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BATTERY PACK DESIGN PROBLEMS - INFLUENCE OF THE TRANSVERSE MAGNETIC FIELD ON INTERNAL BATTERY RESISTANCE

Abstract: *The battery pack represents an essential part of electric vehicles (EV), so its design significantly influences the drive characteristics. The system of energy flow control in EV use high-frequency power electronic components that cause the appearance of high harmonics super-imposed on DC component of the battery current. This paper examines the influence of the distribution of the transversal magnetic field inside of the battery pack depending on battery pack design and its influence on battery parameters. DC component of the transversal magnetic field inside of battery cells cause Hall effect ions path allocation that is reflected on internal battery resistance negative change. AC component of the transversal magnetic field in electrically closed loops within battery pack induced e.m.s. that also cause negative phenomena on battery pack parameters.*

Key words: battery pack design, Hall effect, internal battery resistance, transversal magnetic field.

INTRODUCTION

Energy efficiency and reduction of CO2 emissions as modern trends rapidly to market introduce EV that, at this stage of development, have numerous design solutions of the EV drives. The battery as energy storage is an essential part of the EV drive, which has a duty to respond to the dynamic requirements of the vehicle for energy. The design of a battery pack is based on the cell and its parameters, and by parallel or serial connection it builds a package that must provide the required power level and capacity. In this work cylinder shape cell is observed as the most common solution.

BATTERY PACK DESIGN

The way of cell merging into the total packet depends on a large number of design requirements (energy availability, temperature protection, ...). The most commonly accomplished topology merge cells in parallel to the battery block to secure the capacity and then the blocks are merged serially into the battery pack to ensure adequate voltage levels.

What is often forgotten is that the battery does not store electricity. The battery is a reservoir of chemicals that produce electricity and store energy by chemical reaction [1,2]. Therefore, the battery does not have the possibility of an electric circuit to be switched off or on, instead they are always on. If a short circuit is provided by design (parallel connection of battery cells), the chemicals will react and produce electricity. Even inside one battery cell, there exists a closed loop that provides relatively small self-discharge current (this is the reason why the battery cannot store energy for a long period). For most cases, where by design battery cells are parallel connected, the connection is permanent and any possible short-circuit current within parallel connected battery cells will ultimately cause discharging (rapidly faster process than in a case of a self-discharging caused by uneven voltages of connected cells). It leads to irreversible degradation of the electrolyte (battery potential energy – stored capacity). Basically, stored chemicals inside the cells are not capable to react in the normal way to produce electricity, disintegration and/or dissolution of active material structure bring battery cell to End of Life [2].

As it can be seen on block diagram (Fig.1.) the numerous internal mechanisms of the battery and its surroundings affect the battery health. Most of them cause thermal disintegration of the chemical process. In this paper, an additional effect calculation is proposed. The effect studied is caused by a magnetic field to which battery cell is exposed due to battery block design. Parallel connection of the cells (to provide multiplication of battery current) in industrial

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production usually are made by Spot Welded Nickel buss (Fig.2). This is hard to obtain in small manufacture production (e.g. prototyping design for a solar electric car) due to the problem of completing the set of cells with practically identical characteristics (voltage and capacity). Every inequality can produce balancing currents within unequal battery cells that in the end reduce the capacity of both cells, as it is already explained.

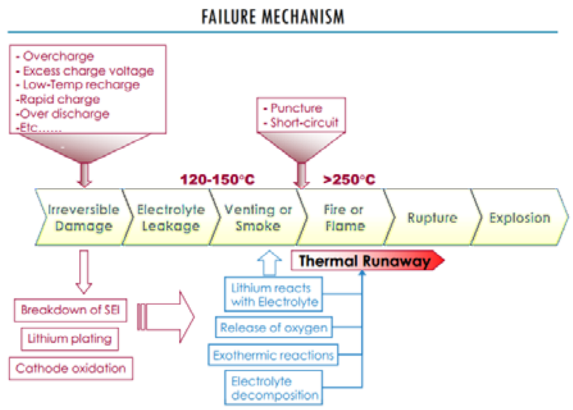

Figure 1. *Block diagram of failures event that can occur at Li-Ion batteries*

Battery block shown in Fig.3 is realized from 15 cells in parallel connection through top and bottom plates with an interconnection bar to provide negative contacts on the upper plate (prototype design of the battery block for solar electric vehicle). Battery block design (Fig.3.a) is often used solution because it's very easy to have all connection points between blocks on one side of a battery pack.

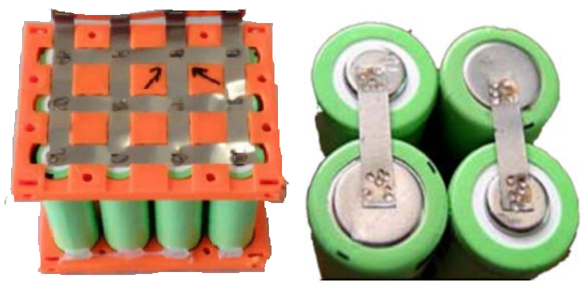

Figure 2. *Battery block example of Spot Welded Nickel buss for WorldSolarChellenge Solar Car* [3]

Problem in this design that each battery cell in parallel block have closed loop with interconnection bar (Fig.3.c) that is practically rectangular shaped, providing the area for inducing the EMF (change of magnetic flux through closed loop area in situation of rapidly changing battery current produces an induced EMF due to Faraday's law of induction. If the battery cell is considered a constant voltage DC source connected to dynamically changing load (as shown in Fig.4), the produced current will be time variant related to the variable load. Therefore, by the Faraday law, an EMF will exist, and it can be modelled as a variable voltage source that opposes the battery voltage source.

Consequently, this effect can be observed, in the battery cell model, as an additional serial connected voltage source (Fig.4.) that is dependent on the total battery block electric current time change and the heat source in battery cell that cause an additional degradation of the batteries chemical reaction. [4]

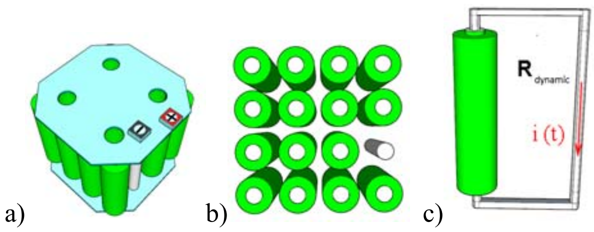

Figure 3. a) *Battery block built by 15 parallel cells and interconnection bar. The contacts are on the same side on the upper plate, b) Cross-section of the block with shown interconnection bar, c) Lumped model of the electric circuit consists of one cell and interconnection bar.*

MAGNETIC CIRCUIT MODELLING

Battery cell models differ mostly in approach to compute lifetime for specific discharge profile in relation to the complexity of the drive model. For relatively precise calculation (huge demand of calculation power and time consumption) the Shepard model is often used [5, 6]. That model determines total battery cell voltage using different parameters in relation to the battery current, polarization resistance, extracted capacity, maximum capacity and drop off exponential capacity. These parameters are obtained from charging/discharging battery characteristics given by the manufacturer, and in the end, this model calculates the voltage of the battery that depends on just one variable: State-Of-Charge (SOC).

In this paper an upgrade of the Shepard model is proposed with an additional internal serial voltage source and parallel resistors for modelling the magnetic effect on battery cell as result of the battery block design.

For introducing the magnetic field influence of battery block design (presented in Fig.1.c) to battery model, it must be taken into consideration that total battery pack power flows through each subsection (battery blocks are in serial connection) presented by the electric circuit (Fig.1c) and apart from the DC component, there are spectral harmonics caused by the power electronics. In the case of the dynamic load of the battery ($di/dt \neq 0$), the induced voltage, modelled as a voltage source dependant on the load current that opposes the change of the current appears. Dynamic resistor presents the load that uses the battery energy for propulsion.

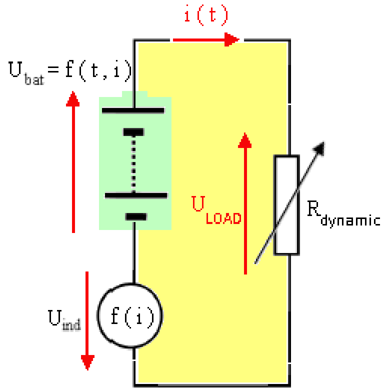

Figure 4. *Lumped model of electric circuit for one battery cell as part of the battery parallel block*

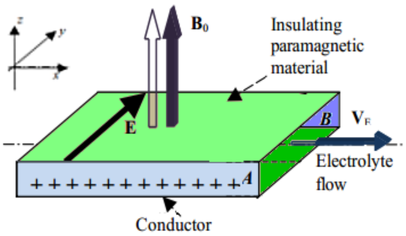

Figure 5. *Hall effect ion path allocation in electro-lyte as result of imposing transverse magnetic field and electric field current flow*

Equation (1) presents the Ohmic law for Lumped model (Fig.4) of the single electric circuit with modelled battery cell as voltage source dependant on the cell current [4].

$$U_{bat}(t,i) - U_{ind}(i) = i(t) \cdot R_{dynamic}(t) \qquad (1)$$

The load, presented as a dynamic resistor, is a function of time (EV drive demand for energy from the battery as a function of time). Finally, the loop surface used to calculate the induced voltage source as a function of cell current (for given geometry presented in Fig.3.c) corresponds to the yellow marked area on Fig.4. To calculate the induced EMF for rectangular shaped design (shown on Fig.3.c) the inductance of the loop needs to be calculated. This is the well-known relation that can be taken in simplified form:

$$L_{\text{square}} \approx N^2 \frac{2w\mu}{\pi}\left[\ln\left(\frac{w}{a}\right) - 0{,}77401\right] \qquad (2)$$

where are: w-dimension of the rectangular loop, a-diameter of the wire, N-number of turns, μ-permeability.

For the design shown in Fig.3.b, the calculated inductance mean value for each cell in battery block is 98μH. This is relatively small value. Now consider the harmonics of current produced by the power electronics that control the energy flow in power drive (normal switching operation of the electronics is above 10 kHz), the induced voltage U_{ind} has the peak value of 23,5% referred to the nominal battery cell voltage (standard driving cycle). The real mean value of the additional voltage source should be calculated for the particular drive cycle (e.g. driving the car through city traffic). Additional problem is to calculate possible recuperation of the braking energy, that is not present every time when the vehicle slows down.

$$U_{\text{ind}}(i) = L_{\text{square}} \frac{\mathrm{d}i}{\mathrm{d}t} \qquad (3)$$

The second effect, that is proposed in this paper to be taken into consideration, is the Hall effect within the battery cell due to magnetic field present in the battery block volume. Within the battery cell, there is an imposed transversal magnetic field from the rest of the battery block elements (Fig.6.) that influence the electrolyte ions by Hall effect.

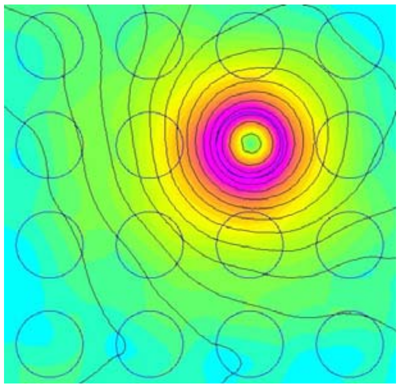

Figure 6. *Transversal magnetic field distribution as result of battery block current*

A simple theory of electrolyte conductance in coupled electric/magnetic fields is presented in early 60's in research from two scientists: Falkenhaim (Germany) [7] and Mohanta (Canada) [8,9]. If we considered that ions flow through electrolyte perpendicular to an imposed transversal magnetic field from the rest of the battery block elements the Lorentz force will separate flow of positive and negative ions creating a resistance to ions flow (Fig. 5) [10,11]. As a result of Hall effect, the electric field that has direction perpendicular to direction of ions (Fig.7) it can be modelled as an additional parallel resistor to the Sheppard model of the cell.

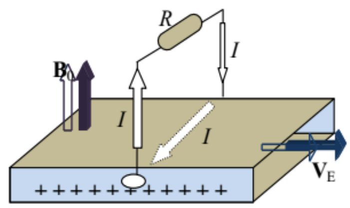

Figure 7. *Lorentz force on electrolyte ions in motion passing under a transverse magnetic field produce Hall effect voltage.*

To calculate this resistance, the model presented in [9,10,11] can be used. An electrolyte solution flows through the model as a rectangular tube with the cross-section 2*w*-wide and *h*-high of the path of the ions), with velocity v_E in a volume of length *L* where the magnetic field B_0 is orthogonal to v_E, and the result is the produced Lorentz force with perpendicular current flow, that can be considered as resistance. [9,11]

The relation that can be obtained for Li-Ion battery cell is shown in Eq.4. Hall effect induced internal resistance is proportional to the effective damping coefficient (β_{eff}) that can be expressed in terms of the corresponding effective value of Van der Waals radii of ions and viscosity of the electrolyte in ratio to ionic charge (*Ze*). Dimensions of the electrolyte are determined through the volume density (ρ_N-volume density of ions in the electrolyte). [9,11]

$$R = \frac{w\beta_{eff}}{hL(Ze)^2 \rho_N} \qquad (4)$$

Magnetic field distribution is shown in Fig.6 where the interconnection bar current is 15 times larger than the individual cell current and in opposite direction. The measurement of the battery voltage change as the influence of the imposed magnetic field is presented on Fig.9 and the measurement setup is presented on Fig.10. The distance of parallel conductor is equal to the battery height, battery voltage is nominal value, battery current is 1A for the time period of less than 5s.

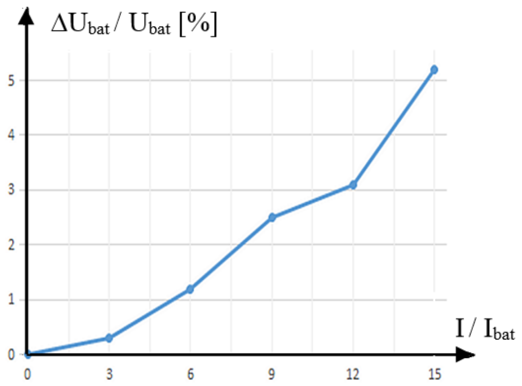

Figure 9. *Battery voltage change in depending on imposed magnetic field caused by parallel conductor current*

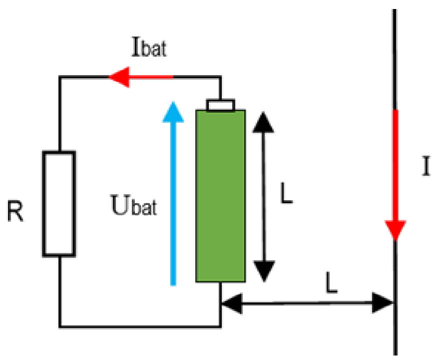

Figure 10. M*easurement setup for Hall effect influence due battery design*

Finally, the total result directly influences on the thermal dissipation and therefore are related to the effect of rising temperature of certain cells. In [12,13] there are presented results of FEM model transient analysis shown in Fig.8 that give verification results but without the influence of the imposed magnetic field previously explained. This effect needs to be additionally calculated using FEM calculation.

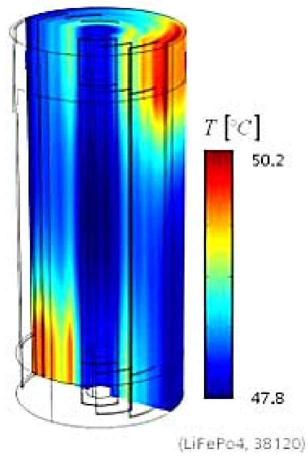

Figure 8. *FEM model results for temperature distribution in the battery cell (transient analysis with current pulse)* [12]

CONCLUSION

The design of the battery pack is not just dependable of the vehicle power drive energy demand, but for precise control, it is necessary to have the model with all parameters. It is shown that even the usually neglected parasitic influence of transversal magnetic field in the construction of battery block can cause substantial damage. In further work coupled fields related to connection that produce loop degradation of the whole battery block will be taken into consideration. The battery management is basically not able to solve or detect problems within parallel cells that can cause irreversible discharge process

REFERENCES

[1] MIT Electric Vehicle Team: "A guide to understanding battery specifications", http://web.mit.edu/, 2008

[2] Steve McMullen: "Battery basic", http://americansolarchallenge.org/ , 2015.

[3] Steve McMullen: "Battery-Pack-Design-Examples SOLAR CAR", http://americansolarchallenge.org/, 2015.

[4] F.A. LeBel, S. Wilke, B. Schweitzer, M.A. Roux, S. Al-Hallaj, J.P.F. Trovao: "A lithium-ion battery electro-thermal model of parallellized cells", Vehicular Technology Conference (VTC-Fall), 2016 IEEE 84th, 1-6.

[5] I. Baboselac, Ž. Hederić, T. Benšić: "MatLab simulation model for dynamic mode of the lithium-ion batteries to power the EV", Tehnički glasnik, Vol.11 No.1-2, pp7-13, 2017.

[6] O. Tremblay, L.A. Dessaint: "Experimental validation of a batterydynamic model for EV applications", World Electric Vehicle Journal, Vol. 3,2009, pp. 289-298.

[7] H. Faklenhagen: "Theorie der Elektrolyte", Section 9-10, Springer, Berlin, 1971.

[8] S. Mohanta: "Some aspects of magnetoelectrolysis", PhD Thesis, University of Waterloo, Canada,1974.

[9] S. Mohanta, T. Z. Fahidy: "The effect of a magnetic field on electrolyte conductivity", Electrochimica Acta, Volume 21, Issue 1, Janu-ary 1976, pp. 25-27.

[10] D. K. Kollerov, A. M. Yargulova: "Hall efect in electrolyte solution", Izmeritelnaya Tekhnika, No. 6, pp. 69–70, June, 1973.

[11] R. De Luca: "Ion motion in salt water flowing under a transverse magnetic field", Proceedings of the 2nd European Energy Confer-ence, EPJ Web of Conferences,Volume 33, 2012.

[12] W. Beckert, C. Freytag, M. Wolter: "Analysis of Electro-Thermal Hot Spot Formation in Li-Ion-Battery-Cells", COMSOL Confer-ence, Tokyo 2013.

[13] L.Cai, R.E. White: "Mathematical modeling of a lithium ion battery with thermal effects in COMSOL Multiphysics software", Journal of Power Sources, 196 (2011) 5985–5989.

[14] M. Y. Pour: "Electro-thermal Modeling of LiIon battery", PhD Thesis, Simon Fraser University, Canada, 2015.

BIOGRAPHY

Tin Benšič was born in Osijek, Croatia 1991. He is a PhD student in Faculty of electrical engineering, computer science and information technology Osijek, where he is also employed as a research assistant. His main research interests include electrical machines and drive systems parameter and state estima-tion in application to industrial processes and electromobility.

PROBLEMI PROJEKTIRANJA BATERIJSKOG PAKETA - UTJECAJ POPREČNOG MAGNETSKOG POLJA NA UNUTARNJE OTPORE BATERIJE

Tin Benšić, Željko Hederić, Marinko Barukčić, Miralem Hadžiselimović, Nenad Cvetković, Dejan Krstić

Rezime: *Baterijski paket predstavlja neophodan elemenat električnog vozila. Zato dizajn baterijskih paketa značajno utječe na vozne karakteristike. Sustav upravljanja tokovima energije u električnom vozilu koristi visoko frekvencijske komponente energetske elektronike koje uzrokuju više harmonike superponirane na istosmjernu komponentu struje baterije. Ovaj rad proučava utjecaj raspodjele transverzalnog megnetskog polja unutar baterije na dizajn baterijskog paketa i na parametre baterijskog modela. Istosmjerna komponenta transverzalnog magnetskog polja unutar baterije uzrokuje Hallov efekt koji razmješta putanje iona unutar baterije te tako negativno utječe na unutarnji otpor baterije. Izmjenična komponenta transverzalnog magnetskog polja u električnim petljama unutar baterije inducira elektromotornu silu koja također uzrokuje negativne utjecaje na parametre baterije.*

Ključne reči: dizajn baterijskog sustava, Hallov efekt, unutarnji otpor baterije, transverzalno magnetsko polje.