Electrical Characterization of Lead-Acid Battery at Load for HEV Applications

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Lead-acid batteries have been widely used as secondary batteries for more than a hundred years. For cost consideration, it is still a good resource for fast starting of cold vehicles, for recharging from either a stop-start braking system, or for a charge from the engine itself, which consumes battery energy or stores electricity back into chemical energy. Battery modeling is a key issue for different battery applications. It is necessary to develop a reliable and easy-to-parameterize battery model. In this work, the impedance technique is applied to dynamic modeling of battery behavior and diagnosis of quantities like actual capacity, state of charge (SoC) and state-of-health (SoH). Interpretation of the test results and proper modeling requires that the experimental setup allows some idealization like separating between working electrodes with reference electrodes or maintaining constant concentrations of reactants at the interface. The measurement and interpretation of the impedance of lead-acid batteries is further discussed, especially on nonlinearity, voltage drift, stability, half-cell measurements, model structure, and parameter extraction from the impedance data. This initial work focuses on the methods and procedures for testing lead-acid batteries at load and development of a reliable circuit model for predicting battery performance, which provides an opportunity to simulate a sophisticated lead-acid battery power system for HEV applications in a real time environment.

***Keywords**: Lead-acid battery; AC impedance; equivalent circuit; electrical characterization.*

The advantages of the lead acid system are its high-rate discharge capability, good specific energy, high reliability, robustness, and low-cost in both manufacturing and recycling, as the battery is manufactured mainly from a single low-cost raw material.[1, 2] Electrochemical impedance spectroscopy (EIS) is an excellent tool to analyze the interfacial process, variation in the internal resistance, state-of-charge, and the residual capacity of a lead-acid battery. *Ac* impedance is a fast, accurate, and non-destructive in nature for the modeling and diagnosis of industrial batteries.[3-5] The basic experiment of the EIS method consists of applying a small, sinusoidal voltage or current signal to an electrochemical cell, measuring the system's response with respect to amplitude and phase, and determining the impedance of the system over a spectrum of frequencies. Interpretation of the results and proper modeling requires that the experimental setup allows some idealization like separating between working electrodes and reference electrodes or maintaining constant concentrations of reactants at the interface.[6] The impedance technique can be applied to dynamic modeling of battery behavior and diagnosis of quantities like actual capacity, state of charge (SoC) and state-of-health (SoH).[7] The SoH influences mostly the ohmic resistance, the charge transfer resistance R_{ct} and the parameters of the constant phase element accounting the diffusion in the pores when the plate is well charged. Battery modeling is a key issue for design of different battery applications. It is necessary to develop a reliable and easy-to-parameterized battery model. However, for the lead acid battery, the impedance spectra depend very much on the short-term charge-discharge history. Karden *et al.*[7] further discussed methodological questions connected with the measurement and inter-

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pretation of the impedance of batteries, especially nonlinearity, voltage drift, stability, reproducibility, half-cell measurements, model structure, and parameter extraction from the impedance data. This initial work uses a 12 V auto lead-acid battery and ac impedance methods to collect the real time data at load conditions. Through the development of a suitable equivalent circuit to simulate the measured impedance data and predict reliable battery performance, the obtained parameters and physical elements can be further applied into PSpcie simulation or dynamic modeling of the HEV power system.

In this work, an EG&G Model 273A/ 5210 impedance system was first applied to the test of a defective lead-acid battery. The battery had no power left inside and could not be charged back to the normal operating condition. The defective battery voltage (several volts or mini-volts) are located in the normal 10 V range of the instrument requirement for impedance test. Secondly, using a Gamry FC350™/TDI electronic load, a 12 V Duralast 51-D lead-acid battery (a healthy battery with a capacity of 85 Ah, cold cranking of 500 Amp) was charged overnight at a current of less than 500 mA with a voltage no more than 12.8 V. The FC350 impedance system, working in hybrid impedance mode, modulates the current from the battery at load. Simultaneously, the current information at the electronic load is sent to the FC350™ monitor. The battery voltage is measured by the FC350 directly. The FC350 system collects these testing data and generates the impedance data files. The Hybrid EIS mode was applied for the experiments in order to observe the EIS behavior at low frequencies. Better results on ultra-low impedance analysis at a high power output can be obtained using this impedance system.

A simplified equivalent circuit R (RC_{pe}) for the defective lead-acid battery was applied to the NLLS fitting process (Figure 1). The three values of physical elements, *i.e.* R_s—uncompensated resistance related to the membrane/ solution, R_p —charge transfer resistance related to the polarization process, and C_{pe}—constant phase element related to electrode surface area or electrode roughness with a distribution of active sites on the surface. In another word, this physical element is a replacement of the double layer capacitor in

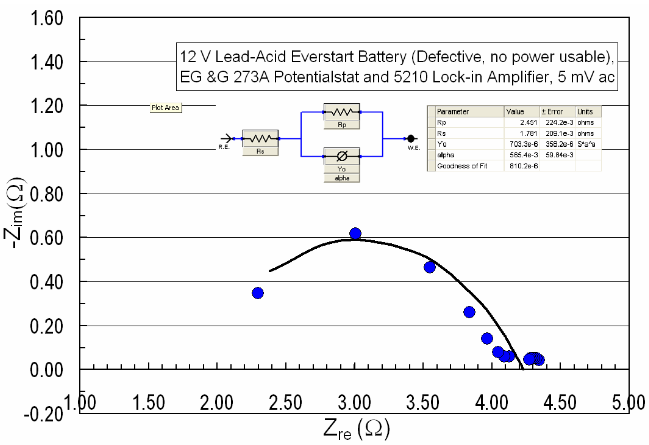

Figure 1. Nyquist plot for a defective Everstart lead-acid battery without a load. Data at high frequency side was not available using this impedance system.

considering the heterogeneous reaction rates on an electrode surface. For the specified defective lead-acid battery, a small amount of charge changes the shape of the Nyquist curve due to the change in resistance of the battery. The impedance test on the defective battery was conducted in order to understand the degradation mechanism. Extensive test for the performance and capacity degradation will be conducted in the future work.

Figure 2 shows the Nyquist plot of a normal healthy lead-acid battery which was tested at 1.0 A load via ac impedance. The battery voltage of 12.3 V before the test, charged overnight at a current of less than 500 mA with a voltage no more than 12.8 V. The assumed equivalent circuit model is written as $LR(RC_{pe})(RC_{pe})$. Impedance data is well fitted to the assumed circuit model. The errors near to the center area of the Nyquist semicircle were not clear. It appears to be related to the chemical crystallization and dissolution processes.[8] Further work will focus on the analysis of the impedance data at a higher current load and development of the circuit model related to the

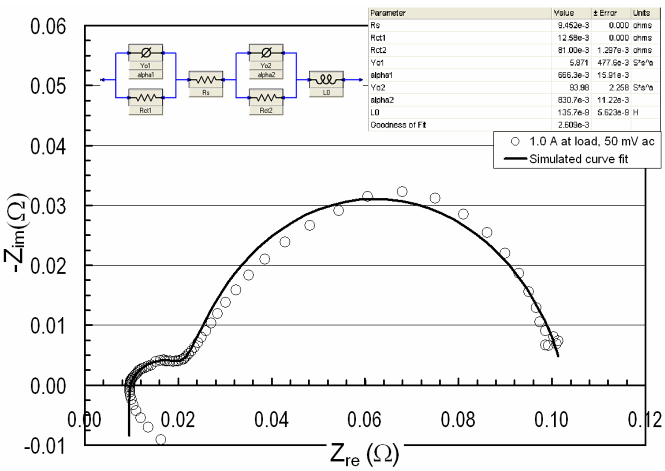

Figure 2. Nyquist plot for testing of a 12 V Duralast 51-D lead-acid battery at load of 1.0 A current (capacity 85 Ah, cold cranking 500 A). Battery voltage 12.3 V before test, charged overnight at a current of less than 500 mA with a voltage no more than 12.8 V.

physical process, chemical and electrochemical mechanism.

From AC impedance data collected at different currents, results are analyzed and compared between the circuit elements and physical processes determined via AC impedance and independent measurements of these same elements. Through different loadings (galvanostatic method), the more understanding about the mechanism and circuit model for the lead-acid battery will be obtained in the future work. The physical elements at load can be applied to PSpice circuit simulation or to test the dynamic load for HEV applications. The real time evaluation of lead-acid batteries potentially gives better understanding of the physical process, chemical reaction, and electrochemical mechanism in the dynamic power system.

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