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# A Novel Battery Equalizer for Plug-in Hybrid Electric Vehicle

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***Abstract***

*In order to meet cost targets for hybrid electric (HEV), Plug-in hybrid electric (PHEV), and all-electric vehicles (EV), an improvement in the battery life cycle and safety is essential. One practical approach to improve performance is to use power electronics intensive cell equalizer, in conjunction with on-board energy storage devices. A new technique based on buck-boost topology to equalize a series-connected battery stack on PHEV is proposed in this paper. The proposed scheme transfers the energy from fully charged cell to the weaker charged cell. Unlike previous battery equalizing schemes was based on terminal voltage, the proposed scheme is based on the THEVENIN model parameters, resulting more precisely and more available energy. Experiment results are provided to verify the operation of proposed battery equalizer with characters as the following: low cost; high equalizer current and high efficiency.*

*Keywords: battery equalizer, buck-boost, plug-in hybrid electric vehicle (PHEV), thevenin model*

## 1. Introduction

Series-connected battery stacks are being utilized to supply high voltage in many applications such as EVs, HEVs, PHEVs. Of these, a PHEV battery is severely exposed to a charge and discharge environment. This exposure occurs because a PHEV can recover energy from the wheels during regenerative braking and reuse it as the energy of the motor [1]. The repeated charge and discharge phenomenon causes a cell mismatch problem because the batteries have inevitable differences in chemical and electrical characteristic from manufacturing, experience mismatched ambient temperatures when they are used, and accelerate asymmetrical cell degradation with aging [3]. These differences lead to large non-uniformities in cell charge level after several cycles of charging and discharging. While charging in a series connected battery stack, some cells can be fully charged before others. Such a process leads to overcharge in a subset of battery cells. If these cells are charged into the gassing phase after severe overcharging, there can be significant degradation in the battery life [4]. Maintaining same charge level of cells is needed to enhance battery life. Therefore, a battery equalizing scheme is required.

Previous equalizing schemes commonly used the mathematical statistical methods to evaluate the consistency of the battery voltage, capacity and internal resistance [5]. Terminal voltage as the consistent characterization indicator is preferably applied to the battery systems such as Lead-acid and Ni-MH etc. Of these batteries, the slope of the curve of terminal voltage versus state of charge (SOC) is larger and the linearity is better. Based on the above principle, in order to simplify the equalization parameters, to reduce the equalizer hardware design complexity, the literature [6] proposed determining timing of switches according to the detecting the terminal voltage. However, the accuracy of above scheme for the smaller SOC-terminal voltage slope such as Lithium-Ion battery lower, and using capacity as indicators of these batteries more appropriate. In the field of PHEV, the range of SOC of the battery is 30%-80%. In this range, the slope of the SOC versus the terminal voltage is sufficiently small. There is a certain deviation based on voltage as the battery equalization. And to obtain the SOC of each cell is extremely complex, because the actual capacity impacted by the state of healthy (SOH), and is closely related to the future condition of the vehicle. Therefore, to achieve equalizing management according to the remaining capacity is relatively complicated. To solve above problems, A buck-boost topology battery equalizer base on thevenin model will be presented. The proposed battery equalizer detect the mutation of the terminal voltage during the vehicle

steady-state conditions, estimating the parameters such as open circuit voltage (OCV), internal resistor and polarization parameters according to the thevenin model, determining the equalizer control signal timing base on the differences of the parameters.

## 2. Equalizer Topology

The proposed equalizer topology is depicted in Figure 1. In an equalizing loop, Inductance and switch in each loop constitute a typical buck-boost circuit. The energy transferred between the adjacent cells according to the inductance base on the switch controlling in order to achieve the equalizing management.
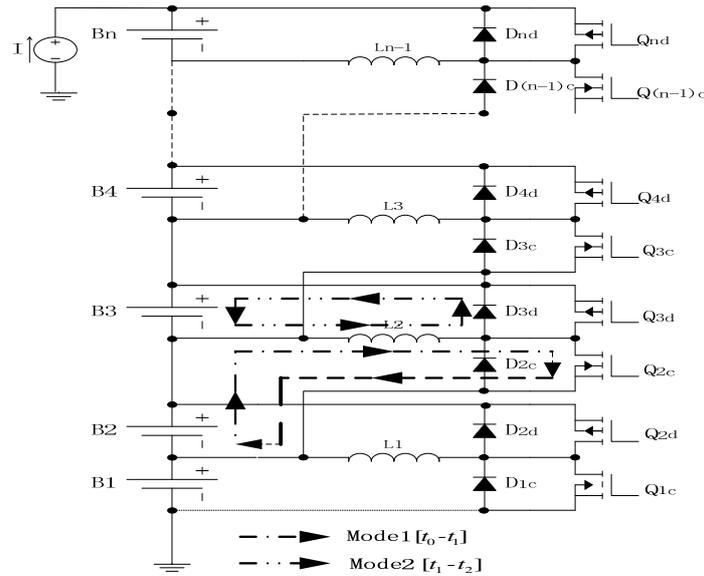


Figure 1. Equalizer Topology

The main operation consists of two continuous modes. For the convenience of the analysis of the operation principle, additional assumptions are made as follows:

1. All switches are ideal.
2. All diodes are ideal and no voltage drop exists.
3. Terminal voltage of battery cells are almost constant during one cycle.

Before describing the analysis, it's assumed that the battery B3 is fully charged and battery B2 is the weakest charged. In this case, the charge or energy flows from battery B3 to battery B2. The current paths of this case are shown in Figure 1. And the parameters of the components in the circuit are shown in Table 1.

The mode operations are explained as follows:

Mode 1 [$t_0$-$t_1$]: The charge is extracted from cell B3. Switch $Q_{3d}$ are turned on and the switch is in the discharging path of cell B3. And then, the current in inductor $L_2$ is built up. The terminal voltage of cell B3 is applied to $L_2$. According to the assumption, the current of inductor or discharging B3 is built up with constant slope as shown in Equation (1). Equation (2) indicates 3 the maximum current of mode 1. During mode 1, the equalizer circuitry transfers the energy of battery B3 to inductor $L_2$. Equation (3) shows the whole transferred energy.

$$i_L(t) = \frac{V_{B3}}{L_2} t \tag{1}$$

$$i_{peak} = \frac{V_{B3}}{L_2} nT \tag{2}$$

$$E_{\text{B3,discharge}} = \int_0^{nT} i\,dt = \int_0^{nT} (\frac{V_{\text{B3}}}{L_2}t)dt = \frac{1}{2}\frac{V_{\text{B3}}}{L_2}(nT)^2 \tag{3}$$

Mode 2 [t1-t2]: When switch Q3d is turned off and switch Q2c is turned on, mode 2 starts. Consequently, the switches in the charging path of battery B2 are turned on such as switch Q2c. In this mode, the energy stored in inductor L2 flows to battery B2. As shown in Figure 1, the terminal voltage of battery B2 is applied to inductor L2 in reverse. The current of inductor decreases with constant slope as presented in Equation (4). When the inductor current becomes zero, the current is blocked by the unidirectional switches and the inductor current will not be negative. During mode 2, all the energy stored in inductor L2 moves to battery B2. Equation (5) shows the whole transferred energy.

$$i_L(\text{t}) = \frac{V_{\text{B3}}}{L_2}nT - \frac{V_{\text{B2}}}{L_2}t \tag{4}$$

$$E_{\text{B2,charge}} = E_{\text{B3,discharge}} = \frac{1}{2}\frac{V_{\text{B3}}}{L_2}(nT)^2 \tag{5}$$

Table 1. Parameters of the Components in the Equalizer

| Components | Part (Manufacturer) | Rating values |
|---|---|---|
| Q1,2,3 …… n-1c, Q2,3 …… nd, | FDD3510H (FAIRCHILD) | N-Channel:80V-13.9A-80mΩ P-Channel:-80V-9.4A-190mΩ |
| D2,3,4…… nd D1,2,3…… n-1c | HER1004G (TAIWAN SEMICONDUCTOR) | 300V-10A-0.5V |
| L1,2,3……n-1 | inductor (MURATA) | 18.25 μH |

The topology of the circuit has been designed for into the symmetry structure, achieving the equalizing management according the equalizing control strategy. As the equalizing topology using the structure of the buck-boost, the energy transfer rate is not limited by a voltage difference of adjacent cells, and the equalizing is not stopped as the terminal voltage of adjacent cells achieve the same level.

## 3. Equalizing Control Strategy

The SOC is typical reflection of the differences between the cells in a series battery pack. The most effective equalizing scheme is to implement the consistency management according to the detecting of SOC of each cell in a series battery pack. As there is contact between the SOC and terminal voltage such as lead-acid and NI-MH battery, in order to simplify the equalizing parameters, previous battery equalizing schemes achieve the consistency management according the differences between the cells. However, such as Lithium-Ion Battery, there is no apparent contact between the SOC and terminal voltage. It's unable to achieve precise control of the equalization process based solely on the terminal voltage differences. So it's necessary to add additional parameters as a basis of equalizing decision. According to the literature [7], SOC is closely related to OCV, internal resistor and polarization parameters. Explore the relationship between SOC and the above-mentioned parameters according to the battery model. Achieve equalizing management according the differences of the parameters.

There exist several equivalent models for batteries, with varying complexities [8-11]. For the equalizer controller explored in this paper, the THEVENIN model presented in [11] has been chosen, because of its simplicity and high precision in the range of SOC typically used in PHEV (from30% to 80% SOC) [12]. The equivalent model of a battery cell is shown in Figure 3. Equation (6-8) shows the mathematical relationship of model.
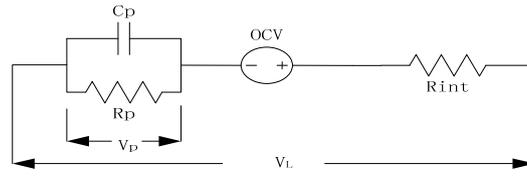
Figure 2. Thevenin Model

$$V_{p(k)} = V_{p(k-1)}e^{-\Delta t/\tau} + iR(1 - e^{-\Delta t/\tau})$$

(6)

$$\begin{bmatrix} V_{p(k)} \\ SOC_{(k)} \end{bmatrix} = \begin{bmatrix} 1 - \dfrac{t_s}{C_p R_p} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_{p(k-1)} \\ SOC_{(k-1)} \end{bmatrix} + \begin{bmatrix} \dfrac{t_s}{C_p} \\ \dfrac{\eta t_s}{C_N} \end{bmatrix} [i]$$

(7)

$$V_{L(k)} = \begin{bmatrix} OCV_{(k)} \end{bmatrix} + [i][R_{int}] + \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} V_{p(k-1)} \\ SOC \end{bmatrix}$$

(8)
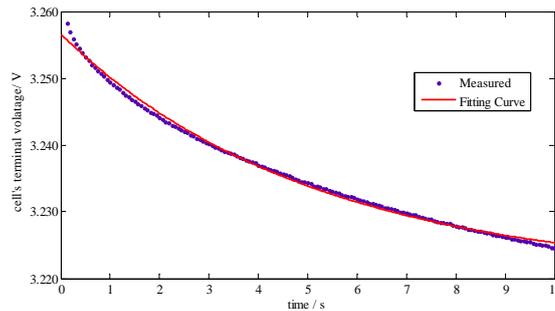


Figure 3. Cell's Terminal Voltage Versus Time

According to the literature [12] description, the technique to find the model parameters is to disconnect the current for a long period of time, in order to pass through the transient response time. Use the nonlinear regression method to fit the transient response curve data of terminal voltage. LM (Levenberg-Marquardt) algorithm [13] is an optimal solution using gradient, which is a kind of the nonlinear least square method, and has been widely used in the field of parameter identification [14-15]. The research use the LM algorithm to fit the curve of the terminal voltage, when the SOC is 100%, excitation current is 25A, and the setting time is 10s. Figure 3 shows the curve fitting of cell's terminal voltage versus time, and table 2 shows the Model's parameter values and curve fitting mean square error.

According to the above method to estimate the model's parameters, the battery will be loaded according to the user demand. In actually, the only controllable load is the equalizer. Equalizing current can be stopped for short periods of time, in order to estimate the parameters. After which the equalizing process can be resumed. Based on above principle, the research proposed equalizing control strategy based on THEVENIN model. When the vehicle energy system load remains essentially the same conditions (such as constant current charging status, start self-test steady-state conditions), open and close of each single match equalizer temporarily, detecting the instant response of each cell's terminal voltage during the process. Use LM algorithm to fit the transient response curve, identify the model's parameters, according to the diversity between the cells in a serious battery pack, to achieve the equalizing management.

Table 2. Model's Parameters and Mean Square Error

| Parameter | values |
|-----------|--------|
| OCV | 3.298V |
| Rint | 1.733mΩ |
| Rp | 1.513mΩ |
| Cp | 0.295mF |
| SSE | 5.806E-005 |

As mentioned above, the cell equalizer controller is composed of several blocks: Detecting cell terminal voltage; Cell model parameters identification; Available capacity difference calculation; A proportional integrative block (PI), desired cell current calculation, based on the PI output; cell current and voltage limiter and the timing calculations for the switches. Figure 4 shows the equalizer controller block diagram.
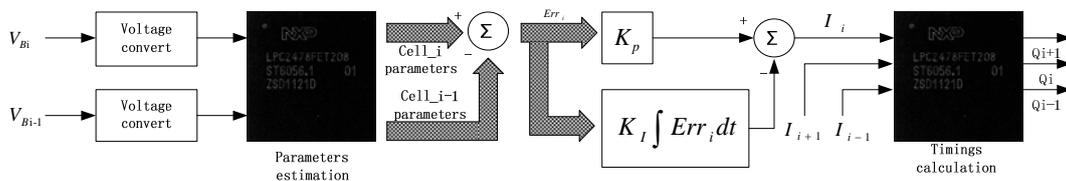


Figure 4. Equalization Controller Schematic
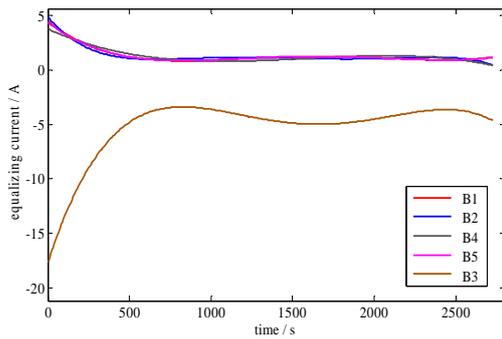


Figure 5. Equalizing Current Versus Time
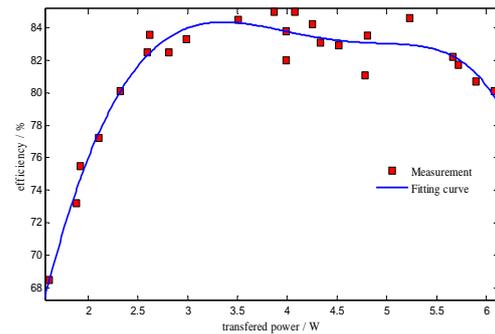
Figure 6. Equalization Efficiency Versus Transferred Power

When the load remains essentially the same conditions in the vehicle energy systems, open and close of each single match equalizer temporarily. The setting time to acquire all of the model parameters is about 4s. As the battery pack used in the PHEV consist of hundreds cells, the setting time to achieve parameters of each cells need to be more than a few minutes. It is not conducive to the actual project implementation. According to the experiment, if only to identify the OCV and internal resistor, the setting time is about 0.01s to achieve enough data to complete the precise estimation. so the objective is to equalize the OCV and internal resistor of each cell, so that that the difference is used as the error signal, as represented in:

$$\text{Err}_i = \left\{ \text{OCV}_i\text{-OCV}_{i-1} \quad R_{\text{int}_i}\text{-}R_{\text{int}_{i-1}} \quad R_{p_i}\text{-}R_{p_{i-1}} \right\} \tag{9}$$

The error signal is passed through a PI block, to avoid stability issues, and to improve the steady-state error, as represented in:

$$\text{PErr}_i = K_p\text{Err}_i + K_i \int \text{Err}_i dt \tag{10}$$

Calculate the desired cell current based on the PI output. The terminal voltage value of cell and the desired equalizing current value are substituted into the formula (1) to calculate the on-timing of each switch. Once the complete equalization is obtained, the error signals are very close to zero, the equalizer can be turned off to reduce consumption, and the error integration is reset.

Additional precautions should be taken as follows, the energy transferred between the adjacent cells changed with the desired current and the efficiency of the equalizer is closely related to the power level. In order to obtain optimum equalization efficiency, it's necessary to limit the range of a equalizing current. To avoid shoot through in the switch chain, minimum turn off times, maximum turn on times, and guard times must be enforced. If the calculated timing violates these limits, then the desired cell currents are reduced, and the timing is recalculated, until an allowed timing scheme is obtained.

## 4. Results and Discussion

To verify the performance and reliable of the proposed equalizer, an experiment is performed for a five cell battery pack. The detailed specifications of the battery pack as shown in Table 3.

Table 3. Spcifications of the Battery Pack

| Parameter | Values |
|---|---|
| Nominal Capacity | 25Ah |
| Nominal Voltage | 3.200V |
| Maximum Operating Voltage | 3.650V |
| Minimum Operating Voltage | 2.500V |

As high precision in the range of SOC typically used in the PHEV (from 30%to 80% SOC) of thevenin model, in order to verity the performance of proposed equalizer, setting the initial capacity of 3rd cell as 7.50Ah (SOC=30%), and the initial capacity of the remaining four are 12.5Ah (SOC=50%). The charge difference was about 5Ah. Figure 5 shows the equalizing current on each cell during the equalization time.

In Figure 5, it is clear that the equalizer provides current to B3 (negative current), while absorbing current (energy) from the rest of the cells (positive current), in an almost equal fashion. It is also clear that the current reduces when the discharged cell comes closer to the rest of the pack, to avoid forcing the equalizer to work in a low-power transfer mode. Figure6 shows the equalizer efficiency versus transferred power, it's clear that the efficiency of proposed equalizer is high at a medium range of equalizing power (form 3.5W-12W). So when the calculated desired current reaches at a low level, the equalizer can be turned off in order to avoid low-efficiency working points as shown in Figure 5.
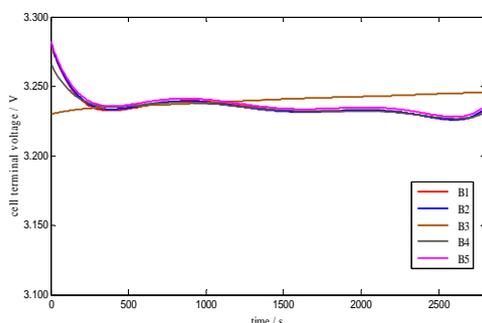


Figure 7. Cell Terminal Voltage Versus Time
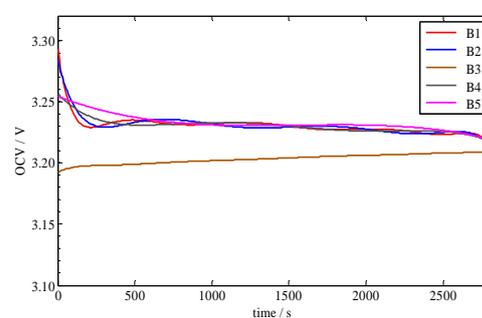


Figure 8. Cell OCV Versus Time

Figure 7 shows the terminal voltage of each cell versus time, and figure8 shows the OCV of each cell versus time, it is clear that , although the terminal voltage of each cell are very

closer to zero, the equalizer can't be turned off,  as the differences of internal resistor of each cell. Compare with other equalizing control method based on terminal voltage, the proposed equalizer's performance and precision ranges have been verified according to the experiment. The equalizer was turned off until the differences of model parameters such as OCV, internal resistor etc reach the minimum value to avoid low efficiency points.

## 5. Conclusion

When the lithium-ion battery is in the voltage platform stage, the slope of the curve of terminal voltage versus state of charge (SOC) is too small to be equalizing indicator. This paper presented a buck-boost topology battery equalizer base on THEVENIN model to estimate the model parameters according to opening and closing of each single match equalizer temporarily using little CPU time. The equalizer implements consistency management according to the differences of model parameters. Its performance and precision range have been verified according to the experiment on battery pack consist of 5 cells, and some issues of the equalizer such as efficiency were highlighted and have been analyzed and overcome. In summary, the feasibility of the novel battery cell equalizer was explored in this paper, demonstrating its strengths. In addition, issues of the equalizer were highlighted, and have been overcome and controlled, while keeping in mind the performance and low cost issues related to PHEV applications. In general, the presented novel battery cell equalizer and the designed controller together prove to be a practical solution for PHEV energy storage systems.

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