (2)$$

where f is the frequency in Hz, P_0 is the resistance in mΩ at f=0, and P_1 and P_2 are constant coefficients to be determined experimentally.

The applied high frequency voltage v(t) and current i(t) to the battery, Fig. 2, are given by

$$v(t)=V_0 \cos(2\pi ft+\Theta_v) \text{ and } i(t)=I_0 \cos(2\pi ft+\Theta_i) \qquad (3)$$

where V_o and θ_v are the amplitude and phase angle of the voltage and I_o and θ_i are the amplitude and phase angle of the current waves, respectively. The DC voltage term corresponding to the battery voltage is excluded from the equation. Using phasor notation, the battery "impedance" Z(f) is expressed in terms of its magnitude and phase.

$$|Z(f)| = \sqrt{R^2(f) + X^2(f)} = \sqrt{(P_0 + P_1 f)^2 + (P_2 f)^2} \qquad (4)$$

$$\Phi(f)[\text{deg}] = \frac{180}{\pi}\tan^{-1}\left[\frac{X(f)}{R(f)}\right] = \frac{180}{\pi}\tan^{-1}\left[\frac{P_2 f}{(P_0 + P_1 f)}\right] \qquad (5)$$

Equation (4) or equation (5) can be used to experimentally obtain the unknown coefficients P_0, P_1 and P_2, through a non-linear least squares curve fitting technique. The process of obtaining these parameters for any battery is described below.

During heating, the RMS current I, flowing through the frequency dependent "resistor" R(f) of the battery generates heat due to the absorbed power $I^2R(f)$. It should be noted that R(f) is fictitious and is used to describe the first order heating effect due to the oscillatory motion of the ions in the electrolyte and the electrolyte medium resistance to the motions, and interactions between the ions. The absorbed power, indicated as P(f, I), can then be expressed as

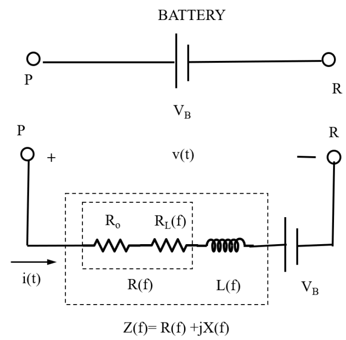

Figure 2: Circuit model for high frequency battery heating.

$$P(f,I) = I^2R(f) = I^2\,[\,P_0+P_1 f\,]\; x10^{-3} \quad [W] \qquad (6)$$

This absorbed power raises the temperature of the battery based on its mass m (kg), specific heat capacity C_p ($J.kg^{-1}.^oC^{-1}$) and duration t(s). The increase in temperature ΔT (°C) is thereby given by

$$\Delta T=P(f,I)t/C_p\, m \qquad (7)$$

The battery heating rate HR (°C/s) is then described by equation (8), where $\beta = m\, C_p$.

$$HR(f,I) = \frac{\Delta T}{t} = \frac{1}{\beta} I^2 \left[P_o + P_1 f\right] \quad [^oC/s] \qquad (8)$$

Validation of the High-Frequency Circuit Model for Heating

The high-frequency circuit model for battery heating of Fig. 2 and the derived heating rate equation (8) were validated using a Li-ion battery model RCR123A. This is a 3.7 V (800 mAh) cylindrical cell, which is 17 mm in diameter and 34.5 mm in length.

The frequency response of the test battery at room temperature (20°C) was characterized over a range of frequencies from 1 kHz to 100 kHz by driving the battery with a low amplitude AC sinusoidal current signal. The measured voltage and current data across the frequency sweep were then used to determine the amplitude ratio of the voltage and current, which is plotted in Fig. 3 (left). The phase angle (leading) between the voltage and current waveforms, Fig. 3 (right), was extracted directly from voltage and current waveforms.

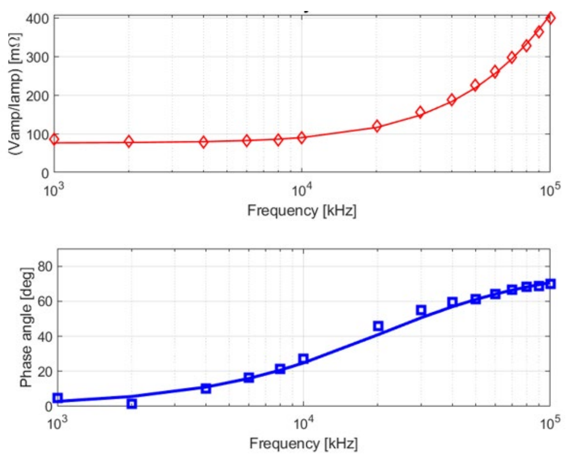

Figure 3: Frequency response of the RCR123 Li-ion battery.

As can be seen in the plots of Fig. 3, as the frequency is increased, the phase shift is increased and approaches 90 degrees, which means that the battery is exhibiting the characteristics of an equivalent non-ideal inductive element. This is exactly the behavior predicted by equations (4) and (5), which include an equivalent frequency dependent heating element R(f) and an ideal reactive inductance X(f) (=2πfL).

The unknown model coefficients P_0 and P_1, equation (2), are then determined by fitting to R(f) data and coefficient P_2 is obtained by fitting to X(f) data as P_0=77.5 mΩ, P_1=5.863x10^{-4} mΩ/Hz and P_2=3.9x10^{-3} mΩ/Hz for the tested battery.

The frequency and current dependent heating rate equation (8) is obtained for the tested RCR123 Li-ion battery using the above model coefficients and the given battery mass and specific heat capacity of m=0.018 kg and C_p =800 J/(kg°C), respectively, and the calculated $\beta = m\ C_p$= 13.4J. $°C^{-1}$, as

$$HR(f,I)=6.95\times10^{-5}[77.5+0.586\times10^{-3}]I^2\ °C/s \quad (9)$$

where f is in Hz and I is the RMS current in A.

The measured heating rate of Fig. 4 confirms the above predicted rate and its increase with frequency. The heating rate data (symbols) and the heating rate calculated from the model (solid line), equation (9), are shown in the plot of Fig. 5. The measured data is observed to show very good agreement with the predicted heating rate described by the model.

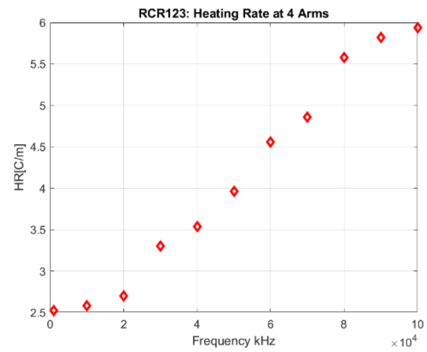

Figure 4

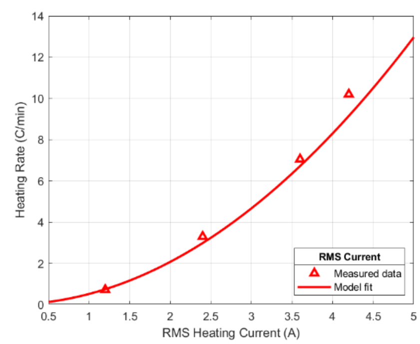

Figure 5

Conclusions

The developed high frequency current battery heating technology is shown to be used for rapid heating of battery electrolyte at low temperatures and maintaining the battery temperature at its optimal performance in low temperature environments. The technology has been extensively tested on a wide range of batteries at temperatures as low as -60°C without causing any damage to the batteries and without interfering with the operation of chargers and existing electronic controls such as the Battery Management System (BMS). The technology is developed based on the experimentally verified model of the behavior of battery electrolyte when subjected to high frequency AC current.

References

1. U. S. Patent Numbers 10,063,076; 10,855,085; 11,183,713; 11,211,810; and 11,211,809 and several U. S. and foreign patents pending.