Automotive Battery Modelling and Management

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Abstract

The estimation of vehicle battery performance is typically addressed by testing the battery under specific operation conditions by using a model to represent the test results. Approaches for representing test results range from simple statistical models to neural networks to complex, physics-based models. Basing the model on test data could be problematical when testing becomes impractical with many years life time tests. So, real time estimation of battery performance, an important problem in automotive applications, falls into this area. In vehicles it is important to know the state of charge of the batteries in order to prevent vehicle stranding and to ensure that the full range of the vehicle operation is exploited.

In this paper, several battery models have studied including analytical, electrical circuits, stochastic and electro-chemical models. Valve Regulated Lead Acid "VRLA" battery has been modelled using electric circuit technique. This model is considered in the proposed Battery Monitoring System "BMS". The proposed BMS includes data acquisition, data analysis and prediction of battery performance under a hypothetical future loads. Based on these criteria, a microprocessor based BMS prototype had been built and tested in automotive Lab,. The tests show promising results that can be used in industrial applications

Keywords: Battery modelling, management, automotive.

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1. Introduction

An automobile's electrical network consists of an alternator, a battery, a voltage regulator and several electrical and electronic loads (fans, computers, motors, etc.). The alternator is an electric generator that is physically coupled to the engine and can be controlled by the voltage regulator to convert mechanical engine power to electric power for on-board electrical loads, as they switch on and off. Standard modern consumer vehicles ship with alternators that can provide up to 100 A; it may therefore be understood that these vehicles are designed to adequately power loads that in total draw this much current [1].

The primary function of the battery in this network is to buffer the output of the alternator by absorbing any high-frequency pulses it may generate and by meeting transients in current draw while the alternator readjusts to meet such a new load. Furthermore, the battery powers the starter motor that cranks the engine to start it. The average driving cycle therefore consists of: the battery providing very high current (more than 600 A) for less than a second to drive the starter motor to start the engine and immediately thereafter powers all electrical loads. The alternator, in a matter of seconds, begins to generate the current drawn by these loads and the battery's discharge current decreases. As the vehicle is driven, the battery lapses to a quiescent state where it discharges only to meet transients in current requested (for example, when the air

conditioner is turned on, it will take the alternator a few seconds to meet this large load; meanwhile, the battery will provide the current needed to power it) but otherwise is steadily recharged [2].

Effectively and efficiently computing the State-of-Charge SOC of a vehicle battery in a dynamic, under hood environment has remained an elusive objective, especially for lead-acid battery designs. The need for these measurements becomes even more important as the battery becomes a more critical safety element in vehicles with increased loads. Electrical system demands for comfort, convenience, and telematics are growing drastically. New developments for fuel, cost and safety improvements are incorporating X-by-wire designs, idle start-stop systems, and other applications requiring higher voltage systems. These developments are driving the movement to 42-volt, deep cycle and HEV applications, and making the battery a critical element for both performance and safety. Calculation of the battery's ability to delivery energy at any moment, and understanding of its ability to accept charge and its state of health are needed. A battery monitoring system becomes essential to ensure vehicle operation. Automotive battery diagnostics historically have derived from discharge testing or load testing measurements. A fixed current discharge is timed and a voltage threshold is set and the resulting timed-discharge test is interpreted for battery capacity.

However, the aim of this work is to study the proposed model representing VRLA battery performance. The model is based on electric equivalent circuit. Moreover, a historical diagnostics of battery performance is presented.

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2. Overview of battery characteristics

The battery is an integral part of the automotive electrical network for many decades and the fundamental lead-acid technology has not changed. It consists of essentially two electrodes immersed in sulfuric acid electrolyte. Some modern advances include adding of valves to the battery and immobilizing the electrolyte (either by being absorbed by an Absorbent Glass Mat "AGM" or by gelling using silicon dioxide), allowing it to be used in any orientation, and also allowing it to be "sealed," making it maintenance-free.

It may be said that the main purpose of the battery in a car is to start the engine; only after this has been accomplished can the battery's secondary roles of providing power during high transient loads and maintaining charge be fulfilled. Therefore, the design of lead-acid batteries for orthodox automotive maximizes power density, cycle life, and ease of manufacture. Ability to perform at high levels of discharge is not important, and therefore it is considered unhealthy to leave a battery at any level of discharge.

2.1 Capacity

The amount of capacity that a battery pack can store is measured in units of Ampere-hours (Ah). This unit of measure is the amount of electricity delivered at one Ampere over one hour, and a capacity defined as such indicates the amount of charge that can be drawn for some length of time before the battery is considered discharged.
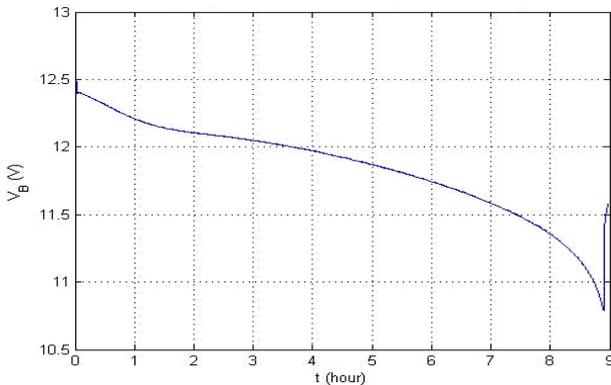

Fig. 1. Example curve obtained from a laboratory capacity test [2]

There is a fair amount of flexibility in what constitutes "completely discharged" and most manufacturers do not conform to any standard.

Theoretically, for a battery rated at 10 A-h, a discharge current of 1 A should deplete the battery in 10 hours, much as a 10 A discharge would in 1 hour. However, these expectations can be extremely inaccurate due to the nonlinear behavior of available capacity as a function of discharge current (in short, the higher the discharge current, the less apparent capacity). The capacity test is done to quantify a battery's capacity. The battery is discharged until the voltage reaches this minimum voltage which may be designated fully discharged. Fig 1 gives an example. The voltage curve obtained by this test proves useful in understanding other battery effects because it represents how the battery's open-circuit voltage, the amount of potential-carrying ions saturating the electrodes, evolves as the battery is discharged. Notice the rebound in voltage that happens when the discharge current is cut off; this will be explained below.

2.2 State of charge

State of charge (SOC) is simply a measure of how much current the battery can deliver after partial discharge or charge. It is an extremely difficult quantity to determine reliably and precisely due to the many nonlinear effects that exist in batteries. A major topic of research in the field is accurate and precise state of charge estimation and much theoretical and experimental work has been done, without the problem being completely resolved. A major result of battery research has been, however, that a lead-acid battery' open-circuit voltage (no-load voltage in a relaxed state) is a linear function of its SOC [3]. Therefore, one of the most important aspects of a battery's operational behavior, the terminal voltage, is strongly influenced by state of charge, as is the amount of charge it can deliver before some threshold capacity is reached. State of charge is a unit-less number between 0 and 1, corresponding to percent.

2.3 Coup de fouet

There exists for lead-acid batteries only a phenomenon that causes the terminal voltage to dip in the first few minutes of a discharge that follows a full charge. This dip is called the coup de fouet, and is shown in Figure 2. Although the effect was explained at least by the mid60s, only in the late 90s was it realized that one could determine reserve capacity of a battery using the coup de fouet, and much research was sponsored in the area. The coup de fouet may be applicable to automotive batteries as well, but has not seen much use because, although in general a car battery can be said to be at full charge after being driven for some time, a constant discharge current is not practical in a car.

The engine will be started with a very high current pulse lasting less than a second, there will be an inrush as the alternator reaches steady state, and then the battery will reach a quiescent state of charging; not much time for a discharge test as required by the coup de fouet.
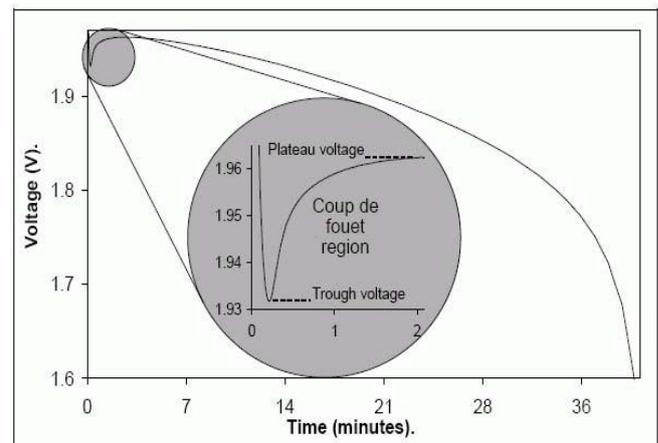

Fig. 2. The Coup de Fouet in a Hawker 2HI275 cell discharged at 275 A at 20 °C [5]

2.4 Aging and failure modes

A battery is conventionally considered to be dead if its available capacity drops below 80% of its nominal capacity (presumably when it was new). While the battery aging

identifies numerous fault modes, that is, internal changes to the battery caused by miss-usage, all of them manifest themselves to the external user as one of two effects: Decrease in capacity, and decrease in power delivery due to internal resistance.

With these two indicators in mind, we can examine some of the most common aging effects in lead-acid batteries. The primary unavoidable aging effect is **corrosion of the positive grid**, composed initially of metallic PbO2, and is probably the most important factor for calendar life. This effect is also called **grid growth** because the electrode physically expands. When this fault mode is activated, the life of the battery may be terminated by complete oxidation, or more often by the positive grid making contact with the negative top-bar of the battery, forming a short circuit. Through either of these two specific modes, grid corrosion is usually the cause of death because they are usually kept at float charge, and manifests itself as the second fault effect, that of increased internal resistance. However, another fault mode, the deterioration of the active mass on the positive electrode, is active in vehicles that experience heavy cycling. **Degradation of the positive active mass** is due to the precipitation of PbSO4 back to PbO2 during charging will cause a morphological shape change in the latter because PbSO4 crystals have much higher volume than PbO2 [6]. As this shape change becomes more and more pronounced, the lead dioxide particles lose coherence and shed from the positive plate. A third major aging mechanism is **sulfation**, and has many meanings among the user community. Recalling that the active mass at both electrodes reacts and becomes PbSO4 during discharge, the danger of it crystallizing into an electrochemically inactive form (not reversible to form lead and lead oxide) is always present. This used to be the scourge of battery designers and users for years but as charging regimes become more streamlined in vehicles, the occurrence rate has also declined.

There exist several other fault modes that operate ancillary to these three prime ones. They include: agglomeration of fine lead particles at the negative electrode, loss of electrolyte, loss of water, inter-cell connector failure, short-circuiting and electrolyte stratification. However, all these effects seem to manifest themselves as some form of capacity reduction or resistance increase.

3. Battery modelling methodologies

The main approaches taken to battery modeling are:

- Chemical modeling of the electrochemistry directly,
- Computational intelligence-based modeling
- Equivalent circuit models.

These models need to minimally provide an estimate of the terminal voltage, but to be at all useful, should give also state of charge, available capacity, and possibly some measure of state of health (that takes into account the aging of the battery).

3.1 Chemical modeling

As the totality of battery behavior is the result of myriad fairly well-understood electrochemical reactions at a molecular level, it should be possible to quantify each of these reactions with an equation and derive, bottom-up, a hyperfine description of the battery. Such a model would use experimental data to identify the static parameters that it needs, and would subsequently derive all dynamic variables; this would not be a phenomenological description of the battery that one might build. The primary disadvantage of this approach is that very few applications warrant the time and resources to empirically determine the many parameters and coefficients that such a physics-based model needs, and indeed many of them (such as average specific heat of electrolyte) cannot be determined for sealed lead-acid batteries in a lab, let alone in a vehicle for battery diagnostics purposes.

3.2 Computational intelligence-based modeling

An opposite school of thought holds that a battery comprises processes too complicated and interrelated to model individually, and seeks a data-driven heuristic approach to predicting battery behavior and state. To this end, computational intelligence techniques such as artificial neural networks and particle swarm optimization may be applied to experimental data to fabricate a nonlinear function that can describe the outputs of the battery. An artificial neural network (ANN) is generally the cornerstone of a computational intelligence model because this is the tool that can be trained on experimental data. The acquisition and selection of this training data is generally the most difficult process in utilizing an ANN. When training has been completed, ANNs' extrapolation and interpolation abilities outside and within its training set can vary due to its design (number of layers and neurons, local weighting function, etc.), which is another dimension of their use, beyond selection of training data.

3.3 Equivalent circuit models

Between the low-level chemical modeling and the input-output heuristic-level modeling exists a compromise. It is possible to understand the chemical processes in the battery, and approximate their effects as the behavior of a lumped-model network of higher-level physical systems.
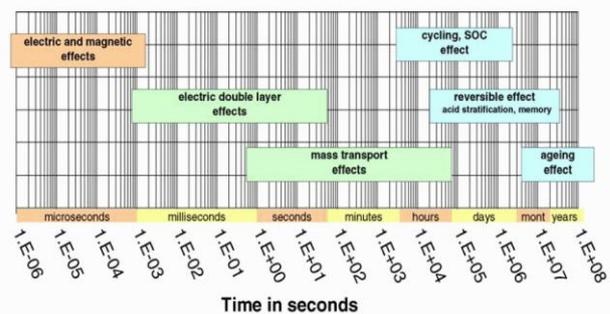

Fig. 3. Listing of major dynamic processes in batteries and their average time constants

In this section, we review a number of ways to reduce complex chemical phenomena to well-understood and well-behaved electrical-level circuit elements in creating a model.

The long-term processes such as irreversible aging, some reversible effects such as minor sulfation or acid stratification, and cycling processes vary greatly from battery to battery due to their dependence on how the battery is used.
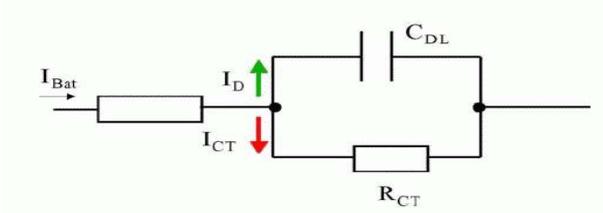
Fig 4 Equivalent circuit modeling double-layer capacitive effects

These effects are desired to be quantified for aging and prognostics studies of batteries and therefore must be domain-specific.

Fig 4 shows that this effect can be reduced to a simple electrical equivalent circuit. The parallel circuit parameters vary by state of charge and temperature, and even battery age and current levels. The series element is an Ohmic resistance.

These equivalent circuit models were derived from a first-principles understanding of the physiochemical processes occurring inside the battery. They lend themselves very naturally to be fleshed out, and their circuit element values identified.
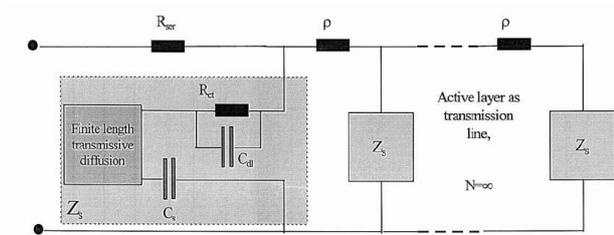

Fig. 5. Universal battery model equivalent circuit

The identification of these circuit parameters at varying states of charge is done using electrochemical impedance spectroscopy, and further nonlinear least-squares fitting to separate some variables.

4. Experimental/modelling setup and results.

The battery model that was used will be introduced and explored. With the model chosen, the need for experimental characterization remains and a fairly thorough overview of the experimental bench that had been built at Automotive Lab and that was used for this study will be given. This includes hardware &software control and some analysis.

The methodology utilized in modeling 12 V lead-acid batteries will then be detailed. As all practitioners of battery engineering know, the equations and values provided by models have great variability. Therefore, exact methodology is very important to give end-users of battery models sufficient insight into the domain of their models and when they may no longer apply, and to compare variations in models.

4.1 Lead acid battery equivalent circuit modeling

The electrical model describes the battery is shown in Fig 6 considering that the circuit elements in this model are assumed to vary as some functions of state of charge, temperature and current magnitude. Current direction is considered positive for discharging and negative for charging.
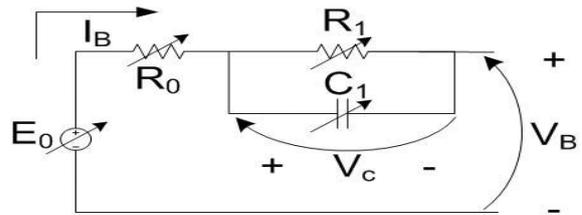

Fig. 6. battery equivalent circuit model with variable parameters

Kirchoff's current rule yields

$$E_0 - I_B R_0 - V_C - V_B = 0 \tag{1}$$

The capacitor Voltage V_C can be obtained by the following differential equation

$$\frac{dV_C}{dt} = \frac{1}{C_1} I_B - \frac{1}{R_1 C_1} V_C \tag{2}$$

Solving equation (2) will result in

$$V_C(t) = V_C(0)e^{-\frac{t}{R_1 C_1}} + R_1 I_B (1 - e^{-\frac{t}{R_1 C_1}}) \tag{3}$$

Combining this result with the battery terminal equation yields the following for the terminal voltage

$$V_B = E_0 - I_B(R_0 + R_1) + (I_B R_1 - V(0))e^{-\frac{t}{R_1 C_1}} \tag{4}$$

This equation can be applied to different situations. These relationships become important when performing parameter estimation based on experimentally obtained input/output current/voltage curves.

When $t \to \infty, I_B = 0$

then $V_B(t \to \infty) = E_0$, $V_C(t \to \infty) = 0$ $\tag{5}$

When $t \neq \infty, I_B = 0$

then $V_B(t) = E_0 - V_C(0)e^{-\frac{t}{R_1 C_1}}$ $\tag{6}$

When $t \neq \infty, I_B \neq 0, V_C(0) = 0$

then $V_B = E_0 - I_B(R_0 + R_1) + I_B R_1 e^{-\frac{t}{R_1 C_1}}$ $\tag{7}$

When $t \neq \infty, I_B \neq 0, V_C(0) \neq 0$,
the complete equation returns as follows

$$V_B = E_0 - I_B(R_0 + R_1) + (I_B R_1 - V_C(0))e^{-\frac{t}{R_1 C_1}} \tag{8}$$

The above explained battery model is embedded in the battery system model shown in Fig 7. An equivalent circuit model is the only type of model that is amenable to simulation as well as fault diagnosis and dynamic system analysis. However, as the three major variables that pervade and strongly influence battery behavior are terminal voltage, state of charge (SOC), and temperature, and only one of

these is a strictly electrical value, the model must include dynamic state equations for SOC and temperature.
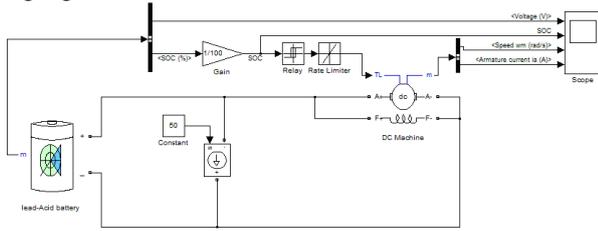Fig 7 gives a schematic of this model

Fig. 7. Lead acid battery system model

The simulation technique using the MATLAB function, in conjunction with a Simulink model of the battery differential equations requires a set of initial parameters of the model (nominal values for open-circuit voltage, resistances, and capacitances) and nonlinearly iterates on the initial guess vector to find a set of parameters that minimizes the discrepancy between the output of the simulated model and the actual battery.

The algorithm of the battery simulator starts with the setup of the battery parameters. These parameters are capacity of the battery, cold cranking Amps, battery temperature, initial state of charge. With these parameters, the initial internal resistance is calculated and the output voltage is set with respect to the output current. Within the operational cycle of the simulator, the current is feed into a charge calculation to determine the discharge history of the simulated battery. The integral of the current by time is therefore corrected by a current and temperature dependent parameter field has been worked out in experiments with real batteries. In the next step, the internal resistance of the battery is calculated with respect to the charge state of the battery.

4.2 Experimental setup

An experimental prototype for battery monitoring had been designed, built and tested in automotive Lab. This microprocessor based prototype including necessary hardware and software to accomplish the battery monitoring tasks. The proposed system Hardware for battery monitoring system As shown Fig 8. The prototype contains microprocessor with its associated circuitry. Also, it has LCD display that shows both battery voltage and SOC in addition to LED's to show the general status of the battery.

Fig. 8. Hardware of battery monitoring and fault diagnosis system

The software controlling the system involves:

a) Measurements of battery voltage & ambient temperature
b) Calculating Battery SOC
c) Displaying battery voltage and SOC
d) Driving LED's that shows battery general status "Good, Fair, Bad"

4.3 Simulation and experimental results

The open-circuit voltage is known to be a function of only SOC and temperature, as it is defined for an unloaded battery. The data gathered at 20 °C is shown in Fig 9 at charge and discharge.
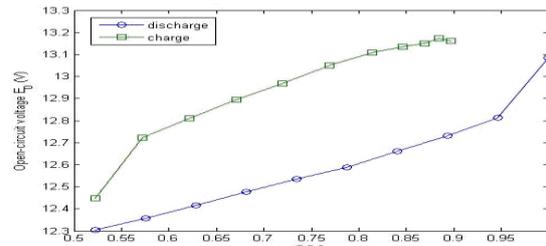

Fig. 9. Battery open-circuit voltage as a function of SOC at 20 °C.

The effect of surface charge is very clear for the discharge case: the experiment was begun with the battery fully charged, and therefore the first open-circuit voltage is elevated. This is useful because the battery model will certainly operate at high SOCs, due to voltage regulation in the vehicle (and in the larger automotive electrical network simulator that it will run in), during which the effects of surface charge must not be ignored. Note the effect Note the effect of surface charge at high SOC, where the experiment began. A second point to note about the open-circuit voltage is that there is a strong hysteresis between open-circuit voltages in the charging and discharging cases, at the same SOCs. This is due to surface charge.
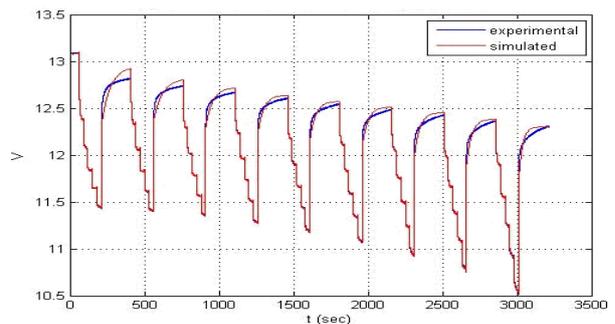

Fig. 10. Battery open circuit voltage (simulation & experimental) at discharge

Fig 10 the plots of the open-circuit voltage during discharging that clearly indicate the effect of surface charge at the beginning of discharge followed by a significant discontinuous jump to the next set of pulses

5. Conclusions

1. The modern vehicle is highly dependant on its electrical system for operation and passenger pleasure. Output of consistent power from the battery is critical to maintain

the vehicle. Battery questions and issues continue to cause major service problems and continuous wasted cost in nearly every vehicle applications.

2. In this paper, several battery models had studied including analytical, electrical circuits, stochastic and electro-chemical models. VRLA battery had been modelled using electric circuit technique. This model is considered in the proposed Battery Monitoring System "BMS".

3. The proposed BMS includes data acquisition, data analysis and prediction of battery of battery performance under a hypothetical future loads. Based on these criteria, a microprocessor based BMS prototype had been built and tested in automotive Lab. The tests show promising results that can be used in industrial applications

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