A Crossed Pack-to-Cell Equalizer Based on Quasi-Resonant LC Converter with Adaptive Fuzzy Logic Equalization Control for Series-connected Lithium-Ion Battery Strings

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Published in:
Proceedings of the 2015 IEEE Applied Power Electronics Conference and Exposition (APEC)

DOI (link to publication from Publisher):
10.1109/APEC.2015.7104574

Publication date:
2015

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
A Crossed Pack-to-Cell Equalizer Based on Quasi-Resonant LC Converter with Adaptive Fuzzy Logic Equalization Control for Series-connected Lithium-Ion Battery Strings

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Abstract—The equalization speed, efficiency, and control are the key issues of battery equalization. This paper proposes a crossed pack-to-cell equalizer based on quasi-resonant LC converter (QRLCC). The battery string is divided into $M$ modules, and each module consists of $N$ series-connected cells. The energy can be transferred directly from a battery module to the lowest voltage cell (LVC) in the next adjacent module, which results in an enhancement of equalization efficiency and current. The QRLCC is employed to gain zero-current switching (ZCS), leading to a reduction of power losses and electromagnetic interference (EMI). Furthermore, an adaptive fuzzy logic control (AFLC) algorithm is employed to online regulate the equalization period according to the voltage difference between cells and the cell voltage, not only greatly abbreviating the balancing time but also effectively preventing over-equalization. A prototype with eight lithium-ion battery cells is implemented. Experimental results show the proposed scheme exhibits outstanding balancing performance, and the equalization efficiency is higher than 98%. The proposed AFLC algorithm abridges the total equalization time about 47%, and reduces the switching cycle about 62% compared with the traditional fuzzy logic control (FLC) algorithm.

Keywords—Equalizers, adaptive fuzzy logic control (AFLC), zero-current switching (ZCS), lithium-ion batteries, plug in hybrid electric vehicles (PHEVs), electric vehicles (EVs).

I. INTRODUCTION

It is well-known that the world is being faced with the unprecedented energy and environmental crisis, which is becoming of paramount concern. To address these crisis, plug in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) are applied and considered to be the most viable and commercially available alternatives to the internal combustion engine vehicles for the future as PHEVs and EVs have the advantages of energy conservation and environmental protection [1]. In addition, as mobile storage equipments, large-scale PHEVs and EVs will be the important pillar of the third industrial revolution. Vehicle power batteries are the power sources of PHEVs and EVs. Their performances have significant impacts on the power performance, fuel economy, and safety for vehicles, and have became the bottleneck in the scale development of PHEVs and EVs. Lithium-ion battery is currently considered to be one of the most popular rechargeable battery due to its high energy density, low self-discharge rate, and no memory effect. It has been dominating the high power products, such as PHEVs and EVs [2]-[3]. However, due to the limited voltage and capacity of one single lithium-ion cell, a battery pack must incorporate thousands of individual cells connected in series and/or in parallel to meet the power and energy requirements of PHEVs and EVs [4]. However, the series-connected lithium-ion pack brings a serious challenge: the variations in manufacturing, environment, and usage will cause the cell voltages to drift apart as the battery pack is charged or discharged, and this imbalance tends to increase as the pack ages [5]. This fact may lead to low efficiency, short lifetime, and high risk of catching fire and explosion. Therefore, equalization is essentially required for the series-connected lithium-ion battery strings.

Numerous equalization schemes have already been developed and well summarized in [6]. According to the energy flow, they can be classified into five groups: adjacent cell-to-cell methods (ACTCMs) [5], [7]-[9], direct cell-to-cell methods (DCTCMs) [4], [10], cell-to-pack methods (CTPMs) [11]-[12], pack-to-cell methods (PTCMs) [13]-[14], and any cell(s) to any cell(s) methods (ACTACMs) [15]. For the ACTCMs and DCTCMs, due to the small voltage difference between cells and the voltage drop across the power devices, the balancing current is very small (only about C/100-C/50) [5], resulting in a long equalization time. For the CTPMs, the energy is transferred from a cell (low voltage) to the pack (high voltage), leading to a very low balancing power. For the ACTACMs, the energy can be transferred from any cell(s) to any cell(s), which
Equalization control is one key issue of battery equalization. The balancing strategies can be classified into three groups, which include the voltage-based, SOC-based, and pack capacity-based methods [4], [16]. SOC-based and pack capacity-based equalization methods require accurate cell SOC estimation, which are difficult to implement in reality. Voltage-based equalization methods, which target the consistent cell voltages, are the most feasible to realize due to the direct measured cell voltages. However, voltage-based equalization is also challenging due to the transient response and the ohmic resistance of cells. When a cell is charged, the cell voltage will increase instantaneously. On the contrary, when the cell is discharged, the cell voltage will decline instantaneously. After charge or discharge stops, the cell will take a long time to return to the open circuit voltage. Therefore, it is difficult to determine when the battery pack can achieve an optimum balance. Voltage-based equalization algorithm cannot directly represent the ultimate purpose of the equalization, hence it often suffers from over-equalization [16]. As shown in Fig. 2, without an appropriate equalization control algorithm, the equalizer depletes the battery instead of equalizing the cell voltages. Over-equalization can be prevented by directly lowering the equalization time and current. But this also increases the total equalization time and switching cycle. In order to overcome these drawbacks, equalization algorithms based on fuzzy logic control (FLC) have been studied in literature [4], [5], [16], [23]. These algorithms are all employed to regulate the equalization current according to the voltage difference, effectively preventing over-equalization. However, the equalization current is limited by the maximum value, which results in a small improvement in the equalization speed. Therefore, an adaptive fuzzy logic control (AFLC) algorithm is proposed in this paper to online regulate the equalization period according to the voltage difference between cells and the cell voltage, not only greatly abbreviating the balancing time but also effectively preventing over-equalization.

The remainder of this paper is organized as follows. The design concept and operation principle of the proposed system are analyzed in Section II. The design of the adaptive fuzzy logic controller is presented in Section III. The experimental results are presented in Sections IV. The conclusion is presented in Section V.

II. PROPOSED EQUALIZER

We have previously proposed a cell-to-cell battery equalizer with ZCS and ZVG based on QRLCC that offers several major advantages over conventional equalizers [4]. Based on
the precedent work, this paper proposes a crossed pack-to-cell equalizer based on QRLCC, which has the similar operational principle and circuit analysis as presented in [4].

A. Configuration of the Proposed Equalizer

Fig. 3 presents the proposed two-module pack-to-cell equalizer based on QRLCC, where each module consists of 4 series-connected battery cells. Each equalizer consists of two parts, the QRLCC and the selection switch modules (SSMs). The QRLCC, as the core of the proposed equalizer, is made up of a LC converter, four MOSFET switches, and four diodes. The MOSFET switches are divided into two pairs (i.e., Q11, Q12 and Q23, Q14, i=1, 2.), which are controlled by a pair of complementary pulse width modulation (PWM) pulses, enabling the QRLCC to alternatively operate between the state of charging and the state of discharging. Particularly, zero-current switching (ZCS) is achieved when the switching frequency is equal to the inherent resonant frequency of the QRLCC. The diodes are used to isolate the balanced cell from the battery pack. The major role of the QRLCC is to achieve the energy transfer with zero switching loss. The SSMs consist of N pairs of relays, through which the energy can be transferred from a module to the LVC at any position in the next adjacent module without unnecessary energy waste.

B. Operational Principle

In order to simplify the analysis for the operation modes, the following assumptions are made: the energy is transferred from Module 1 (M1) to the LVC, e.g., B21 in Module 2 (M2). Thus, the SSM 2 S22+, S22− are first turned ON. As shown in Figs. 4 (a) and (b), the proposed topology has two consecutive working states.

Working state I: Q11, Q12 are turned ON, and Q13, Q14 are turned OFF. QRLCC1 is connected in parallel with M1 through Q11, D11 and Q12, D12, as shown in Fig. 4 (a). M1, L1, and C1 form a resonant loop, and the current path from M1 is constructed. C1 is charged by M1. Then, the capacitor voltage \( V_{C1} \) begins to increase. In an ideal world, the current flowing into QRLCC1 is equal to that flowing out of M1. Meanwhile, because Q13 and Q14 maintain OFF, and B21 acts as an open path, the charge current into B21 is zero (see the state I in Fig. 5).

Working state II: Q11, Q12 are turned OFF, and Q13, Q14 are turned ON. QRLCC1 is connected in parallel with B21 through Q13, D13 and Q14, D14, as shown in Fig. 4 (b). L1, C1, and B21 form a resonant loop. The current path from QRLCC1 into B21 is constructed. B21 is charged by C1. Then, \( V_{C1} \) begins to decrease. Simultaneously, M1 acts as an open path, so the discharge current out of M1 is zero (see the state II in Fig. 5).

C. Circuit Analysis

The proposed equalization circuit can be simplified as shown in Fig. 6, and the following notations are to be used.
1) $R_{eq}$: the equivalent resistance of QRLCC$_1$, which can be expressed as

$$R_{eq} = R_{LC} + 2R_{DS(on)}$$  \hspace{1cm} (1)

where $R_{LC}$ is the internal resistance of the LC converter. $R_{DS(on)}$ is the static drain-source resistance of the MOSFET switch.

2) $T$: the switching period of the MOSFET switches, satisfying:

$$T = 2\pi \sqrt{L_1C_1}.$$  \hspace{1cm} (2)

3) $\omega_0$: the characteristic angular frequency, satisfying:

$$\omega_0 = \frac{2\pi}{T} = \frac{1}{\sqrt{L_1C_1}}.$$  \hspace{1cm} (3)

4) $V_{B21}(t)$: the voltage of the LVC $B_{21}$ in $M_2$.

5) $V_{M1}(t)$: the battery pack voltage of $M_1$.

6) $V_d(t)$: the voltage difference between the battery pack and the LVC, which can be represented by

$$V_d(t) = V_{M1}(t) - V_{B21}(t) - 4V_F$$  \hspace{1cm} (4)

where $V_F$ is the diode’s forward voltage drop.

7) $f(t)$: the AC square wave input of QRLCC$_1$, which can be expressed as

$$f(t) = \begin{cases} V_d(t)/2, & t \in (kT, (k+1/2)T) \\ -V_d(t)/2, & t \in ((k+1/2)T, (k+1)T) \end{cases}$$  \hspace{1cm} (5)

where $k=\lfloor \frac{t}{T} \rfloor$, and $\lfloor \cdot \rfloor$ is Gaussian function. The Fourier transform of $f(t)$ can be expressed as

$$f(t) \approx \frac{2V_d(t)}{\pi} \left( \sin(\omega_0 t) + \frac{\sin(3\omega_0 t)}{3} + \frac{\sin(5\omega_0 t)}{5} + \ldots \right).$$  \hspace{1cm} (6)

Then, the current $i$ in QRLCC$_1$ can be approximatively represented by

$$i \approx \frac{2V_d(t)}{\pi R_{eq}} \sin \omega_0 t.$$  \hspace{1cm} (7)

Thanks to (7), the transferred charge $\Delta q_T$ from $M_1$ to $V_{B21}$ in one switching cycle can be simplified as

$$\Delta q_T \approx \int_0^T \frac{2V_d(t)}{\pi R_{eq}} \sin \omega_0 t \, dt \approx \frac{4V_d(t)\sqrt{L_1C_1}}{\pi R_{eq}}.$$  \hspace{1cm} (8)

By dividing (8) by $T$, the transferred charge in unit time can be derived from

$$\frac{\Delta q}{\Delta t} = \frac{\Delta q_T}{T} = \frac{2V_d(t)}{\pi^2 R_{eq} C_C} = \frac{I_1}{\pi}$$  \hspace{1cm} (9)

where $\Delta q$ is the transferred charge in the time period $\Delta t$. $I_1$ is the fundamental wave amplitude of the resonance current $i$. (9) shows that the amplitude of the resonance current decides the balancing speed, which is not affected by $L_1$ or $C_1$ values.

The relationship between the cell voltage and SOC is piecewise linear [4], which can be represented by

$$\Delta V = \lambda \Delta SOC = \lambda \frac{\Delta q}{C_C} = \frac{2V_d(t)}{\pi^2 R_{eq} C_C} \Delta t$$  \hspace{1cm} (10)

where $\Delta V$ is the variation of the cell voltage according to the SOC variation $\Delta SOC$ within the time period $\Delta t$. $\lambda$ is the proportionality coefficient between the voltage and SOC in one approximate linear segment, and $\lambda$ can be viewed as a constant in the balancing process for relatively small SOC variation. $C_C$ represents the whole charge stored in the battery in Coulomb.

By (10), the equalization time $t$ can be calculated as follows:

$$t = \frac{\pi^2 R_{eq} C_C}{2\lambda} \ln \frac{V_d(0)}{V_d(targ)}$$

$$= \frac{\pi^2 R_{eq} C_C}{2\lambda} \ln \frac{V_{M1}(0) - V_{B21}(0) - 4V_F}{V_d(targ)}$$  \hspace{1cm} (11)

where $V_{M1}(0)$ and $V_{B21}(0)$ are the initial voltages of $M_1$ and $B_{21}$, respectively. $V_d(targ)$ is the target voltage difference of the equalization.

According to (11), the equalization time $t$ is proportional to $R_{eq}$ and $C_C$, is inversely proportional to $\lambda$, and has no relationship with $L_1$ or $C_1$. The larger the equivalent resistance $R_{eq}$, the longer the equalization time $t$ and the larger the loss. Therefore, the components, such as MOSFET switches, diodes, inductances, and capacitances with low equivalent resistances, should be selected accordingly to satisfy the equalizer fine requirements.
III. DESIGN OF ADAPTIVE FUZZY LOGIC CONTROLLER

As shown in Fig. 3, with the proposed topology, the energy can be transferred directly from $M_1$ ($M_2$) to the LVC at any position in $M_2$ ($M_1$). Due to lithium-ion battery nonlinear behavior, one single equalization cycle cannot guarantee all cells will be fully balanced, it is necessary to take numerous equalization cycles to complete the energy exchange. Obviously, an appropriate equalization switching period is very important for the consistency of the battery pack. A long equalization time $t_{eq}$ and a short standing time $t_{st}$ are ample in the equalization capability but might lead to over-equalization, while a short equalization time $t_{eq}$ and a long standing time $t_{st}$ can efficiently prevent over-equalization but leads to a long equalization stage and a high switching frequency. To solve these problems, an AFLC algorithm is employed to online regulate the equalization period according to the voltage difference and the cell voltage. The equalization switching period is composed of the equalization time $t_{eq}$ and the standing time $t_{st}$, which can be regulated through controlling the cell SSMs.

A. Design of Fuzzy Logic Controller

There are two cell states affecting the equalization period as follows.

1) The cell voltage difference

Actually, the aim of the battery equalization is to make all cell voltage equal. The cell voltage imbalance is essentially the SOC imbalance. A large $\Delta V$ indicates a serious situation, which requires a comparative long equalizing time and a comparative short standing time to accelerate the equalizing speed. On the contrary, a small voltage difference stands for a slight imbalance, which is not in hurry to be equalized and requires a comparative short equalizing time and a comparative long standing time to prevent over-equalization of the battery pack. In this situation, the equalizing process can focus more on the improvement of the battery pack consistency.

2) The cell voltage

As shown in Fig. 7, the uniform charging cell voltage curve of LiFePO$_4$ battery can be divided into about five linear segments (LSs), i.e., $[2.5V, 3.16V], [3.16V, 3.32V], [3.32V, 3.4V], [3.4V, 3.48V]$, and $[3.48V, 3.65V]$ according to the cell voltage. In each LS, the proportionality coefficient between the cell voltage and SOC can be viewed as a constant, but is unequal in different LSs. In other words, the same cell voltage difference in different LSs represents different SOC difference, which need different equalization period. Fig. 8 shows the voltage response curves under pulse charge current in different LSs. The recovery time varies with the cell voltage. Therefore, the equalization standing time also should be adjusted according to the LSs.

Therefore, the inputs of the fuzzy logic controller are the maximum voltage difference between cells $\Delta V$ and the balanced cell voltage $V$. The outputs are the desired battery equalizing time $t_{eq}$ and the standing time $t_{st}$. As shown in Fig. 9, the FLC system consists of four parts, namely fuzzifier, rule base, inference engine, and defuzzifier [5]. The numerical input of the voltage difference $\Delta V$ is converted into two sets of fuzzy variables, i.e., $\mu_{eq, \Delta V}$ and $\mu_{st, \Delta V}$ by the fuzzifiers.
Fig. 10. Surfaces of the fuzzy logic controller outputs corresponding to the cell voltage difference $\Delta V$ and the cell voltage $V$. (a) $\omega_{eq}$ with respect to $\Delta V$ and $V$. (b) $\omega_{st}$ with respect to $\Delta V$ and $V$.

\[
\begin{cases}
  t_{eq} = \omega_{eq} \times t_{0_{eq}} \\
  t_{st} = \omega_{st} \times t_{0_{st}}
\end{cases}
\]

where $t_{0_{eq}}$ and $t_{0_{st}}$ are the nominal equalization time and the nominal standing time, respectively.

**B. Design of Adaptive Controller**

Since the consistency of the battery pack will change with time, an appropriate nominal equalization period cannot be preset according to the consistency of the battery pack. Hence, we propose an AFLC algorithm to ongoing revise the nominal equalization period according to the present cell voltage difference $\Delta V(k)$, the previous voltage difference $\Delta V(k-1)$, and the previous nominal equalization time $t_0_{eq}(k-1)$. The $k$th nominal equalization time is given by

\[
ts_{eq}(k) = \frac{\Delta V(k)}{\Delta V(k-1) - \Delta V(k)} \times t_0_{eq}(k-1).
\]

It can be seen from (14) that the larger present cell voltage difference $\Delta V(k)$ or the smaller previous equalization voltage difference $\Delta V(k-1) - \Delta V(k)$ will enable the algorithm to generate a longer nominal equalizing time in order to accelerate the equalization process. On the contrary, the algorithm will generate a shorter nominal equalizing time in order to prevent over-equalization. The control system of the proposed AFLC is further displayed in Fig. 11.

**IV. EXPERIMENTAL RESULTS**

In order to evaluate the performance of the proposed equalizer and verify the validity of the AFLC algorithm, a prototype of eight lithium-ion cells, as shown in Fig. 12, is implemented and tested. Table I summarizes the parameters of the QRLCCs and the selection switch modules in Fig. 3. The inductances, capacitances, and resistances in Table I are measured by an Agilient 4263B LCR Meter. The cell voltages are monitored by LTC6802-1 (made by Linear Technology), and are recorded every second.

Fig. 13 shows the experimental waveforms of the resonant current $i$ and the capacitor voltage $V_c$ with $L_1=0.87 \mu H$ and $C_1=0.49 \mu F$. It can be observed that the resonant current $i$ is sinusoidal, whose root mean square is up to 5.8 $A$. The corresponding capacitor voltage $V_c$ is also a sinusoidal waveform lagging 90° phase from the resonant current $i$, and the peak value of the capacitor voltage will occur at zero-crossing point of the current $i$. The MOSFETs are switched at the near-zero-current state with the frequency of 129.2 kHz, reducing the switching losses.

Fig. 14 shows the experimental results for eight cells with
Fig. 14. Experimental results for the eight-cell voltage trajectories with the constant equalization switching period ($t_{eq}=10$ s and $t_{st}=10$ s).

Fig. 15. Experimental results for the eight-cell voltage trajectories with the maximum voltage control strategy.

the constant equalization switching period, i.e., $t_{eq}=10$ s and $t_{st}=10$ s. The initial cell voltages are 2.687V, 2.695V, 2.673V, 2.676V, 3.282V, 3.289V, 3.287V, and 3.288V, respectively. After about 6800 s, zero-voltage gap (ZVG) between cells is achieved with about 340 switching cycles.

Fig. 15 shows the experimental results for eight cells with the maximum voltage control strategy, i.e., within each equalization cycle, the equalizer charges the LVC until its voltage catches up the maximum cell voltage of the battery pack, then the equalizer stops for 10 s. It can be observed that after about 7000 s and 180 switching cycles, the maximum voltage difference between cells is reduced from 0.62 V to 0.08 V, but ZVG between cells cannot be obtained due to the ohmic internal resistances of cells.

Fig. 16 presents the equalization results with the traditional FLC algorithm. After about 6000 s, ZVG between cells is achieved with about 112 switching cycles. Fig. 17 presents the equalization results with the proposed AFLC algorithm, whose initial voltages are the same as that in Figs. 14, 15, and 16. It can be observed from Fig. 17 (a) that the equalizing time $t_{eq}$ and the standing time $t_{st}$ are adjusted according to the cell voltage difference and the cell voltage. The larger cell voltage difference will enable the adaptive fuzzy logic controller to generate a longer equalizing time and a shorter standing time in order to accelerate the equalization process. On the contrary, the smaller cell voltage difference will enable the adaptive fuzzy logic controller to generate a longer standing time and a shorter equalizing time in order to prevent over-equalization of the battery pack. Moreover, through ongoing regulating the nominal equalization time according to the history equalization information, the total equalization time and the switching cycle are reduced to 3200 s and 43 cycles, respectively. A 47% reduction of the total equalization time and a 62% reduction of the switching cycle are achieved compared with the traditional FLC algorithm in Fig. 16. The proposed equalization scheme with the designed AFLC algorithm not only reduces the total equalization time and the switching cycle but also effectively prevents over-equalization. As shown in Fig. 17 (b), during the balancing process, the energy conversion efficiency varies from 99% to 98%, showing high balancing efficiency.

V. CONCLUSION

In this paper, a crossed pack-to-cell equalizer based on QRLCC is proposed to gain large balancing current, high equalization efficiency, and effectively prevent over-equalization. The proposed scheme configuration, the operation principle, and the design of the adaptive fuzzy logic controller are presented, and a prototype with eight lithium-ion cells is optimally implemented. Experimental results show the proposed scheme exhibits outstanding balancing performance with ZCS and ZVG, and the balancing efficiency is higher than 98%. The AFLC algorithm abridges the total equalization time about 47%, and reduces the switching cycle about 62% compared with the traditional FLC algorithm.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China under grant No.61034007.

<table>
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<tr>
<th>Parameters</th>
<th>Value</th>
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<tr>
<td>MOSFETs, Q11, Q14, Q22, Q24</td>
<td>80NF70, $B_{DS(on)} \leq 0.0098 \Omega$</td>
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<td>Diodes, D11, D14, D21, D24</td>
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<td>Inductances, $L_1, L_2$</td>
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<td>Capacitances, $C_1, C_2$</td>
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<tr>
<td>Battery Pack, $B_{10}\ldots B_{23}$</td>
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<td>$R_{DS(on)}$ Static drain-source on resistance.</td>
<td></td>
</tr>
<tr>
<td>$V_F$ Forward voltage.</td>
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TABLE I. COMPONENT VALUES USED FOR THE PROTOTYPE
Fig. 17. Experimental results for the eight-cell battery pack with the proposed AFLC algorithm. (a) The 8-cell voltage trajectories. (b) Energy conversion efficiency.

No.6132016011, NO.51277116, No.61273097, and No.61104034.

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