

Universal model of the galvanic battery as a tool for calculations of electric vehicles

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ABSTRACT: In this paper, a model of the galvanic battery is presented. This model is composed of equations which are suitable for the simulation of various types of galvanic batteries if the proper coefficients are used. The model can be used as a tool for the calculation of electric vehicle performances, such as the estimation of fuel-saving potential and the verification of efficiency of the state-of-charge management strategies. The technique for an evaluation of the necessary equations' coefficients on the rated data of a battery is given.

1 INTRODUCTION

The battery is the core element of either a hybrid or pure electric vehicle. Other components like electric motors, electric power converters of various types and even internal combustion motors are believed to have reached their maximal possible efficiencies. Their further improvement is hardly possible in the near future. Moreover, with the current performances of energy storage devices, which are primarily galvanic batteries, improvement of other electric components is inexpedient. For a hybrid electric vehicle (HEV) of any topology, it is the battery that limits fuel-saving and, usually, vehicle's dynamics.

To prove this statement, we have to consider the sources of fuel saving and their potential. A hybrid electric vehicle derives its economy from three basic processes: recovery of vehicle's kinetic energy during braking, improvement of internal combustion engine (ICE) operation regime and turning the engine off during stops (microhybrid technologies).

Utilization or recovery of kinetic energy means capturing it during braking (otherwise it dissipates as heat on the brake disks) and storing it in the battery or other device like an ultracapacitor or a superflywheel. This approach gives the best fuel saving for driving patterns with frequent starts and stops. Also, it can be done only if the electric part of the powertrain has enough power rating to provide necessary deceleration. In most modern HEVs only a small part of the kinetic energy is recovered, mainly due to constraints from the battery charging rate.

Shifting the ICE's operation point into more efficient zone is done mainly in vehicles of a series topology. The engine rotates with constant speed and torque and charges the battery with optimal current. Then the ICE is turned off and the vehicle propels itself using the energy accumulated. This principle can also be realized in parallel hybrids, though it requires a more complicated control approach. Generally, the principle is best suited for driving patterns with relatively long cruising. Again, the battery energy capacity defines the vehicle's efficiency.

Finally, many modern vehicles employ so called microhybrid technologies. In microhybrids, there is no mechanical connection between the electric motor and the wheels and no electric powertrain. The electric part of the vehicle is used only to provide operation of auxiliary equipment when the ICE is turned off. This approach is especially effective for city driving with frequent stops at traffic lights, saving fuel and reducing CO₂ emissions.

The potential of the three sources is shown in Fig. 1.

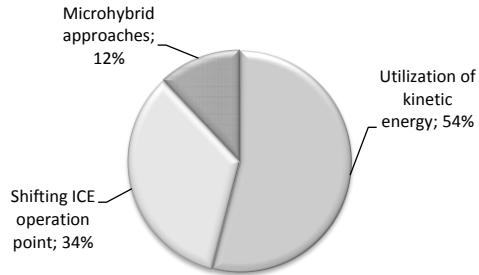


Figure 1. Potential of the main fuel-saving sources

The value of maximum fuel saving, provided by all three technologies, is taken to be 100%. So, the recovery of kinetic energy provides the biggest share of maximal possible fuel saving, but, at the same time, this principle requires the highest demands for battery ratings, particularly, its charging current.

Today, electric double-layer capacitors, or ultracapacitors, have emerged on the market and became rather cheap. Their application for energy recovery in HEVs is very promising, but the need to stabilize the voltage makes such solutions still very expensive. So, galvanic batteries will remain the prevailing energy storage in the near-term scenario.

All energy-saving strategies for electric vehicles rely on certain management of the battery's state of charge (SOC). To apply one, it is necessary to know the behavior of the battery and its limiting factors during charging/discharging modes. We shall try to provide researchers with the tool for the estimation of efficiencies of their energy-management strategies and verification of vehicles' performances.

2 BATTERY MODEL

Assumptions. Physical phenomena occurring in galvanic batteries are complicated and, generally, described by nonlinear equations. In context of calculations for HEVs the model of battery should be simplified as much as possible. Thus, the following assumptions should be taken:

- the battery's internal resistance is constant during charge and discharge cycles and does not depend on the amplitude of the current;
- all required coefficients in the equations and model parameters are taken from discharge characteristics, and accepted the same for charge mode;
- the temperature does not affect the model's behavior;
- the self-discharge of the battery is neglected;
- the memory effect is neglected.

General equation. The battery model represented below reflects all electrical processes occurring in galvanic elements of various types. Equations reflect the voltage dynamics under current variation and take into account the value of open circuit voltage (OCV) as a function of state of charge (SOC). The effect of polarization is induced into equations in order to improve the accuracy of simulations for no-load operation modes.

The battery voltage is described by the following equation:

$$V_{batt} = E_0 - K \frac{Q}{Q - it} \cdot it - R \cdot i + A \exp(-B \cdot it) - K \frac{Q}{Q - it} \cdot i^* \quad (1)$$

where V_{batt} – battery voltage, V;

E_0 – battery constant electromotive force, V;

K – polarization constant (V/(Ah)) or polarization resistance (Ω);

Q – battery capacity, Ah;

it – actual battery charge, Ah;

A – exponential zone amplitude, V;

B – exponential zone inverse time constant, Ah;

R – internal resistance, Ω ;

i – battery current, A;

i^* – filtered current, A.

Model limitations:

- minimum voltage of non-load battery is 0 V, maximum voltage is $2 \times E_0$;
- minimum battery capacity is 0 Ah, maximum capacity is Q.

The equation contains the component of voltage drop caused by the filtered current flowing through polarization resistance. This element of equation reflects the process of slow voltage decrease down from its maximum level with the rate proportional to the current magnitude. Using filtered current allows one to exclude algebraic feedbacks, a typical problem of galvanic batteries simulation.

Another problem is that the OCV depends nonlinearly from SOC. This effect can be simulated using so called polarization voltage. The last element in the equation represents nonlinear function of battery voltage from discharge current and actual battery charge.

The exponential discharge zone in the equation is typical for Li-Ion batteries. Batteries of other types (Lead-Acid, NiMH and NiCd) have hysteresis between charge and discharge, which does not depend on their actual SOC. The voltage drop caused by this phenomenon can be calculated using nonlinear dynamical system given below:

$$Exp(t)' = B \cdot |i(t)| \cdot (-Exp(t) + A \cdot u(t)) \quad (2)$$

where $Exp(t)$ – voltage in the exponential zone, V;

$i(t)$ – battery current, A;

$u(t)$ – charge or discharge mode.

Voltage in the exponential zone depends on its initial value $Exp(t_0)$ and operation mode (charge or discharge). It should be taken into account that charge and discharge processes' description depends on the type of battery. Proper equations for different batteries are given in the table below.

Table 1. Functions of voltage drop for various types of batteries.

Type of battery	Equations for charge and discharge modes
Lead-Acid	Discharge $V_{batt} = E_0 - R \cdot i - K \frac{Q}{Q - it} \cdot (it + i^*) + Exp(t)$ Charge $V_{batt} = E_0 - R \cdot i - K \frac{Q}{it - 0.1 \cdot Q} \cdot i^* - K \frac{Q}{Q - it} \cdot it + Exp(t)$
Li-Ion	Discharge $V_{batt} = E_0 - R \cdot i - K \frac{Q}{Q - it} \cdot (it + i^*) + A exp(-B \cdot it)$ Charge $V_{batt} = E_0 - R \cdot i - K \frac{Q}{it - 0.1 \cdot Q} \cdot i^* - K \frac{Q}{Q - it} \cdot it + A exp(-B \cdot it)$
NiMH and NiCd	Discharge $V_{batt} = E_0 - R \cdot i - K \frac{Q}{Q - it} \cdot (it + i^*) + Exp(t)$ Charge $V_{batt} = E_0 - R \cdot i - K \frac{Q}{ it - 0.1 \cdot Q} \cdot i^* - K \frac{Q}{Q - it} \cdot it + Exp(t)$

Having these equations and interdependencies between voltage components and battery current, we can compose the universal model of galvanic battery (see Fig. 2).

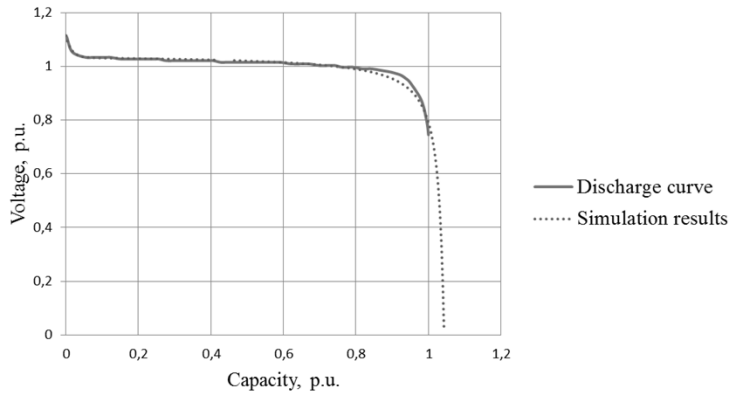


Figure 4. Simulation results

As we can see, the model rather accurately reflects the discharge process. Dynamical behavior of the battery during several charge/discharge cycles is shown in the figures below. The curves are built in per units.

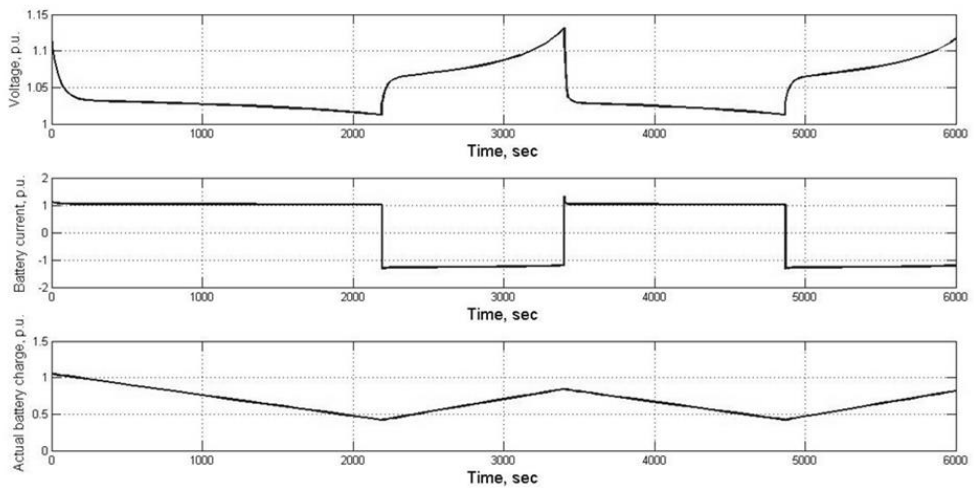


Figure 4. Dynamic processes during charge/discharge cycles

Conclusions and further studies. The structure and dependencies reflect correlations between battery state of charge, its voltage and current in various operation modes. Thus the model can be used for simulation of energy exchange processes in hybrid or pure electric vehicles, estimation of necessary battery parameters in order to obtain target performances on fuel saving or vehicle's dynamics and for other purposes.

In order to improve the description of battery behavior it is necessary to consider the dependence of battery capacity on the magnitude of discharge current. It is especially important when dealing with Lead-Acid batteries.

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