Lithium-Ion Battery Charge Equalization Algorithm for Electric Vehicle Applications

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Lithium-Ion Battery Charge Equalization Algorithm for Electric Vehicle Applications

M A Hannan, M M Hoque, S E Peng, M N Uddin

Abstract—The lithium-ion batteries are commonly used in electric vehicle (EV) applications due to their better performances as compared to other batteries. However, lithium-ion battery have some drawbacks such as the overcharged cell which has a risk of explosion, the undercharged cell eventually reduces the life cycle of the battery, and unbalanced charge in series battery gradually reduces overall charge capacity. This paper presents a battery charge equalization algorithm for lithium-ion battery in EV applications to enhance the battery’s performance, life cycle and safety. The algorithm is implemented in series connected battery cells of 15.5 Ah and 3.7 V nominal each using a battery monitoring integrated circuit for monitoring and equalization of an 8-cell battery pack using bidirectional flyback DC-DC converter as the channel for charging and discharging of the battery cell. The obtained results show that the developed charge equalization controller (CEC) algorithm performs well in equalizing both undercharged and overcharged cells and equalizes the cell within the safety operation range of 3.81 V. To validate the charge equalizer performance, the proposed algorithm outperforms with other studies in terms of balancing, equalization speed, low power loss, and efficiency. Thus, the proposed battery charge equalization algorithm proves an effective and automated system to modularize the battery charge that improves the safety and life cycle of battery.

Keywords—Charge equalization algorithm, lithium-ion battery, charging and discharging lithium-ion battery, monitoring IC, electric vehicle.

I. INTRODUCTION

NOW DAYS, the vehicles on the road are mainly operated with the combustion engine and fossil fuel is used as the power source. However, the use of fossil fuel poses some issues on the environmental problem and has the risk of the shortage of fuel shortage in the future. This contributes to the need for development of the pure electric vehicle. Electric vehicle is operated based on the energy store in the battery pack and the ultimate power source is the electricity supplied from the generating plant. Moreover, the advanced regenerative braking uses in electric vehicle help in reducing the energy waste. The braking process of the vehicle absorbs its energy, converts it back to electrical energy and returns to the batteries [1,2]. In electric vehicle, the important characteristic is that the electrical energy would be efficiently used to power electric motors and the other basic systems of a battery-powered electric vehicle. The electric vehicle is categorized as a system with higher engine efficiency and no polluted emission through tailpipe, fuel evaporation or fuel refining and make it known as ‘zero emission vehicle’[3,4].

There have been many efforts to find and develop a battery pack for electric vehicle which can provide long lasting and high total storage capacity of energy. Currently, lithium-ion battery is the well-known battery type used in electric vehicle due to its specific characteristics and better performance as compared to its counterparts. Lithium-ion battery has high energy and power density, high energy capacity, no memory effect, long life span, low self discharge and low temperature effect [5,6]. However, it has some drawbacks that overcharged cell has a risk of explosion, undercharged cell has eventually reduce the life cycle of the battery, and unbalanced charge in series battery gradually reduces overall charge capacity [5,7]. A battery management system (BMS) as the battery charge controller is essential to enhance the battery’s performance, life cycle and safety. Thus, the BMS has to be effective in performing battery charge equalization.

A number of developments of BMS with charge equalization control have been serving the existing EV systems with the fulfillment of their minimum requirements [1-3]. Nevertheless, the existing BMS still have some problems in cell charge equalization. The more common method is using the resistive current shunt. The battery is discharged through the shunt resistor which is very simple in design, control and execution. However, the heat energy is lost through resistor and it shortens the battery runtime [7]. The equalization control is simple in the switched capacitor control in terms of control and execution. Switched capacitor method is an energy recovery cell-balancing method where capacitor is used as energy storage to transfer excess energy from high voltage cell to lower voltage cell, but it is imperfect for fully balancing due to the voltage drop at the switches [8]. The inductor and transformer based equalization control methods are effective in EV application. A centralized multi-winding transformer with isolated forward converter modules is across each battery cell. When overcharging occurs, the corresponding switch of the cell is turned on and the voltage across all windings is dictated by the overcharged battery cell. This system has effective low
The power converters such as buck-boost [13-15], resonant [16-19], are also the energy recovery cell-balancing methods and highly used in EV due to their high equalization speed, high efficiency and reliability. They consist of bidirectional DC-DC converter and switches. The systems choose two cells to undergo balancing at one time, the energy flows from the cell with higher energy to the cell with lower energy. However, no more than two cells can be connected and this system requires highly complex procedure, design and control strategy, and it is costly [14,17]. More research and development [19,20] towards the betterment of the performance of BMS is still necessary for efficient energy storage system for EV application.

Therefore, this paper proposes the implementation of a charge equalization algorithm using a monitoring integrated circuit (IC). This IC is able to monitor a series of battery up to 12 cells per IC and it is also able to connect and communicate in series with other ICs to monitor up to hundreds of battery cells [21]. For the prototype and algorithm development, one IC is used, and 8 battery cells are monitored and equalized. This proposed method is an active equalization that uses two flyback DC-DC converters as the channel for the charge and discharge purpose of the battery pack. The monitoring IC communicates with a NI myRIO as microcontroller and carries out the modularization algorithm. This project is started with the design of charge equalization algorithm and simulation using MATLAB/Simulink. Then, it is followed by the model development in the experimental setup. The control program is built in LabVIEW works to fine in controlling the monitoring IC and the overall system. The proposed BMS method is found as an effective and automated system to modularize the battery charge that improves the safety and life cycle of battery.

II. OVERVIEW OF BATTERY CHARGE EQUALIZATION

In this work an equalization control algorithm is developed, where the charge is modularized among the battery pack instead of power loss as heat, or charging from external source or discharging to external sink [19]. All the cells are sharing a DC-DC converter and reduce the circuit complexity.

A. Battery Charge Equalization

The battery charge equalization is necessary to equalize the battery charge level of overcharged cell by transferring the excess energy to cell back to or to equalize that of undercharged cell by feeding the required charge from the cell pack. The proposed battery charge equalization algorithm development is divided into two parts, a master board which comprises the microcontroller and flyback DC-DC converter and the module board that consists of the measurement and the cell monitoring device with battery cells and bidirectional cell switches as shown in Fig.1. The microcontroller communicates with the monitoring IC where the IC monitors the cell status and switches on/off the bidirectional cell switches. Based on the cell status, the microcontroller executes the charge equalization algorithm and generates regulated PWM signal for the flyback DC-DC converter to protect and equalize the battery cell by discharging the overcharged cell or by charging undercharged cell accordingly. The flyback DC-DC converter provides the channel of current flow during charging or discharging process. The cell switch allows a specific cell to be connected through flyback DC-DC converter to cell pack for discharging or charging based on the cell condition as overcharged or undercharged respectively.

![Equalization control system in (a) block diagram and (b) schematic diagram.](image)

The equalization of the cell-1 as undercharged (assume) is performed by switching on the corresponding bidirectional cell switch \( S_1 \) from the respective output control pin of the monitoring IC. Then the controller generates regulated PWM signal for switch \( Q_1 \) of the stepdown flyback converter to allow the undercharged cell to be charged from the cell pack.
Similarly, the detected overcharged cell-8 can discharge to the cell pack for equalization by activating the corresponding bidirectional cell switch \( S_8 \) and sending regulated PWM signal to switch \( Q_8 \) of the stepup flyback converter. The amount of energy carried to the undercharged cell \( Q(T_e) \) during equalization period \( T_e \) from the battery pack is contented as Eq.(1) which is the average amount of energy released from the battery pack during that time or vice versa, and the average power \( P_{\text{out,avg}} \) extracted from the pack is equal to the average input power, \( P_{\text{in,avg}} \), multiplied by the converter efficiency \( \eta \) as Eq.(2).

\[
Q_1(T_e) = \frac{1}{7} \sum_{i=2}^{8} Q_i(T_e) \quad (1)
\]
\[
P_{\text{out,avg}} = \eta \times P_{\text{in,avg}} \quad (2)
\]

B. Characteristics of Lithium-ion Battery

Lithium-ion battery is one of the most promising battery technologies now-a-days and has high potential to dominate the battery field for energy storage applications particularly, in electric vehicles. Lithium is one of the lightest elements with high reactive and electrochemical potential which makes it an ideal material for battery [5,6]. Lithium-ion is used instead of metallic lithium so that no metal lithium is formed in the reaction [6]. Lithium-ion battery is able to achieve high energy density, good life cycle, higher cell voltage, easier maintenance and environmental friendly compared with other type of batteries. Moreover, lithium-ion battery has no memory effect and low self-discharge rate at idle state [2,4]. Lithium-ion battery is posed some safety regarding the electric, electromechanical, thermal and mechanical impacts, yet they still manageable with proper battery management system [8,22-23]. The high production cost is the main problem for this battery development [1]. Fig.2 shows the model of 15.5Ah lithium-ion battery with the experimental results of the open circuit voltage (OCV) characteristics at various state of charge (SOC) values. This characteristic has a good relationship as defined by Eq.(3), which is obtained by curve fitting approximation of Fig.2. The SOC of batteries can be estimated using Eq.(3), which is needed to develop the charge equalization controller algorithm. The real time SOC of lithium-ion battery can be estimated by Eq.(4) where \( SOC_0 \) is the initial SOC and \( C \) is the nominal capacity of the battery [24-26].

\[
V_{OC} = -8.4306 \times 10^{-10} \times SOC^5 + 1.9306 \times 10^{-7} \times SOC^4 -1.4512 \times 10^{-5} \times SOC^3 + 3.0999 \times 10^{-4} \times SOC^2 -1.1312 \times 10^{-2} \times SOC + 3.4395 \quad (3)
\]
\[
SOC = SOC_0 - \frac{1}{C} \int_{0}^{T_e} i(t)dt \quad (4)
\]

C. Flyback Converter Model

A bidirectional flyback DC–DC converter is used in this proposed system to transfer energy from the cell to cell pack and vice versa for equalization [7]. The flyback converter model is shown in Fig.3. The maximum duty of PWM switching signal \( D_{\text{max}} \) for the flyback DC–DC converter is considered to operate the switch in the safe region of voltage stress expressed as Eq.5 [7]. The turns ratio of transformer, \( n \), the filter capacitor, \( C_f \) of the DC–DC converter and the mutual inductance of transformer \( L_m \) can be calculated using Eqs.(6)-(8) [7]. The converter efficiency is considered as 85% to regulate the required converter output power by setting the mutual inductance of the flyback transformer, transformation ratio, voltage transmission factor, and filter capacitor of the power converter so that the converter operates with tolerable voltage/current stress for equalization.

\[
D_{\text{max}} = \frac{V_{\text{ds, min}} - V_{\text{ds, max}}}{V_{\text{ds, min}} - V_{\text{ds, max}}} \quad (5)
\]
\[
n = \frac{N_1}{N_2} = \frac{\eta V_{\text{ds, max}} D_{\text{max}}}{V_{\text{out}} (1 - D_{\text{max}})} \quad (6)
\]
\[
C_f = \frac{\eta P_{\text{out,avg}} D_{\text{max}}}{V_{\text{out}} V_{\text{ds, max}}} \quad (7)
\]
\[
L_m = \left( \frac{(nV_{\text{rs}} (1 - D_{\text{max}}))^2}{2\eta P_{\text{in}} f} \right) \quad (8)
\]

where \( V_{\text{in, min}} \) and \( V_{\text{in, max}} \) are the minimum and maximum voltages for the battery cell pack, \( V_{\text{ds, min}} \) and \( V_{\text{ds, nom}} \) are the minimum and nominal voltage stresses on the switch, \( N_1 \) and \( N_2 \) are the number of primary and secondary turns, \( V_{\text{out}} \) is the output voltage, \( P_{\text{in}} \) is the input power, \( f \) is the switching frequency and \( \eta \) is the converter efficiency.

III. CHARGE EQUALIZATION ALGORITHM

The modularization method is an active equalization method. The monitoring IC is the sensor to make measurements on the status of the battery cell. The
monitoring IC reads the voltage level of the cells and communicates with the microcontroller. The microcontroller collects data from monitoring IC, then estimates SOC and compares the result with the threshold value set, detects the unequalized cell and sends instruction to the monitoring IC to activate the bidirectional switch of the corresponding detected cell and the operation of flyback DC-DC converter to carry out charge equalization according to the proposed algorithm. The flowchart of the proposed charge equalization algorithm is shown in Fig.4. The charge equalization algorithm makes decision based on the SOC of battery cells’ voltage readings obtained from the monitoring IC. The charge equalization algorithm is included in the charge equalization algorithm is shown in Fig.4. The charge equalization algorithm makes decision based on the SOC of battery cells’ voltage readings obtained from the monitoring IC. The charge equalization algorithm is included in the charge equalization algorithm. The flowchart of the proposed charge equalization algorithm is shown in Fig.4. The charge equalization algorithm makes decision based on the SOC of battery cells’ voltage readings obtained from the monitoring IC. The charge equalization algorithm is included in the charge equalization algorithm. The flowchart of the proposed charge equalization algorithm is shown in Fig.4. The charge equalization algorithm makes decision based on the SOC of battery cells’ voltage readings obtained from the monitoring IC. The charge equalization algorithm is included in the charge equalization algorithm.

The following steps are used for the proposed charge equalization algorithm.

1. Initialize the system.
2. Record the voltage readings, $V_i$ of the battery cells and sort in descending order, $V_1$ to $V_8$.
3. Check the cells’ status whether they are normal or abnormal.

if cells are operated at normal
    goto step2
else ; a cell is found as abnormal.
    goto next
4. Check the condition of cell
   if $V_1>V_{\text{max}}$ : a cell is found as overcharged.
5. Execute overcharge modularization and goto step7.
   if $V_8<V_{\text{min}}$ : a cell is found as undercharged.
7. Start the cell equalization process.
8. Estimate SOC$_i$ corresponding to the cells.
9. Check the SOC value for discharge balancing.
   if SOC$_1$>OSOC : the respective battery cell of SOC$_1$ is classified as overcharged battery, where SOC$_1$ is the highest SOC reading of the battery cells and OSOC is the threshold value of the overcharged battery SOC which is corresponding to $V_{\text{max}}$.
10. Execute the discharge mode
11. Control the bidirectional MOSFET switch corresponding to detected battery cell, generate the PWM signal for discharging the overcharged battery cell, control the stepup flyback DC-DC converter, and allow the equalization current for discharging.
12. Check the balancing of discharging cell.
   if $|\text{SOC}_1-\text{SOC}_{\text{avg}}|>2\%$; the respective cell is unbalanced, where SOC$_{\text{avg}}$ is the average SOC of all battery cells and $|\text{SOC}_1-\text{SOC}_{\text{avg}}|$ is $\Delta$SOC.
   goto step7
   else ; the cell is balanced.
   goto step2
13. Check the SOC value for charge balancing.
   if SOC$_8$<USOC : the respective battery cell of SOC$_8$ is classified as undercharged battery, where SOC$_8$ is the lowest SOC reading of the battery cells and USOC is the threshold value of the undercharged battery SOC which is corresponding to $V_{\text{min}}$.
14. Execute the charge mode
15. Control the bidirectional MOSFET switch corresponding to detected battery cell, generate the PWM signal for charging the undercharged battery cell, control the stepdown flyback DC-DC converter, and allow the equalization current for charging.
16. Check the balancing of charging cell.
   if $|\text{SOC}_8-\text{SOC}_{\text{avg}}|>2\%$; the respective cell is unbalanced, where $|\text{SOC}_8-\text{SOC}_{\text{avg}}|$ is $\Delta$SOC.
   goto step7
   else ; the cell is balanced.
   goto step2

The algorithm repeats to maintain the continuous execution of the battery charge equalization process.

IV. PROTOTYPE IMPLEMENTATION

A. Hardware Configuration

The hardware part is divided into two parts, a master board
which is the microcontroller and a DC-DC converter for charge equalization and the module board where the measurement and the cell monitoring devices are located. The circuit diagram in hardware implementation of the system are shown in Fig.5. The system is initialized by setting up all hardware parts together according to the design requirement and confirming the equalization control switch. The equalization algorithm operation is started by detecting the unprotected or unequalized cell.

The microcontroller used in master board is the National Instruments NI myRIO. Its main function is to communicate with the monitoring IC and to generate PWM signal for the DC-DC converters. The flyback DC-DC converters are the channel of current flow during charging and discharging processes. When the MOSFET switch is turned on at duty ON of PWM signal, the primary coil of the transformer charges from the overcharged cell. When the switch is open at duty OFF stage of PWM signal, the stored energy in primary coil is transferred to the secondary coil and the charge is shifted to the battery pack during overcharged battery discharging. The cycle is repeated to achieve cell balancing [12,19]. The procedure is same to the undercharged cell where the flyback DC-DC converter is in reverse direction, the equalization charge is transferred from battery string to the selected undercharged cell. In this system, the flyback DC-DC converter is controlled by the PWM signal from the microcontroller with frequency of 40 kHz. The converter operates in a closed loop system where the converter output is maintained and corrected with minimum error through the feedback by auto adjusting of duty of PWM converter output is maintained and corrected with minimum error.

TABLE I: SPECIFICATION OF THE PROPOSED SYSTEM

<table>
<thead>
<tr>
<th>Part</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery cell</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td></td>
<td>15.5Ah, 3.7V</td>
</tr>
<tr>
<td>Flyback Converter switch</td>
<td>FQP7N10</td>
</tr>
<tr>
<td></td>
<td>IRF7811A</td>
</tr>
<tr>
<td>Bidirectional Cell switch</td>
<td>FDS9958</td>
</tr>
<tr>
<td></td>
<td>FDS9945</td>
</tr>
<tr>
<td>Stepdown Transformer</td>
<td>N1:N2</td>
</tr>
<tr>
<td></td>
<td>80:35</td>
</tr>
<tr>
<td></td>
<td>Lm</td>
</tr>
<tr>
<td></td>
<td>25e-6 H</td>
</tr>
<tr>
<td>Steup Transformer</td>
<td>N1 : N2</td>
</tr>
<tr>
<td></td>
<td>35:80</td>
</tr>
<tr>
<td></td>
<td>Lm</td>
</tr>
<tr>
<td></td>
<td>2e-6 H</td>
</tr>
<tr>
<td>Cm</td>
<td>25e-5 F</td>
</tr>
<tr>
<td>Cset</td>
<td>22e-5 F</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>40 kHz</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>NI myRIO</td>
</tr>
<tr>
<td>Monitoring IC</td>
<td>LTC6804-2</td>
</tr>
<tr>
<td>Interface</td>
<td>LabVIEWworks</td>
</tr>
</tbody>
</table>

B. Software Interfacing

In the experimental setup, the NI myRIO microcontroller communicates with monitoring IC and LabVIEW in host PC by using SPI communication interface. The microcontroller is programmed with the equalization control algorithm and the control interface is created in host PC by using LabVIEW. In the control interface, an indicator for the IC registers; battery voltage readings and charging/discharging status are presented to figure out the overall system performance. A control program is set for the over charged and undercharged threshold values, charging and discharging time, and PWM control for the DC-DC converter.

V. RESULTS AND DISCUSSIONS

A. System Testing

The proposed prototype is built to monitor the equalization among 8 lithium-ion battery cells. Table II shows the comparison between the voltage readings obtained by the monitoring IC and manual reading by using a multimeter. A negligible error is found between the two sets of readings of cell voltage values. The program is tested with NI myRIO and the monitoring IC. The switches are controlled by the signal sent from the monitoring IC to construct the bidirectional channel for equalization current flow. However, the charging or discharging process starts only when the DC-DC converter is activated by the PWM signal from the microcontroller. At any certain time, only one unbalanced cell undergoes in equalization process.
### Table II: Battery cell voltage reading

<table>
<thead>
<tr>
<th>Battery</th>
<th>IC Reading</th>
<th>Multimeter Reading</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>3.596</td>
<td>3.570</td>
<td>+0.026</td>
</tr>
<tr>
<td>Cell 2</td>
<td>3.751</td>
<td>3.730</td>
<td>+0.021</td>
</tr>
<tr>
<td>Cell 3</td>
<td>3.855</td>
<td>3.831</td>
<td>+0.024</td>
</tr>
<tr>
<td>Cell 4</td>
<td>3.828</td>
<td>3.800</td>
<td>+0.028</td>
</tr>
<tr>
<td>Cell 5</td>
<td>3.919</td>
<td>3.890</td>
<td>+0.029</td>
</tr>
<tr>
<td>Cell 6</td>
<td>3.825</td>
<td>3.797</td>
<td>+0.028</td>
</tr>
<tr>
<td>Cell 7</td>
<td>3.828</td>
<td>3.800</td>
<td>+0.028</td>
</tr>
<tr>
<td>Cell 8</td>
<td>3.822</td>
<td>3.799</td>
<td>+0.026</td>
</tr>
</tbody>
</table>

#### B. Charging Evaluation

The flyback DC-DC converter plays an important role in the charge transfer during charging and discharging. There are two flyback DC-DC converters used in two modes, which are charging and discharging. In the charging mode, the converter processes the equalization by transferring the required charge from battery string to the detected undercharged cell. Fig. 6 shows the waveforms of the input and output voltages, and the charging current during charge mode. In Fig. 6, the first waveform is the input voltage supplied by the battery string about 31.63V, the second waveform is the charging voltage approximate 4.32V, the third waveform is the output current of the charging converter, also is the charging current of the cell known as equalization current which is 1.75A in average.

![Fig.6. DC-DC converter waveforms at charging mode.](image)

#### C. Discharging Evaluation

In the discharging mode operation of flyback DC-DC converter, the step-up converter performs the equalization by transferring the excess energy from the detected overcharged cell to the battery string. Fig. 7 presents the waveforms of input-output voltage and current for the discharging mode. The first waveform is the input voltage of the converter which is the voltage value of overcharged cell of 3.90V. The second waveform is the output voltage of converter connected to the battery string, about 31.684V, slightly higher than the battery string voltage. The third waveform is the input current to the converter which is the discharge current of the unbalanced overcharged cell known as equalization current. The discharge current is at a mean about 1.0A. The input and output voltages of both converters is not perfect as the open circuit battery reading due to the connection between two sources and some drops in the circuit components.

![Fig.7. DC-DC converter waveforms at discharging mode.](image)

#### D. Charge Equalization Evaluation

Table III presents the equalization time for the battery cell at SOC difference (∆SOC) of 5%, 10% and 15% to be charged and discharged to the average level of SOC of battery cells. The average SOC is about 38% for the 15.5Ah lithium-ion battery cell of nominal voltage of 3.70V. The SOC of the unequalized battery increases when charging and decreases while discharging with longer time as more as SOC differs from the average SOC as depicted in Fig. 8.

![Fig.8. Results of charge equalization of lithium-ion battery cells at ∆SOC of 5%, 10%, 15% during charging and discharging.](image)

As data in Table III, with a large ∆SOC, longer time is needed to charge or discharge the unequalized battery to the average value. In comparison between the charging time and
discharging time, the battery takes shorter time to be charged than to be discharged at the same ∆SOC. This is due to larger the charge equalization current than the discharge equalization current as shown in Fig.6 and Fig.7.

<table>
<thead>
<tr>
<th>TABLE III: CHARGING/DISCHARGING TIME AT DIFFERENCE SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆SOC (%)</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>15</td>
</tr>
</tbody>
</table>

| ∆SOC (%) | Discharging Time (s) |
| 5        | 2842         |
| 10       | 5731         |
| 15       | 8617         |

The higher charging and discharging equalization current, the charge of the battery flows in or out at a higher rate compared with lower current. During charge equalization operation by charging or discharging, the bidirectional flyback converter operates at the efficiency of approximately 92%, where the losses mainly contribute for the switching, winding and diode conduction of the converter.

E. Cell equalization profile

Fig. 9 shows the cell equalization profile before and after the charge equalization process. The columns in Fig.9 present the cell voltage values at unequalized state. The area depicts the equalized feature of lithium-ion battery cells in Fig.9. The undercharged cell (see Cell1 in Fig.9) is allowed to be charged and the overcharged cell (see Cell5 in Fig.9) is considered to be discharged for equalization by means of the proposed charge equalization algorithm. The cell voltage levels are obtained at approximately 3.81V after charge equalization.

![Cell Voltage Graph](image)

Fig.9. Voltage levels of battery charge equalization

F. Comparative analysis of proposed charge equalizer

The proposed battery charge equalizer is compared with the common equalizer that is illustrated in Table IV [8-20]. The comparison analysis is depicted in Table IV based on the speed of balancing, execution, design and control difficulty, electrical stresses, power loss and efficiency. Moreover, the analysis describes the size and cost of design, and required number of switches and balancing component for 8-cell battery charge equalization. The shunting resistor equalizer is simple and cost effective, nevertheless, its balancing speed and efficiency are low; it loses power into heat and needs temperature control [7,9]. The switched capacitor equalizer is simple in implementation and cheap; nonetheless, the efficiency and balancing speed are satisfactory [8]. The multi-windings transformer equalizer has good balancing speed and efficiency, however, it has high electrical stresses, magnetizing loss; the design is bulky and expensive; and needs complex control [9-11]. The balancing speed, execution and efficiency are excellent with low stress in the Buck-Boost converter equalizer; nevertheless, it is costly, complex [13-15]. On the contrary, the efficiency and balancing speed are good with low power loss in the resonant converter equalizer, however, the voltage stress is high; it needs complex design and is expensive [16-18].

The proposed battery charge equalizer has excellent balancing speed, execution, good control and efficiency. The power loss and stresses are low. It need less balancing components compared to other equalizers. However, it needs more switch and intelligent control. The proposed battery charge equalizer is a bidirectional charge equalization controller for the battery cell charge and discharge balancing and could be applicable for battery storage equalization in EV with high rating and modular design.

| TABLE IV: COMPARISON ANALYSIS OF PROPOSED CHARGE EQUALIZER |
|-----------------|----------------|----------------|----------------|----------------|
| Type             | Parameter      | Shunting       | Switched       | Multi-windings |
|                  |                | Resistor       | Capacitor      | Transformer    |
| Speed            | Execution      | S              | G              | E              | G              | E              |
| Execution        | Control        | E              | G              | S              | G              | S              |
| Power loss       | Cost           | H              | L              | N              | N              | N              |
| Cost             | Size           | L              | M              | H              | H              | M              |
| Size             | Voltage/Current Stress | N/N | L/L | H/H | L/L | H/L | L/L |
| Switch          | (for 8 cells) | 8              | 16             | 18             | (1x8) | (2x8) | (1x8) | (2x8-2) | (2x8+2) | (2x8+2) |
| Balancing component Efficiency | 8R | 8C | 8T | 8BBC | 8RC | 2FC |
| Efficiency      | L              | S              | G              | G              | G              | G              |

E: Excellent; VG: Very Good; G: Good; S: Satisfactory; H: High; M: Medium; L-Low; N: Negligible; R: Resistor; C: Capacitor; T: Transformer; BBC: Buck-Boost Converter; FC: Flyback Converter;

VI. Conclusion

A novel battery charge equalization algorithm among lithium-ion battery cells for electric vehicle (EV) applications has been presented in this paper. The detail development of the control algorithm, operating principle, and prototype implementation for the proposed charge equalization system has been provided. Only 8 lithium-ion battery cells and one slave board are used for testing and implementation. It has been found from real-time results that the proposed charge equalization algorithm is able to equalize and modulate the battery charge in order to improve the efficiency, reliability and safety issues of the battery drive system. The results also indicate that utilizing some algorithm more slave boards can be implemented to monitor and equalize the charging among more cells, possibly up to 100 cells, to achieve the real power and voltage supplies in EV applications. However, the cost of
the proposed charge equalizer will vary for additional monitoring ICs and bidirectional switches with increase of battery cell which might be acceptable with the cost of battery pack itself. Moreover, the proposed charge equalization algorithm reduces the risk of explosion for overcharged cells and improves the life cycle of undercharged cells. Furthermore, for real-life applications conditions of charging and discharging of the battery may also be taken into consideration based on the battery charge flow direction when the battery is in use during charging or idle condition. A comparison is made to show outperforms of the developed algorithm with the other studies.

REFERENCES


