Electrical Component Model for a Nickel-Cadmium Electric Vehicle Traction Battery

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Abstract **Saft STM 5.140 Nickel Cadmium batteries were evaluated at the UMASS Lowell Battery Evaluation Laboratory. An electrical component model was developed based on the test data. Step responses of the battery from seconds to days were considered. Faster time constants than this were not considered because they are presumed to be attenuated within the input filter of the traction motor drive controller. An impedance element model was developed with components associated with the current collection grid, the active plate materials, the electrolyte, and the self discharge. Model elements may be approximated as resistors and capacitors, however some of the values of capacitor and resistor elements vary as a function of load current or state of charge. Constant current charge and discharge tests provided baseline characteristics. Element values were determined using data from self discharge and pulse test cycles. The model was validated using a realistic electric vehicle test in which the response of the battery model to an actual electric vehicle load profile was compared to that of the actual battery.**

Introduction

Deep cycle type lead acid batteries manufactured by companies including East Penn-Deka, Exide-Sonnenschein, Enersys-Genesis and EaglePicher-Horizon are generally used in electric vehicles are a mature technology. An electrical component model described in [1] was developed for a lead acid battery.

A test facility using computer software controlled current regulators [2] was used to collect battery characteristic data to determine model element values. The UMASS Lowell Battery Evaluation Laboratory has a complete battery test system. The equipment is designed to test single cells or entire battery modules ranging from 2 to 12 Volts at 1mA to 320 Amps. Stand-alone and computer-controlled sources and loads are included. The current regulators are capable of current sinking or sourcing and can change from charge to discharge mode instantaneously. The circuit diagram for a battery current regulator shown in Figure 1 includes power MOSFETS which are used as linear regulators, as well as the analog control and interface circuitry. Both continuous and pulse charging and discharging algorithms using active loads can be implemented by the data aquisition and control system. The data acquisition and control system provides a controlled current and stores data including voltage, current, impedance, and temperature for one to eight batteries under evaluation in a controlled temperature environment.

Nickel-cadmium batteries are also a relatively mature technology. The familiar small type cylindrical cells are manufactured by Gold Peak and the larger modules such as the STM 5-140 nanufactured by Saft which is the battery evaluated and the model which is the subject presented in this paper. Other battery technologies including nickel metal hydride and lithium ion polymer such as those manufactured by GP Industrial and Eagle Picher-KOKAM provide higher energy density and are generally available for small consumer electronic devices, but larger units such as those manufactured by Ovonic-Cobasys and Valence are also being developed for electric vehicles.

The nominal cell voltage and electrochemical equation can also be derived from standard half-cell reactions available in tabular references such as [3] and WebElements on line periodic table. The net electrochemical equation is the sum of the two equations and the nominal cell voltage is the potential difference.

(1) $Cd + 2OH^- \rightarrow Cd(OH)_2 + 2e^-$ - 0.82 V

(2) $NiO_2 + 2H_20 + 2e^- \rightarrow Ni(OH)_2 + 2OH^-$ 0.49 V

(3) $Cd + NiO_2 + 2H_2O \rightarrow Cd(OH)_2 + Ni(OH)_2$ 1.31 V

A battery model can be applied in simulations such as [4] used for electric vehicle applications.

Model Development

The battery model shown in figure 2 includes three impedance elements, a non-linear bulk capacitance and a self-discharge zener diode shunt element. V_t is the load or battery charger voltage. IL is the load current which is negative when the battery is being charged. R_{ac} is the ac impedance of the battery. It is measured automatically by the battery evaluation system, which generates a 120-hertz ripple current and determines the impedance by measuring the magnitude of the resulting ripple voltage. The shunt element diode D_s is characterized by the self discharge current I_s loss. The battery current I_b is the difference between the Load current and the self-discharge current. A relatively short time constant impedance element consisting of C_d and R_d is presumed to result from a charge depletion layer on the plates. A slower time constant impedance element consisting of C_e and R_e is presumed to result from diffusion of electrolyte from plate pores. The open circuit float voltage V_f is the sum of nominal voltage V_n and the voltage across the bulk capacitance C_b.

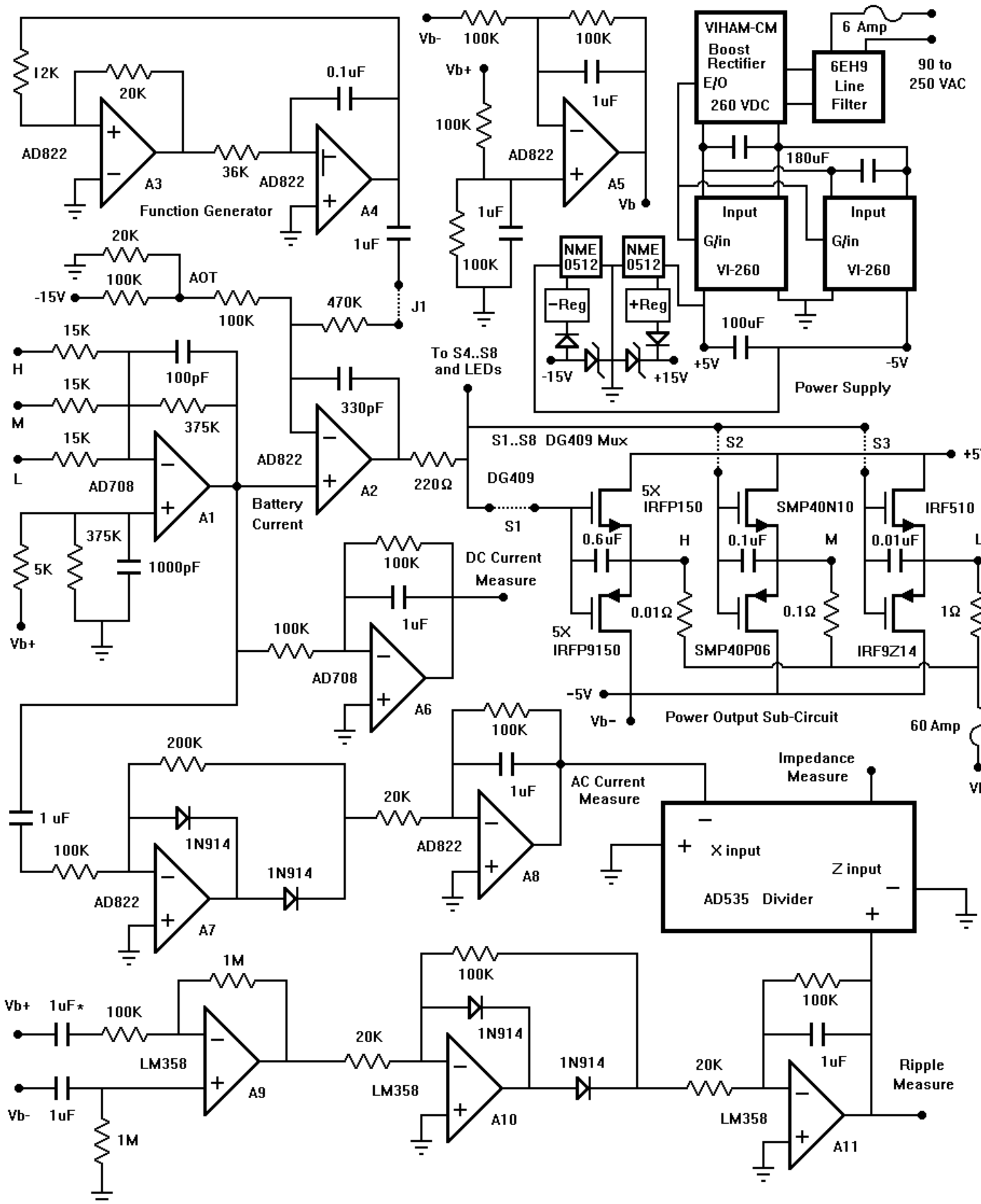

Figure 1 Linear Current Mode Battery Tester with Impedance Measurement

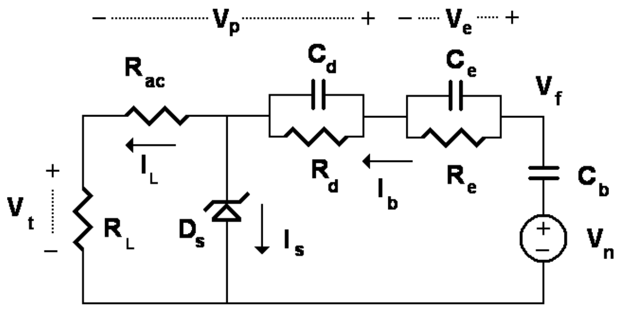

Figure 2 Electrical Component Battery Model

MODEL ELEMENT VALUES

Model element values are determined by experimental battery cycle test data. Measurements of the AC impedance at various test current levels are plotted in figure 3. This value is a function of current, however it is fairly close to 3 milli-ohms.

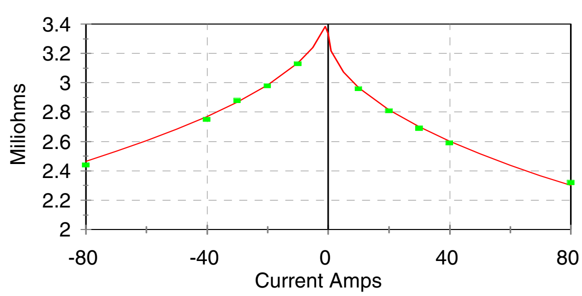

Figure 3 Measured values of AC impedance

The shunt element characteristics are determined by the results of the self-discharge test as shown in table 1.

Ta Deg C	Cap AH	Loss AH	Is Amps	Vf
0	143.5	6.2	0.037	6.91
10	146.6	9.7	0.058	6.86
20	148.8	14.8	0.088	6.75
30	149.6	19.0	0.113	6.61
40	149.0	21.3	0.127	6.50
50	146.5	25.4	0.151	6.44

Table 1 Self-Discharge Test Results

These data values as well as other experimental data including over charge current draw were fit to the following equation Where V_z = 8.17 and K_s = 0.021, and Tb is the battery temperature which result in the following characteristics depicted in figure 4.

(4) $I_s = 10\text{\^{}}(V_s - V_z + T_b * K_s)$

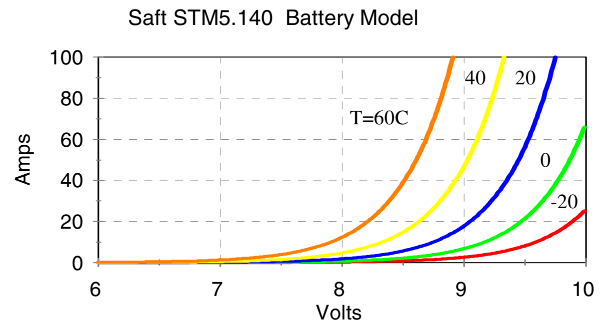

Figure 4 Self discharge Zener Diode I/V Characteristic

The pulse test depicted in figure 5 is a charge and discharge cycle with periodic rest time and current reversal. Results of the pulse test were used to determine element values of depletion layer related components and the bulk capacitance. The measured voltage drop across V_p is the sum of voltages V_{ac} and V_d. The resulting component characteristics are depicted in Figures 6a, 6b, and 6c.

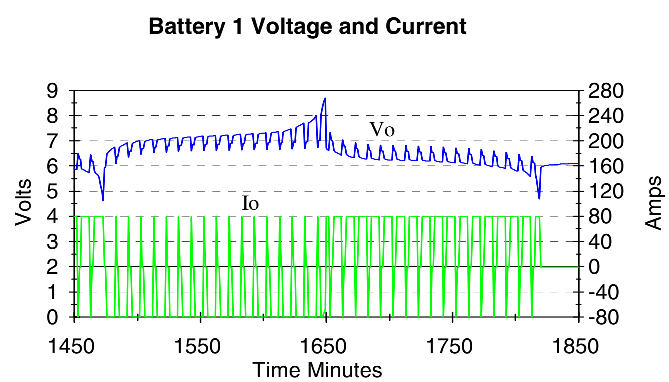

Figure 5 Pulse Test Single Cycle

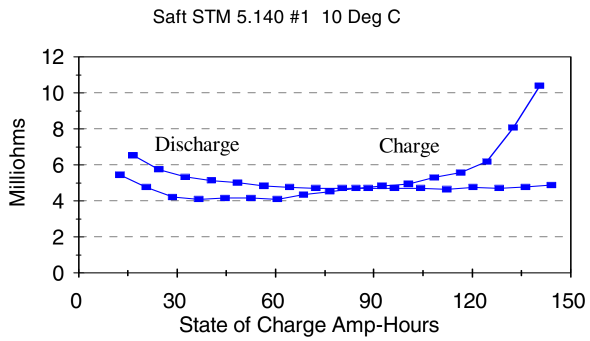

Figure 6a Effective Pulse Impedance of Voltage drop V_p

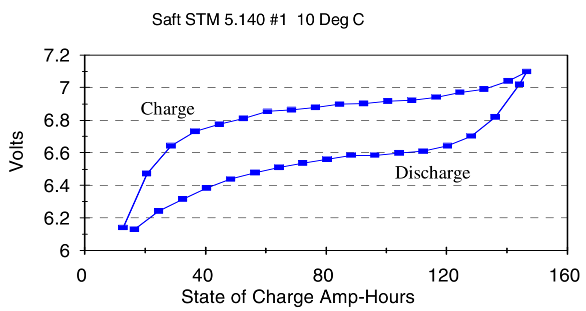

Figure 6b Open Circuit Voltage measured at test pause points

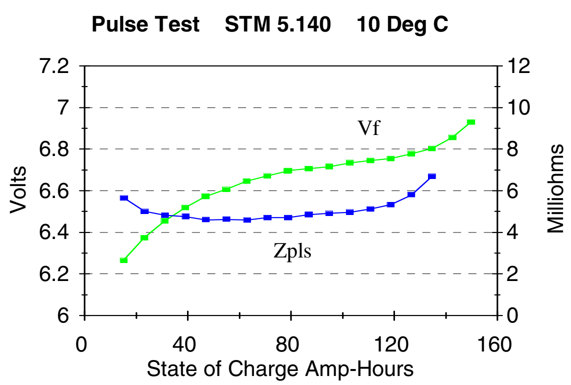

Figure 6C Average Pulse Impedance and V_f

Subtracting the AC impedance of 3 milliohms results in a nominal value for R_d of 1.5 milliohms at moderate SOC, but it is higher at very low or very high SOC. The value of C_d was found from the step response time constant. The voltage across capacitor element C_b is a strong function of state of charge, therefore it is not a constant. The value of the capacitor element found through numerical differentiation is plotted in figures 7a and 7b.

(5) $V_b=(80\text{-SOC})*\exp((80\text{-SOC})^\wedge 2/3000)/600$

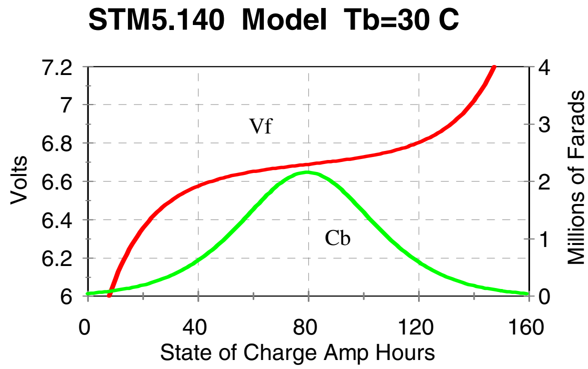

Figure 7a Bulk Capacitor Element V_b Characteristic

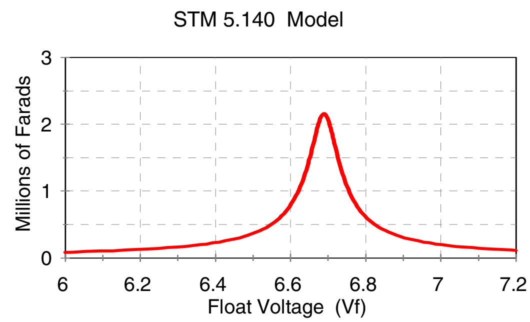

Figure 7b Bulk Capacitor Element V_b as a function of V_{oc}

Finally the voltage across the electrolyte impedance element V_e is determined by measuring the response of the battery to a current ramp cycle shown in figure 8 and subtraction of other element voltages. Its I/V characteristic is plotted in Figure 9a. An approximation of this characteristic generated using an RC circuit element is depicted in figure 9b, however a diode like component could more accurately model this component.

(6) $V_e=V_t-V_p-V_{oc}$

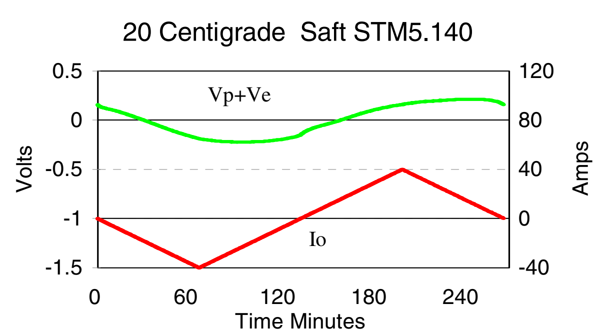

Figure 8 Ramp Current Test Cycle

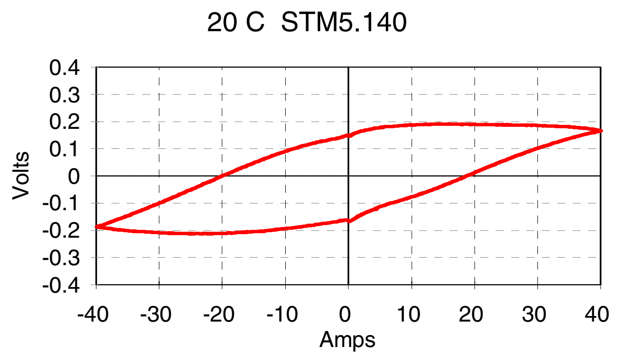

Figure 9aX/Y Plot of V_e from measured Ramp Cycle Data

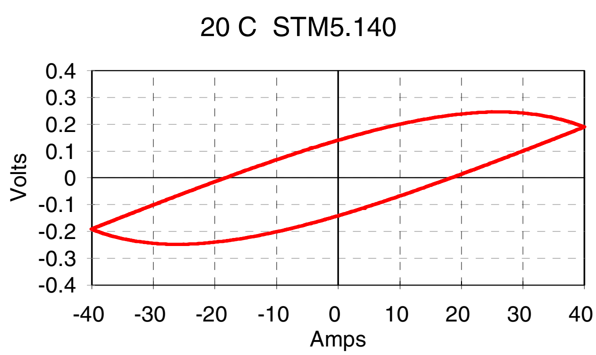

Figure 9b Model Element V_e Characteristic

Conclusions and Future Work

The Battery Model with typical component values as indicated in Figure 10 was developed for the Saft STM 5-140 Nickel Cadmium battery module using test data generated using the UMASS Lowell battery test facility. Models for other types of batteries and possibly other energy storage and conversion devices such as ultracapacitors could also be developed.

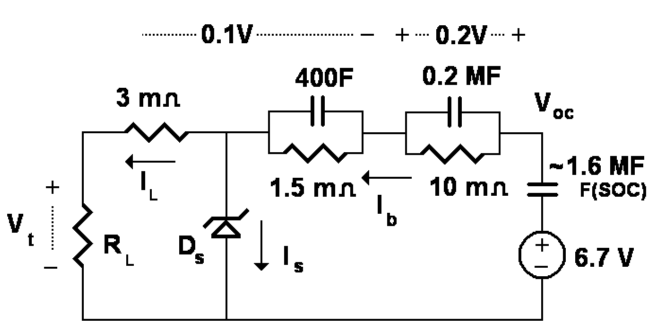

Figure 10 Battery Model With Typical Element Values

References

[1] Z. Salameh, M. Casacca, and W. Lynch, "A Mathematical Model for Lead-Acid Batteries", IEEE Trans. Energy Conversion, Vol.7, No.1 pp. 93-98 March 1992.

[2] M. Casacca, W. Lynch, and Z. Salameh, "Linear Current Mode Controller for Battery Test Application", IEEE Trans. Energy Conversion, Vol.8, No.1 pp. 20-25 1993.

[3] David R. Lide, "CRC Handbook of Chemistry and Physics", CRC Press, 2001.

[4] W. Lynch and Z. Salameh, "Realistic Electric Vehicle Battery Evaluation", IEEE Trans. Energy Conversion, Vol.12, No.4, 1997.

The following Internet links were available at the time of submission. These are subject to change by the companies that provided them.

http://www.eastpenn-deka.com/products/pdfs/epm0909.pdf
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I. Biographies

William A. Lynch was born in Cambridge, Massachusetts, USA on January 29, 1963. He received his B.S. M.S. and Doctor of Engineering. degrees in Electrical Engineering from the University of Massachusetts Lowell, in 1987, 1991 and 1997. He is a member of the IEEE Power Engineering and Power Electronics Societies and the Northeast Sustainable Energy Association. He is currently at the NSWC Philadelphia Naval Machinery Technology Center. His areas of interest include power electronics, electric motor drive systems, battery evaluation, solar electric vehicle racing, photovoltaic energy conversion systems and high performance current collector devices. He authored and co-authored 17 papers.

Ziyad M. Salameh was born in Agraba, Jordan in 1944. He received his B.S. in Electrical Engineering form Moscow Power Engineering Institute, Russia, in 1974 and his M.S. and Ph.D. from the University of Michigan, Ann Arbor, in 1980 and 1982 respectively. He is a senior member of IEEE. He taught in the department of Electrical Engineering at Yarmouk University in Irbid, Jordan from 1982 to 1985. He has taught at the University of Massachusetts Lowell (UML) since 1985. Professor Salameh chaired the ECE department at UML from 2001 to 2004. Currently he is the Director of the Center for Electric Cars and Energy Conversion. His areas of interest are renewable energy sources and electric vehicle technologies. He authored and co-authored more than 100 papers.