

An Integrated High Power Self-Equalized Battery Charger Using a Voltage Multiplier and Phase-Shifted Full-Bridge DC-DC Converter for Lithium-Ion Batteries

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A Conventional energy storage systems (ESSs) such as super-capacitors and lithium-ion batteries require voltage
B equalization systems to eliminate voltage imbalances, and bidirectional dc-dc converters to complete the charging process.
S These separated systems require some sensors, inductors, switches, and transformers. Consequently, the ESSs volumes,
T prices, and their complexity are dramatically increased by increasing the required series connected batteries count. Here,
R a self-equalized battery charger is proposed for lithium-ion batteries by combining a voltage multiplier (VM) and a
A phase-shifted full-bridge (PSFB) dc-dc converter. In the proposed self-equalized battery charger, the voltage multiplier
C eliminates the voltage imbalances and the PSFB dc-dc converter carries out the charging process. By combining the
T voltage equalizing and the charging systems into a single system, an integrated converter is obtained which leads to
simultaneous charging and equalization operations, power and control sections simplicity, as well as low volume and price.
By utilizing the phase-shift control method, zero-voltage-switching (ZVS) operation of power MOSFETs is obtained which
leads to high efficiency and low EMI noise. The experimental results for 8 batteries including 48 lithium-ion cells, are in
good agreement with the given mathematical analyses and simulation and clearly show the simultaneous charging and
voltage equalizing operations, as well.

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I. INTRODUCTION

Due to high energy storage capability, low self-discharge rate, long lifespan, and no memory effect, lithium-ion batteries are more widely used in low power applications such as laptops and high power systems including electric vehicles (EVs) and hybrid electric vehicles (HEVs) as compared with the convectional batteries. Considering the fact that the voltage value of a single lithium-ion cell,

approximately 3.7-4.2 V, is too low, to provide the required power for loads, these cells are connected in series or/and parallel to obtain higher voltages or/and capacities [1]. The ESS consists of two different sections; the battery charger, and the battery management system (BMS). The charger plays an absolutely essential role in the ESS and it needs to have specific features including; high efficiency, low cost, low volume, and high reliability [2-5]. According to the lithium-ion battery charging profile, the battery charger should provide a wide output voltage range [4, 5]. The PSFB dc-dc converter benefits from high power density, high efficiency, and low electromagnetic interference (EMI).

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Owing to the aforementioned advantages, the PSFB dc-dc converter is widely used in battery chargers [6-10]. Generally, the dissimilarity between internal resistance, capacity, self-discharge rate, and the environment temperature result in voltage imbalances in series-connected lithium-ion cells[1]. These voltage imbalances are progressively increasing during the discharging/charging intervals. Therefore, some cells may be over-discharged/charged even when the battery pack voltage is within the safe boundaries[10-13]. Consequently, the battery pack capacity is reduced and sometimes an explosion may occur. Thus, for the sake of the batteries and assuring safety, some equalization strategies are crucial to eliminate the voltage imbalances. Due to the aforesaid reasons, battery equalizing has become an important part of the BMS[1].

The equalization topologies are roughly classified into two groups: dissipative and non-dissipative methods [1]. In the dissipative method, the extra energy of over-charged cells is dissipated across some resistors or Zener diodes which decrease the efficiency, and cell capacity but, the equalization speed is relatively high. Besides, there is a considerable number of switches, and gate drivers in the equalizing circuit. Therefore, this method suffers from high cost, and control complexity. In contrast to the previous method, in the non-dissipative method, the additional energy in the over-charged cells is exchanged between cells or between cells and battery pack. As a result, higher efficiency and reliability are achieved. Based on the energy flow direction, the non-dissipative method consists of six major groups including adjacent cell to cell (AC2C), direct cell to cell (DC2C), any cell to any cell (AC2AC), cell to pack (C2P), pack to cell (P2C), and cell to pack to cell (C2P2C). In the AC2C method, the additional energy is transferred between two adjacent cells which may reduce the equalization speed. Moreover, the number of switches and inductors are proportionally increased by increasing the number of series-connected cells. Therefore, this method suffers from control complexity and bulky size [13-17]. In [13] a modified buck-boost converter is used across the two adjacent cells and, the equalization path is controlled by turning the power MOSFETs on and off. [14] proposes a Cuk converter with a fuzzy logic control system, where operation of the employed Cuk converter is similar to the buck-boost converter. In the switched-capacitor converters (SCCs), one switched-capacitor unit is implemented across every two adjacent cells [15]. By switching the complementary MOSFETs across two adjacent cells, the extra energy is transferred between these cells. In the DC2C method, the extra energy can be transferred between different cells in different positions. Consequently, the number of switches is more than twice of the number of cells which results in more control complexity, and larger size [18-21]. In [18] by utilizing a shared multi-secondary windings transformer,

energy transportation can be obtained by forming buck-boost and flyback converters. In [19] four power MOSFETs and four diodes connected across each battery. By switching these MOSFETs, the charge transport can be provided for batteries in different paths. [20] proposes an ESS by using an LC resonant tank, where four MOSFETs have been connected across each battery. By turning these switches on and off and operating near the resonant frequency, the DC2C charge equalization is obtained. The additional energy can be exchanged simultaneously among all cells in all positions in the AC2AC method. Although the equalization speed is higher as compared to the AC2C and the DC2C methods, numerous switches, relays, and gate drivers are required [1, 22]. Thus, this method has some drawbacks; high cost, voluminous size, and control complexity, for instance. [1] uses a combination of a boost converter with an LC resonant converter for the voltage equalization. The boost converter is used to regulate the output voltage and the ZCS operation is obtained via the LC resonant converter. By switching the MOSFETs and relays, the equalization paths are obtained in different positions. Operation principle of the given converters in [1] and [22] are the same. In the C2P method, the extra energy is displaced from the over-charged cells to the battery pack [23-27]. A considerable number of switches and transformers are the main drawbacks of this method. Consequently, low efficiency and low modularity are obtained. In [25] the batteries are connected with each other through the multi-secondary windings transformer. The extra energy in batteries is stored in the magnetic core and by switching the MOSFETs it is transferred to the low voltage batteries. Similar to [25] in [26-27], the extra energy is stored in the magnetic core. But, these equalizers employ the flyback converter with one secondary winding transformer. Owing to the transferring energy between the high voltage and low voltage cells by a transformer, the C2P2C method is more efficient and faster than the C2P method [28-31], but it still suffers from a sizeable number of switches and multi windings transformers. The equalization system in [29] is based on a bidirectional flyback dc-dc converter and, therefore, the energy can be transferred either from one battery to another battery or from the pack to the batteries. Also the equalization system in [30-31] consists of two bidirectional dc-dc converters. In [30] the batteries voltages are sensed by one monitoring IC. But, in the [31] this action is done by using a transformer with multi-secondary windings. In these both topologies, the energy is transferred either from one cell to another cell or from the pack to the cells via magnetic cores. In the P2C method, the battery pack provides the required energy for low voltage cells. This method encompasses the full-bridge dc-dc converter [32], multi secondary windings transformer [33], and the VM. The VM based P2C method is also called as integrated converter [13-15, 34-35]. In [32] the required energy for batteries with

low voltages can be achieved from the pack voltage by sensing the batteries voltages and switching the MOSFETs. When one battery has a low voltage value, its bridge MOSFETs are turned-on to get its required energy from the other batteries. In contrast to all of the aforementioned methods, the equalization systems or both charging and equalization sections are integrated into a single system in the integrated method without increasing the number of switches or magnetic components. This feature leads to a simple, small, and competitive. But, all of the previously proposed

integrated converters are only applied for low power applications and they have low efficiencies, too. This paper proposes a high power self-equalized battery charger by using the PSFB dc-dc converter with a voltage multiplier. By utilizing the proposed converter, both power and control circuits are significantly simplified. Due to the lack of power switches, sensors, and bulky magnetic components in the equalization circuit, both complexity, and cost of the Proposed self-equalized battery charger are significantly reduced.

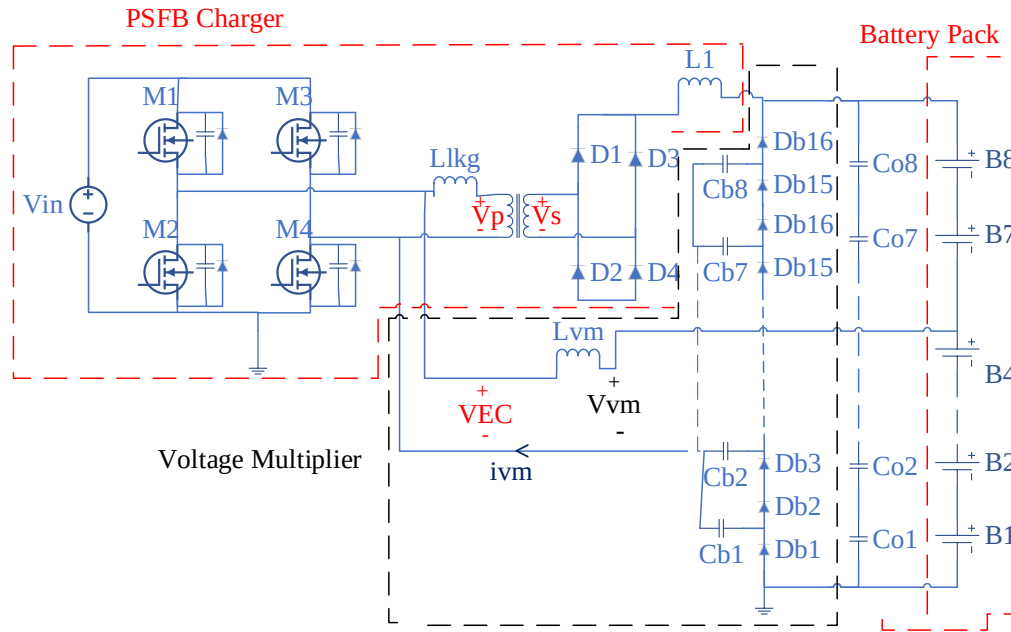


Fig. 1. Proposed self-equalized battery charger for lithium-ion batteries.

By employing the PSFB converter in the charger section, the charger can transfer more power to the battery pack. Moreover, by applying the phase-shift control method, ZVS operation for all of the power MOSFETs is obtained. Thus, the efficiency of the proposed self-equalized battery charger is high and EMI issues are reduced, as well. Also, the switching frequency can be increased to reduce the size of passive components to achieve high power density.

The proposed self-equalized battery charger is introduced in Section II and its major benefits over the traditional equalizers are discussed in Section III. Then, its mathematical analyses and operational principles are explained in Section IV. Finally, the simulation, experimental results, and conclusion and future works are given in Sections V-VII, respectively.

II. PROPOSED SELF-EQUALIZED BATTERY CHARGER CONFIGURATION

The proposed self-equalized battery charger is shown in Fig. 1. By switching power MOSFETs ($M_1 - M_4$) in the charger section, a square voltage waveform is generated across the transformer primary side to adjust the output voltage/current during constant current (CC) and constant voltage (CV) charging intervals, respectively. The current

rating of the transformer secondary winding in the current doubler rectifier (CDR) is only half of the load current. Therefore, when the load current is high, the CDR is more efficient than the other rectifiers. Regarding to the CC charging in this project, the CDR is well-suited for this application [6]. By using the phase-shift control strategy in some periods of time each power MOSFETs solely is turned-on. During these periods, the stored energy in the leakage inductance charges and discharges the MOSFETs drain-source capacitors in the other leg. When MOSFET drain-source capacitor is completely discharged completely, its body diode is turned-on. Consequently, the ZVS operation for aforesaid MOSFET is achieved. Therefore, by utilizing the transformer leakage inductance and power MOSFETs drain-source capacitors, the ZVS operation for power MOSFETs is obtained [6-8]. According to Fig. 1, the equalization circuit of the proposed self-equalized battery charger consists of 8 batteries ($B_1 - B_8$), 16 diodes ($D_{b1} - D_{b16}$) in the voltage multiplier, 8 energy-coupling capacitors ($C_{b1} - C_{b8}$), and one equalization inductor (L_{vm}) which limits the equalization current. When an ac input voltage is applied to the voltage multiplier circuit, the

equalization system is activated. As a result, 8 uniform voltages are applied across the batteries. Consequently, all the batteries are properly equalized after some times.

III. CONVENTIONAL EQUALIZERS DRAWBACKS IN COMPARISON WITH THE PROPOSED SELF-EQUALIZED CONVERTER

As mentioned earlier, the ESS should have a bidirectional dc-dc converter to charge the batteries and also an equalization system to remove the voltage imbalances across the series-connected batteries. The situation is exacerbated considering that the equalization system should have an equalization circuit and a bidirectional dc-dc converter to eliminate the voltage imbalances completely. Therefore, the ESS suffers from the following drawbacks:

- Numerous MOSFETs

Considering the relatively high cost of the power MOSFETs, the total cost and complexity of the conventional equalizers are high [1], [13-33]. Since the proposed converter does not have power MOSFETs in the equalization circuit, it has lower cost and complexity.

- Magnetic components

In contrast to the conventional equalization circuits [18-22], [29], the proposed integrated converter employs just a small inductor in its equalization circuit. Therefore, the proposed converter benefits from lower cost, lower size and, higher efficiency.

- Lack of the current and the voltage sensors

To detect the batteries voltage and current, some sensors are required in [1], [13-33]. Due to the lack of sensors in the proposed converter, its cost and the control complexity are significantly reduced.

- Control complexity

Traditional ESSs needs separate control systems for both charging and equalization circuits. By using the phase-shift control strategy, and considering lack of power MOSFETs in the proposed equalization circuit, a simple control system is obtained.

A complete comparison between the equalization circuit of the proposed self-equalized battery charger and previously proposed converters is given in Table I that clearly demonstrates the benefits of the proposed battery charger.

IV. ANALYSIS OF THE PROPOSED CONVERTER

According to Fig. 1, all of the batteries are simultaneously charged and equalized by utilizing the transformer and the voltage multiplier circuits in the proposed battery charger. The proposed self-equalized battery charger can charge and balance all the batteries during the charging and the discharging intervals. For simplicity, operation of the proposed charger during the charging interval is discussed, here.

A. Simultaneous Charging and Equalization Mechanism

During the CC charging mode, the batteries are charged by I_{CC} and the battery pack voltage is increased from the

initial value to V_{CC} . At the same time, the equalization circuit generates the equalization current which charges all the batteries. During the CV charging mode, the battery pack voltage reaches to its maximum value (V_{CV}) and its current is decreased to a preset value. At the same time, the equalization current balances all the series-connected batteries and prevents from any voltage imbalances in the battery pack.

B. Operation of the Converter under the Cells Imbalances Condition

For simplicity and better understanding, the key current and voltage waveforms of the proposed self-equalized battery charger for four batteries are shown in Fig. 2 when B_1 and B_4 have the lowest and highest voltage values, respectively. Besides, the operational modes of the proposed self-equalized charger are depicted just for four batteries which are shown in Fig. 3. However, the simulation and experimental tests are done for 8 batteries, that each of them consists six parallel lithium-ion cells. Based on Fig. 2 and Fig. 3, since in a switching period, i.e. $(t_0 - t_{17})$ the waveforms are the same during $(t_0 - t_9)$ and $(t_9 - t_{17})$ time sub-intervals, only the first sub-interval is analyzed, here. It is noteworthy to mention that, the PSFB dc-dc converter performance in the proposed self-equalized battery charger is roughly similar to the conventional one [6-8]. Therefore, this paper is mainly focused on the equalization circuit analysis.

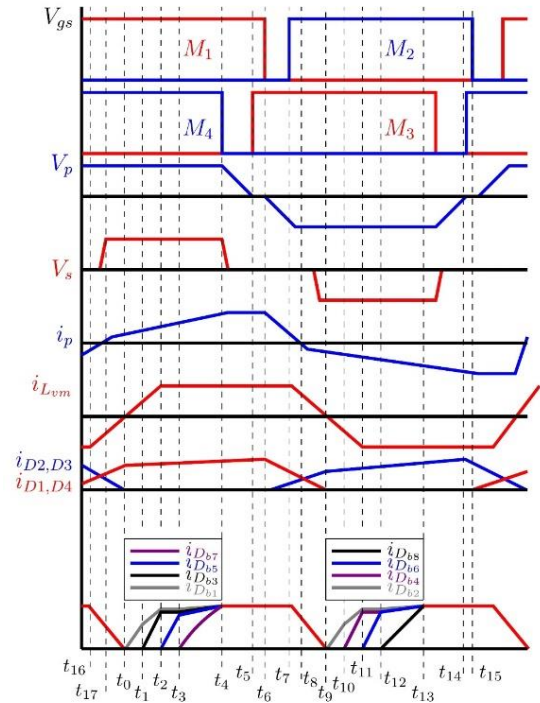


Fig. 2. The key current and voltage waveforms of the proposed battery charger.

Mode 1 $[t_0 - t_1]$: During this state M_1 , M_4 , D_1 , and D_4 are on. Therefore, the battery pack is charged by I_{CC} and its

voltage is being increased. Since B_1 has the lowest voltage value, diode D_{b1} in the equalization circuit is switched on. Consequently, the equalization current charges $B_1 - B_2$, and we can write:

$$\begin{cases} v_{Lvm}(t - t_0) = v_{EC}(t - t_0) - v_{vm}(t - t_0) \\ v_{EC}(t - t_0) = v_p(t - t_0) \\ v_p(t - t_0) = V_{in} \end{cases} \quad (1)$$

Also, by using Equ. (1) and considering volt-balance principle across the equalization inductor

$$\begin{aligned} < v_{Lvm} >_{T_s} = < v_p >_{T_s} - < v_{vm} >_{T_s} \\ < v_{vm} >_{T_s} = 0 \end{aligned} \quad (2)$$

Equ. (2) indicates that the $v_{vm}(t)$ has an alternative voltage waveform which is crucial for enabling the equalization circuit. The equalization current can be expressed as follows:

$$i_{vm}(t - t_0) = \frac{V_{T1}}{Z_1} e^{-Y_1(t-t_0)} \sin \omega_{r1}(t - t_0) \quad (3)$$

Also, the diode current can be expressed as below:

$$i_{Db1}(t - t_0) = i_{vm}(t - t_0) \quad (4)$$

The energy-coupling capacitor voltage is given by

$$v_{Cb1}(t - t_0) = \frac{V_{T1}}{Z_1} (1 - e^{-Y_1(t-t_0)} \cos \omega_{r1}(t - t_0)) \quad (5)$$

where

$$\begin{cases} V_{T1} = V_{in} - (V_{B1} + V_{B2} + V_{Cb1t0}) \\ R = R_{vm}, Y_1 = \frac{R}{2L_{vm}} \\ Z_1 = \sqrt{\frac{L_{vm}}{C_{b1}}}, \omega_{o1} = \frac{1}{\sqrt{L_{vm}C_{b1}}}, L_{vm} = \sqrt{\omega_{o1}^2 - Y_1^2} \end{cases} \quad (6)$$

Here, V_{Cb1t0} is the initial value of the $v_{Cb1}(t)$.

During this operational mode, $B_1 - B_4$ and $B_1 - B_2$ are charged by the charging and the equalization currents, respectively. When V_{B1} is large enough, D_{b3} is switched on and this state is finished.

Mode 2 [$t_1 - t_2$]: Fig. 3(b) shows the equivalent circuit of this operational mode. The charger operation is similar to operation mode 1. D_{b3} is switched on in the equalization circuit and, therefore, the equalization current can be expressed as follows:

$$\begin{aligned} i_{vm}(t - t_1) = \frac{V_{T2}\sqrt{2}}{Z_1} e^{-Y_1(t-t_1)} \sin \omega_{r1}(t - t_1) \\ + \frac{1}{r_D} e^{-\frac{(t-t_1)}{r_D C_{b2}}} (V_{Cb1t1} - V_{B1}) \end{aligned} \quad (7)$$

Also, the energy-coupling capacitors voltages are written

$$\begin{cases} v_{Cb1}(t - t_1) = \frac{V_{T2}}{Z_1} (1 - e^{-Y_1(t)} \cos \omega_{r1}(t - t_1)) \\ v_{Cb2}(t - t_1) = v_{Cb1}(t) + V_{Cb1t1} - V_{Cb2t1} - V_{B1} \end{cases} \quad (8)$$

where,

$$V_{T2} = V_{in} - (V_{B1} + V_{B2} + V_{Cb1t1}) \quad (9)$$

Also, we can write

$$\begin{cases} i_{vm}(t - t_1) = i_{Db1}(t - t_1) + i_{Db3}(t - t_1) \\ i_{Db1}(t - t_1) = \frac{V_{T2}}{Z_1\sqrt{2}} e^{-Y_1(t-t_1)} \sin \omega_{r1}(t - t_1) \\ i_{Db3}(t) = i_{Db1}(t) + \frac{1}{r_D} e^{-\frac{(t-t_1)}{r_D C_{b2}}} (V_{Cb1t1} - V_{Cb2t1} - V_{B1}) \end{cases} \quad (10)$$

When $V_{B1} + V_{B2}$ is large enough, then D_{b5} is switched on and this operation mode is ended.

Mode 3 [$t_2 - t_3$]: The equivalent circuit of this operational state is shown in Fig. 3(c). During this mode, the charger state doesn't change, but D_{b5} is turned on. The equalization current can be expressed as below:

$$\begin{aligned} i_{vm}(t - t_2) = \frac{V_{T3}\sqrt{3}}{Z_1} e^{-Y_1(t-t_2)} \sin \omega_{r1}(t - t_2) + \\ \frac{1}{r_D} e^{-\frac{(t-t_2)}{r_D C_{b2}}} (V_{Cb1t1} - V_{Cb2t1} - V_{B1}) + \\ \frac{1}{r_D} e^{-\frac{(t-t_2)}{r_D C_{b3}}} (V_{Cb2t2} - V_{Cb3t1} - V_{B2}) \end{aligned} \quad (11)$$

Where,

$$V_{T3} = V_{in} - (V_{B1} + V_{B2} + V_{Cb1t2}) \quad (12)$$

The energy-coupling capacitors voltages are given as below:

$$\begin{cases} v_{Cb1}(t - t_2) = \frac{V_{T3}}{Z_1} (1 - e^{-Y_1(t-t_2)} \cos \omega_{r1}(t - t_2)) \\ v_{Cb2}(t) = v_{Cb1}(t - t_2) + V_{Cb1t2} - V_{Cb2t2} - V_{B1} \\ v_{Cb3}(t) = v_{Cb2}(t - t_2) + V_{Cb2t2} - V_{Cb3t2} - V_{B2} \end{cases} \quad (13)$$

Also, we can write:

$$\begin{cases} i_{vm}(t) = i_{Db1}(t - t_2) + i_{Db3}(t - t_2) + i_{Db5}(t - t_2) \\ i_{Db1}(t) = \frac{V_{T2}}{Z_1\sqrt{3}} e^{-Y_1(t-t_2)} \sin \omega_{r1}(t - t_2) \\ i_{Db3}(t) = i_{Db1}(t) + \frac{1}{r_D} e^{-\frac{(t-t_2)}{r_D C_{b2}}} (V_{Cb1t2} - V_{Cb2t2} - V_{B1}) \\ i_{Db5}(t) = i_{Db1}(t) + \frac{1}{r_D} e^{-\frac{(t-t_2)}{r_D C_{b3}}} (V_{Cb2t2} - V_{Cb3t2} - V_{B2}) \end{cases} \quad (14)$$

When $V_{B1} + V_{B2} + V_{B3}$ is large enough, then D_{b7} is switched on and this operation state ends.

Mode 4 [$t_3 - t_4$]: According to Fig. 3(d), during this operational mode diode D_{b7} in the equalization circuit is turned on and $B_1 - B_3$ are charged by the equalization current through the low side diodes in the equalization network. The equalization current during this state can be expressed as below:

$$\begin{aligned} i_{vm}(t - t_3) = \frac{2V_{T4}}{Z_1} e^{-Y_1(t-t_3)} \sin \omega_{r1}(t - t_3) \\ + \frac{1}{r_D} e^{-\frac{(t-t_3)}{r_D C_{b2}}} (V_{Cb1t1} - V_{Cb2t1} - V_{B1}) + \\ \frac{1}{r_D} e^{-\frac{(t-t_3)}{r_D C_{b3}}} (V_{Cb2t2} - V_{Cb3t1} - V_{B2}) + \\ \frac{1}{r_D} e^{-\frac{(t-t_3)}{r_D C_{b4}}} (V_{Cb3t3} - V_{Cb4t3} - V_{B3}) \end{aligned} \quad (15)$$

$$\frac{1}{r_D} e^{-\frac{(t-t_3)}{r_D C_{b3}}} (V_{Cb2t2} - V_{Cb3t1} - V_{B2}) +$$

$$\frac{1}{r_D} e^{-\frac{(t-t_3)}{r_D C_{b4}}} (V_{Cb3t3} - V_{Cb4t3} - V_{B3})$$

Where,

$$V_{T4} = V_{in} - (V_{B1} + V_{B2} + V_{Cb1t3}) \quad (16)$$

TABLE I
COMPARISON BETWEEN THE PROPOSED SELF-EQUALIZED BATTERY CHARGER AND THE CONVENTIONAL EQUALIZERS

Topology			Charge Capability	Control Complexity	Application	S*	L**	C***	D [†]	T ^{††}
AC2C	Buck-Boost Converter	[13]	No	Complex	Low Power	2n-2	2n-2	n-1	-	-
	Cuk Converter	[14]				2n-2	2n-2	n	-	-
	Switch-Capacitor Converter	[15]				2n	-	n	-	-
DC2C	Coupled Inductor	[18]	No	Complex	Low Power	2n	-	n	2n	1
	Flying Inductor	[19]				2n+2	-	-	2n+2	-
	Selection Switches	[20]				4n	1	1	3	-
AC2AC		[1]	No	Complex	Low Power	4n+5	2	2	2	-
		[22]				n+2	n	-	n+2	1
C2P	Multi-secondary Windings	[25]	No	Complex	Low Power	n	-	-	1	1
	Flyback Converter	[26]				2n+2	-	-	2n+2	1
C2P2C	Multiple Transformer	[29]	No	Complex	Low Power	2n	-	-	-	2n
	Switched-Transformer	[31]			Medium Power	2n+2	-	2	2	1
P2C	Full-Bridge Converter	[32]	No	Complex	High Power	4n	-	-	-	-
	Integrated Converter	[10]		Simple	Low Power	2	-	n+2	2n	1
		[11]				2	-	n+3	2n	1
		[12]				1	-	n+2	2n+1	1
	Proposed Self-Equalized Battery Charger		Yes	Simple	High Power	4	2	n	2n	1

S*=Switch

L**= Inductor

C***=Capacitor

D[†]=Diode

T^{††}=Transformer

Also, the energy-coupling capacitors voltage are given as following:

$$\begin{cases} v_{Cb1}(t-t_1) = \frac{V_{T3}}{Z_1} (1 - e^{-Y_1(t-t_3)}) \cos \omega_{r1}(t-t_3) \\ v_{Cb2}(t) = v_{Cb1}(t-t_3) + V_{Cb1t3} - V_{Cb2t3} - V_{B1} \\ v_{Cb3}(t) = v_{Cb1}(t-t_3) + V_{Cb2t1} - V_{Cb3t3} - V_{B2} \\ v_{Cb4}(t) = v_{Cb1}(t-t_3) + V_{Cb3t3} - V_{Cb4t3} - V_{B3} \end{cases} \quad (17)$$

Different components' currents are easily expressed as:

$$\begin{cases} i_{vm}(t-t_3) = i_{Db1}(t) + i_{Db3}(t) + i_{Db5}(t) + i_{Db7}(t) \\ i_{Db1}(t-t_3) = \frac{V_{T3}}{2Z_1} e^{-Y_1(t)} \sin \omega_{r1}(t) \\ i_{Db3}(t-t_3) = i_{Db1}(t) + \frac{1}{r_D} e^{-\frac{(t)}{r_D C_{b2}}} (V_{Cb1t3} - V_{Cb2t3} - V_{B1}) \\ i_{Db5}(t-t_3) = i_{Db1}(t) + \frac{1}{r_D} e^{-\frac{(t)}{r_D C_{b3}}} (V_{Cb2t3} - V_{Cb3t3} - V_{B2}) \\ i_{Db7}(t-t_3) = i_{Db1}(t) + \frac{1}{r_D} e^{-\frac{(t)}{r_D C_{b4}}} (V_{Cb3t3} - V_{Cb4t3} - V_{B3}) \end{cases} \quad (18)$$

Modes 5-9 [$t_4 - t_9$]: During these operational modes, the equalization circuit operation is similar to mode 4. But, states of the charger are changed during these operation modes which are roughly the same as in conventional PSFB dc-dc converter. To shorten the discussion, it is not addressed, here.

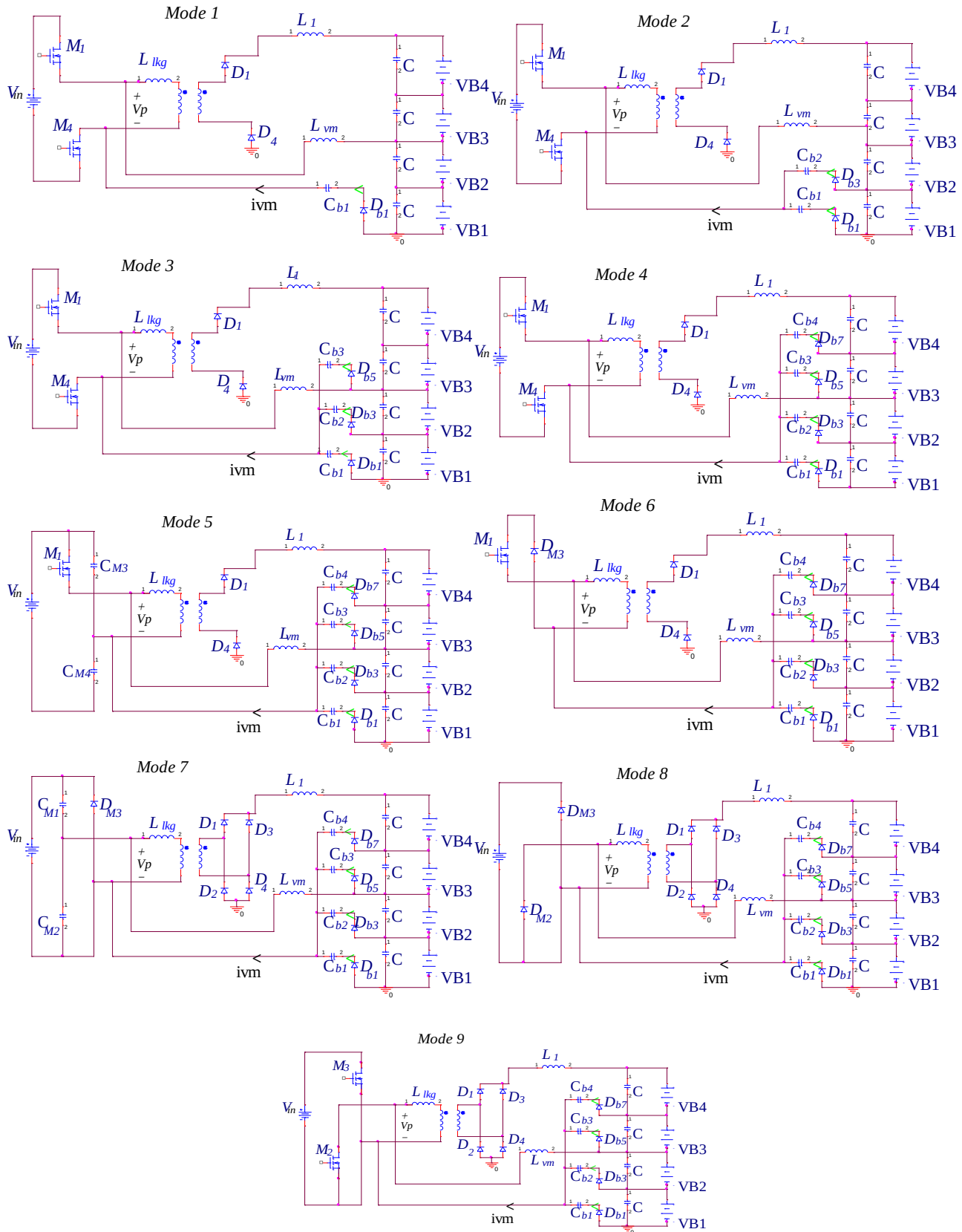


Fig. 3. Operational modes of the proposed self-equalized battery charger.

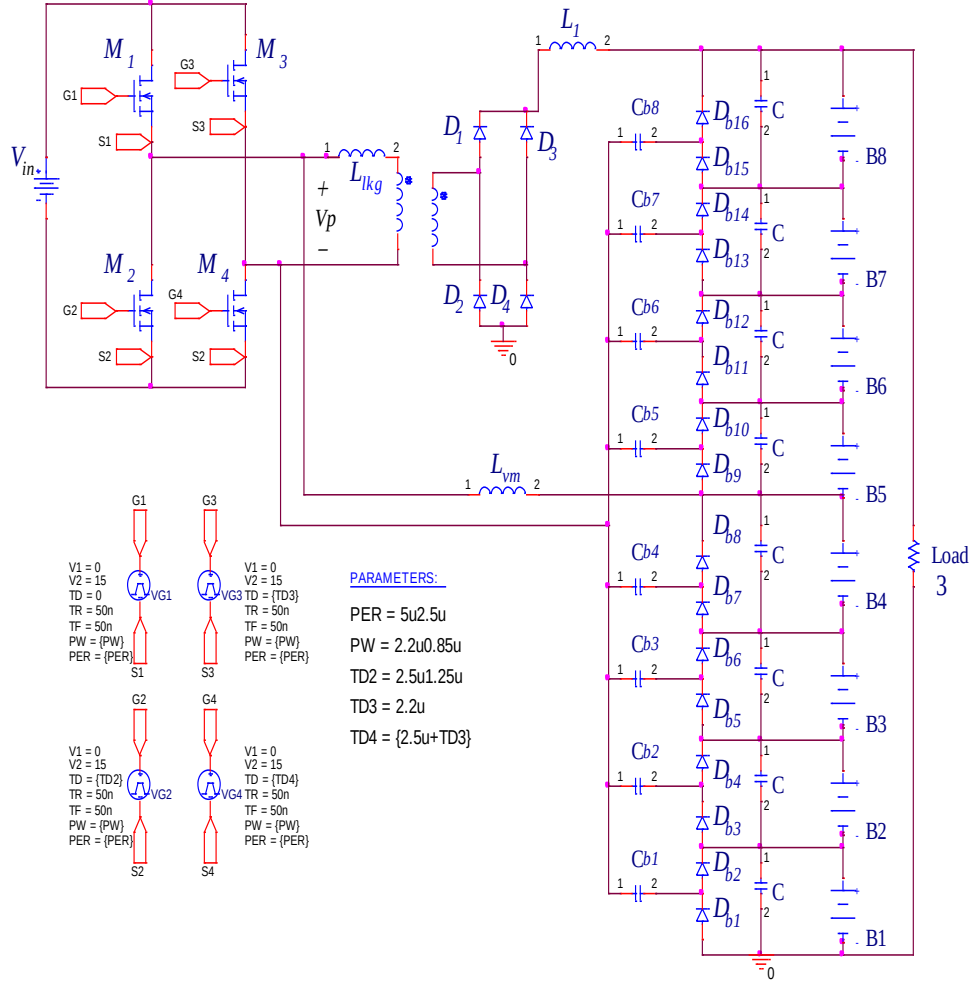


Fig. 4. The simulated circuit of the proposed self-equalized battery charger.

C. Operation of the Converter under the Cells Balances Condition

At the time $t = t_b$, when all the batteries equalized, the batteries voltage can be expressed as follow:

$$\begin{cases} V_{Pack} = V_{B1} + V_{B2} + \dots + V_{B8} \\ V_{B1} = V_{B2} = \dots = V_{B8} = \frac{V_{Pack}}{8} \end{cases} \quad (19)$$

Since the proposed self-equalized battery charger has a symmetrical structure, the energy-coupling capacitors voltages for the i^{th} battery are given by:

$$\begin{cases} v_{Cb(i-1)}(t - t_b) - v_{Cb(i)}(t - t_b) = \frac{V_{Pack}}{8} \\ v_{Cb(i-1)}(t - t_b) = -v_{Cb(9-i)}(t - t_b) \\ v_{Cb(i)}(t - t_b) = \frac{9 - 2i}{16} V_{Pack} \end{cases} \quad (20)$$

where $1 \leq i \leq 8$,

D. Design Considerations

The main parameters for designing the proposed self-equalized battery charger are listed in Table II. Since the voltage of a single lithium-ion cell is around 3.7- 4.2 V, for producing 8 uniform voltages, the applied voltage to the equalization circuit must have a square voltage waveform with an amplitude of 3.7 V. Thus, the equalization inductor is easily identified:

$$L_{vm} = \frac{v_{Lvm} \times D \times T_s}{\Delta I_{Lvm}} = \frac{200 \times 0.4 \times 5}{4} = 110 \mu H \quad (21)$$

Also, the energy-coupling capacitors are calculated as follow:

$$C_{bi} = \frac{T_s \times D \times \Delta i_c}{\Delta v_{cb}} = \frac{T_s \times D \times i_{Lvm}}{(9 - 2i) \times \Delta v_{cb}} = 470 nF \quad (22)$$

The main transformer secondary side voltage is calculated as follow:

$$V_s = \frac{V_{pack, min}}{D} = 200V \quad (23)$$

So, the main transformer turns ratio is given by

$$n_1 = \frac{N_s}{N_p} = \frac{V_{pack,min}}{V_{in,min}} = 0.26 \quad (24)$$

Also, the output filter inductor value is given by

$$L_1 = \frac{T_s \times V_{B,min} \times D}{2\Delta I_L} = \frac{5 \times 23 \times 0.44}{3.6} \approx 15 \mu H \quad (25)$$

V. SIMULATION RESULTS

The performance of the proposed self-equalized battery charger is verified by simulation the converter by using PSpice, as shown in Fig. 4. The key parameters are listed in Table II. Some parameters have been optimized via simulation. The simulation is done for three different conditions including low voltage imbalances, high voltage imbalances, and light load (10 % of nominal load) with the maximum input voltage conditions.

During the first test, the batteries voltages are 2.8, 2.85, 2.9, 2.95, 3, 3.1, 3.15, 3.2 volts, respectively. Fig. 5 verifies the equalization operation of the proposed self-equalized battery charger during this test.

Besides, some diodes currents waveforms in the equalization circuit are shown in Fig. 6. According to this figure, the diode which connects to the battery with the lowest voltage value is turned on before the other diodes to charge and increase its battery voltage. The power MOSFETs currents and voltages waveforms are also shown in Fig. 7. According to the Fig. 7, the ZVS operation for all power MOSFETs is obtained. Therefore, the proposed self-equalized battery charger benefits from high efficiency during the simultaneous charging and equalization operation and high switching frequency is possible to achieve high power density.

TABLE II
THE KEY PARAMETERS VALUE OF THE PROPOSED
SELF-EQUALIZED BATTERY CHARGER

Description	Symbol	Value
Input Voltage	V_{in}	200-250 V
Battery Pack Voltage	V_{pack}	23-33.6 V
Constant Current Charging	I_{CC}	10 A
Constant Voltage Charging	V_{CV}	33.6 V
Switching Frequency	f_{sw}	200 kHz
Capacitor Voltage Ripple	ΔV_{Cb}	1.5 mV
Output Inductor	ΔI_{L1}	3.6 A
Current Ripple		
Equalizer Inductor	L_{vm}	110 μH
Energy-Coupling Capacitors	C_b	470 nF
Dead-Time	T_d	200 ns
Transformer Turns Ration	n	0.26
Batteries	B	10 mF
Output Inductor	L_1	15 μH

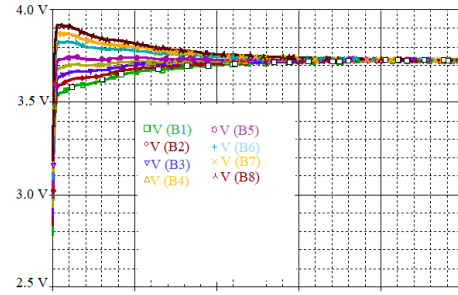


Fig. 5. The resultant batteries voltages of the proposed charger with low voltage imbalances at $V_{in} = 200 V$, $f_s = 200 kHz$.

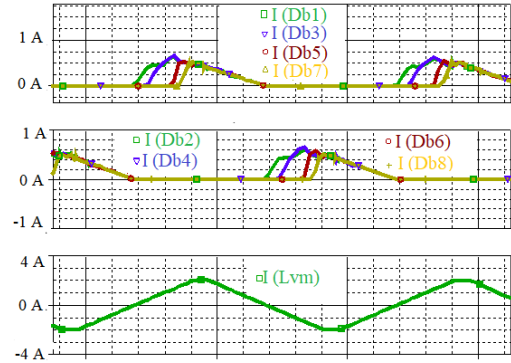


Fig. 6. The key current waveforms of the equalization circuit with low voltage imbalances at $V_{in} = 200 V$, $f_s = 200 kHz$.

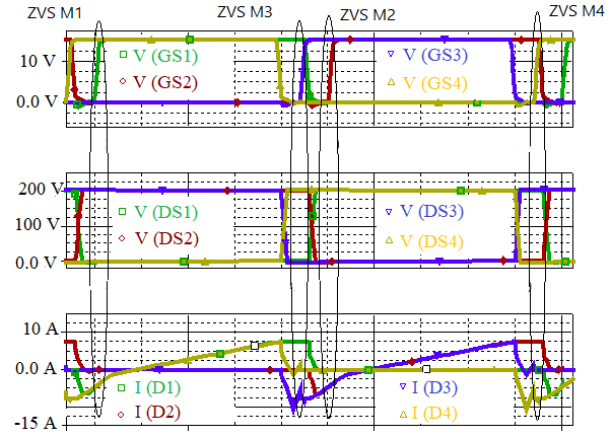


Fig. 7. The voltage and current waveforms of the power MOSFETs in the proposed self-equalized battery charger at $V_{in} = 200 V$, $I_{out} = 10 A$, $f_s = 200 kHz$.

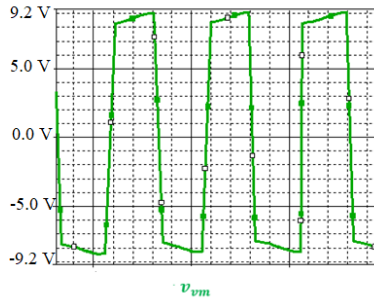


Fig. 8. The applied ac voltage to the VM network under low imbalance condition at $V_{in} = 200\text{ V}$, $f_s = 200\text{ kHz}$.

The applied ac voltage to the VM network is shown in the Fig. 8. According to this figure, the PSFB charger generates the required ac voltage to enable the VM network.

In the second test, the batteries voltages are 1.5, 2, 2.5, 2.8, 2.9, 3, 3.9, 4 volts, respectively. Fig. 9 validates the equalization operation of the proposed self-equalized battery charger under this test. In addition, some equalization circuit diodes currents waveforms are shown in Fig. 10. Based on Fig. 6 and Fig.10, the equalization current is shared between batteries proportional to their voltages. Consequently, the lowest battery with the lowest voltage value receives the maximum portion of the equalization current. Besides, Fig.6 and Fig. 10 indicate that for n batteries the amplitude of the equalization current remains constant.

This feature results in high reliability and a simple control system without any current sensor. The applied ac voltage to the VM network under high voltage imbalance condition is shown in the Fig. 11. According to this figure, the PSFB charger generates the required ac voltage to enable the VM network.

In the third case, the ZVS operation of power MOSFETs under the light load condition is tested. The power MOSFETs currents and voltages under this condition are shown in Fig. 12. According to this figure, the ZVS operation for all power MOSFETs is roughly obtained. The measured efficiencies of the proposed self-equalized battery charger under two different conditions in the PSpice software are listed in Table IV.

VI. EXPERIMENTAL RESULTS

In this paper, 48 lithium-ion cells are employed for experimental implementation. 6 lithium-ion cells are connected in parallel to form a battery and 8 batteries are connected in series to form the battery pack. To verify the simulation results, a 300 W prototype was implemented as shown in Fig. 13. The prototype components and elements are listed in Table III. In this study, the proposed self-equalized battery charger works at a constant switching frequency and a constant duty cycle. Therefore, the proposed

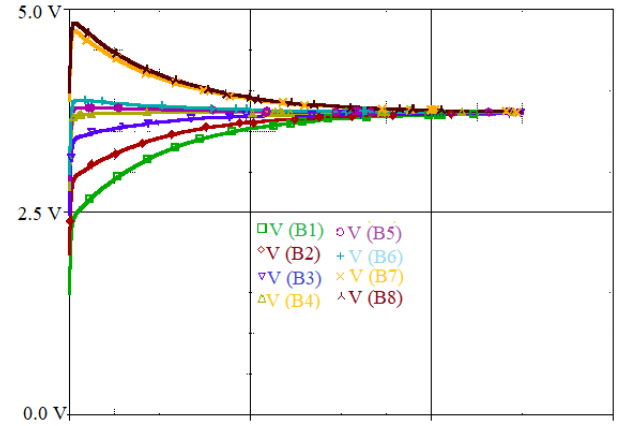


Fig. 9. The resultant batteries voltages of the charger with high voltage imbalances at $V_{in} = 200\text{ V}$, $f_s = 200\text{ kHz}$.

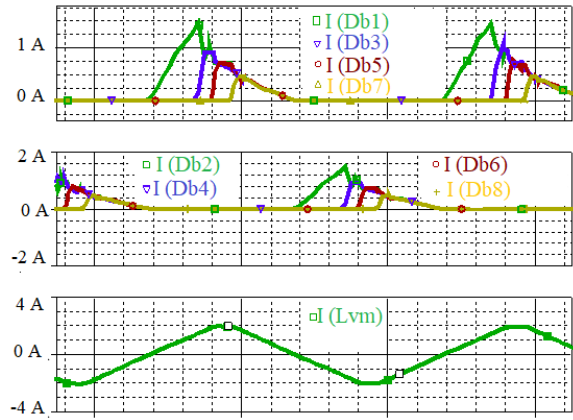


Fig. 10. The key current waveforms of the equalization circuit with high voltage imbalances at $V_{in} = 200\text{ V}$, $f_s = 200\text{ kHz}$.

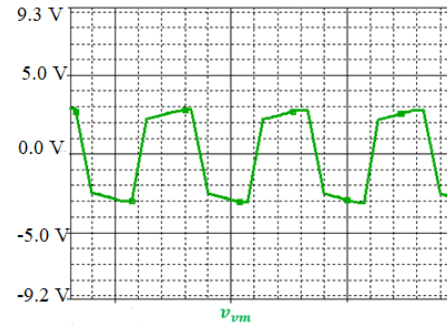


Fig.11. The applied ac voltage to the VM network under high imbalance condition at $V_{in} = 200\text{ V}$, $f_s = 200\text{ kHz}$.

charger benefits from control simplicity. Generally, the equalization current is much smaller than the charging current, consequently, the equalization network power losses are much smaller than the charger circuit losses.

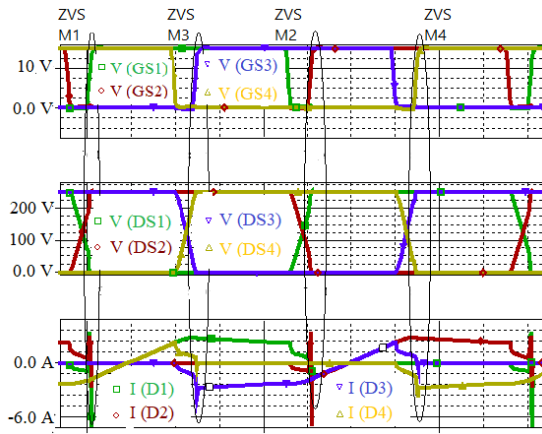


Fig. 12. The voltage and current waveforms of the power MOSFETs in the proposed self-equalized battery charger at $V_{in} = 250\text{ V}$, $I_{out} = 1\text{ A}$, $f_s = 200\text{ kHz}$.

A. Simultaneous equalization and charging test

This test is done under voltage imbalances condition. By using the current probe (PA-677, PINTEK), the equalization current of all batteries are measured. The batteries voltages, $V_{B1} - V_{B4}$, are equal to 2.5, 2.6, 2.7, 2.8, 2.8, 2.9, 2.9, 3, respectively. During the constant current charging process, the battery pack is charged by the $I_{CC} = 9\text{ A}$ and the battery pack voltage is increased from 22.2 V to 29.7 V. During this condition, the voltage imbalances are being removed by the equalization current. During the constant voltage charging process, the charging current is reduced to the pre-set value and the voltage imbalances are reduced to 24 mV. The equalization current is shown in Fig. 14 and the resultant voltages and the equalization current of some batteries of this test are depicted in Fig. 15.

Considering this fact that the equalization current is much smaller than the charging current, the power losses in the equalization circuit can be neglected. Therefore, the majority of the power is transferred to the battery pack by the charging circuit. The voltage multiplier losses distribution is shown in the Fig. 16. Based on this figure, when the total power in increased the equalization circuit losses are proportionally reduced and they can be neglected. Consequently, the efficiency of the charger circuit is predominant. Fig. 17 and Fig. 18 show the power MOSFETs voltage waveforms under the nominal load with the nominal input voltage, and light load with the maximum input voltage conditions, respectively. According to Fig. 17 and Fig. 18, the ZVS operation of the power MOSFETs is obtained under these conditions. Therefore, the proposed self-equalized battery charger benefits from high efficiency and low EMI noise, as well.

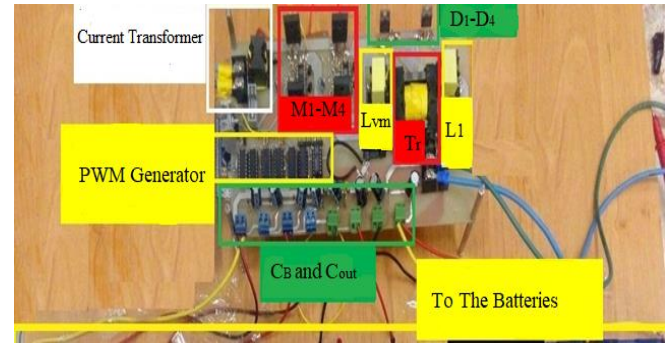


Fig.13. The 300 W prototype of the proposed self-equalized battery charger for 48 lithium-ion cells.

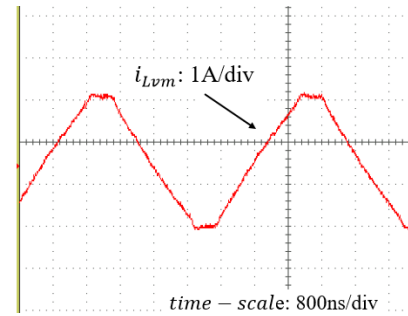


Fig.14. Experimental equalization current at $V_{in} = 200\text{ V}$, $f_s = 200\text{ kHz}$, and $I_{CC} = 9\text{ A}$.

TABLE III
THE COMPONENTS LIST OF THE PROPOSED SELF-EQUALIZED BATTERY CHARGER

Section	Components	Value & Part
Charging Circuit	$M_1 - M_4$	IRFP460
	$D_1 - D_4$	MUR1520G
	T_r	ETD29, $n = 0.26$
Equalization Circuit	Output Inductor	PQ2016, $L_1 = 15\text{ }\mu\text{H}$
	$D_{b1} - D_{b16}$	SM5820
	$C_{b1} - C_{b8}$	Tantalum, 470 nF, 50 V
Phase-Shifted Modulator	C_B	470 μF , 50 V
	L_{vm}	PQ2020, 110 μH
	JK Flip-Flop	74HC73
Batteries	RS Flip-Flop	SN7470
	Mono Stable	74HC4538
	And Gate	SN74HC04N
Current Probe		INR18650, 2200 mA.h
	Oscilloscope	PINTEK, PA-677
	Multi-Meter	HANTEK, DSO5102P
		SANWA, CD771
		MASTECH, MS8229

The experimental efficiencies of the proposed self-equalized battery charger for the two aforementioned conditions are listed in Table IV. A comparative study between the

proposed integrated converter experimental results and previous integrated converters experimental results is shown in the Table V. This table demonstrate the effectiveness of the proposed integrated converter over the traditional integrated converters, clearly.

TABLE IV

THE MEASURED EFFICIENCIES OF THE PROPOSED SELF-EQUALIZED BATTERY CHARGER UNDER TWO DIFFERENT CONDITIONS

	Input Voltage	Output Power	Output Current	Efficiency
Simulation	200 V	330 W	10 A	94 %
	250 V	33 W	1 A	87 %
Experimental	200 V	300 W	10 A	89 %
	250 V	30 W	1 A	83 %

TABLE V

COMPARISON BETWEEN EXPERIMENTAL RESULTS OF THE PROPOSED INTEGRATED CONVERTER AND THE PREVIOUS RESEARCHES

Reference	Power	Number of Cells	Charging Capability	Efficiency
[10]	10 W	12	No	At best case 75 %
[11]	3 W	8	No	At best case 70%
[12]	6 W	8	No	At best case 68%
[34]	3 W	3	Yes	At best case 84 %
Proposed Converter	300 W	48	Yes	83-89 %

VII. CONCLUSION AND FUTURE WORKS

In this study, a novel self-equalized battery charger using a voltage multiplier and the PSFB dc-dc converter for lithium-ion batteries is proposed. By utilizing the main transformer and the equalization circuit inductor, the battery pack is charged and its series connected cells are equalized simultaneously by the charging and the equalization currents, respectively. The equalization circuit generates 8 uniform voltages across the batteries and equalizes their voltages. By combining the charging and the equalization circuits, an integrated converter has been obtained which provides some major benefits over the conventional equalizers including the simultaneous charging and equalization operations, control simplicity, high efficiency, low cost, and low size without using power MOSFETs or bulky magnetic components in the equalization circuit. Finally, the theoretical analyses were validated with the simulation and the experimental results for 48 lithium-ion cells.

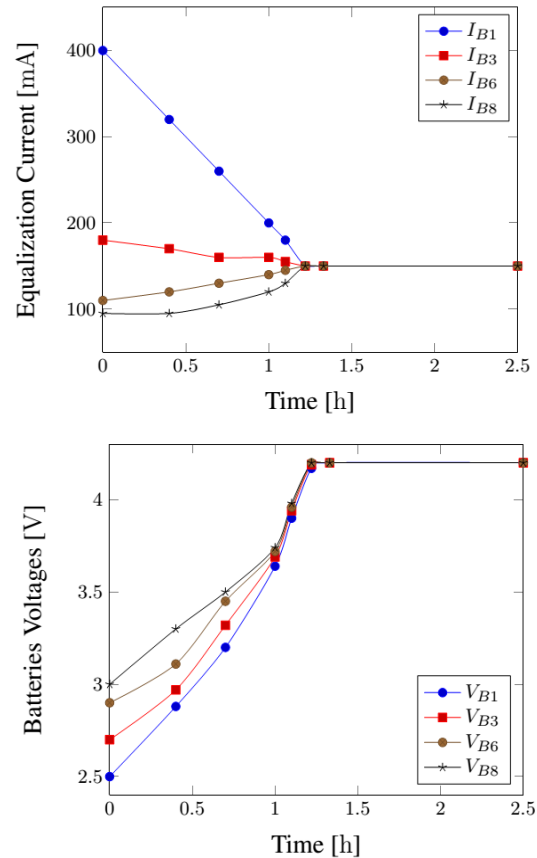


Fig.15. The resultant batteries voltages and the equalization currents in this test.

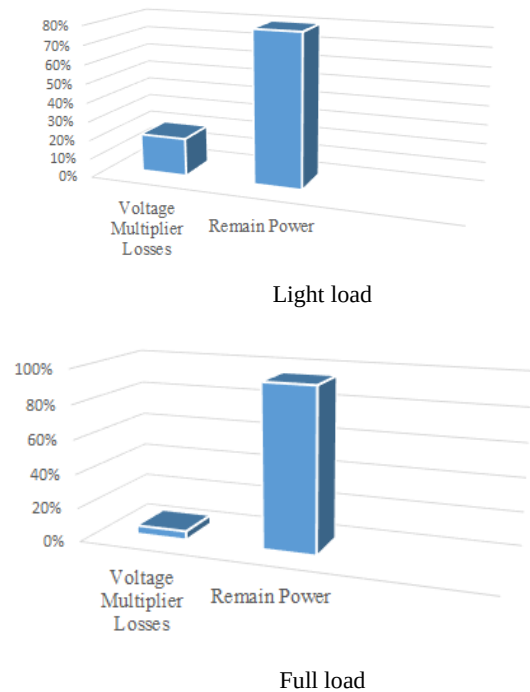


Fig.16. The equalization circuit losses distribution under different load conditions.

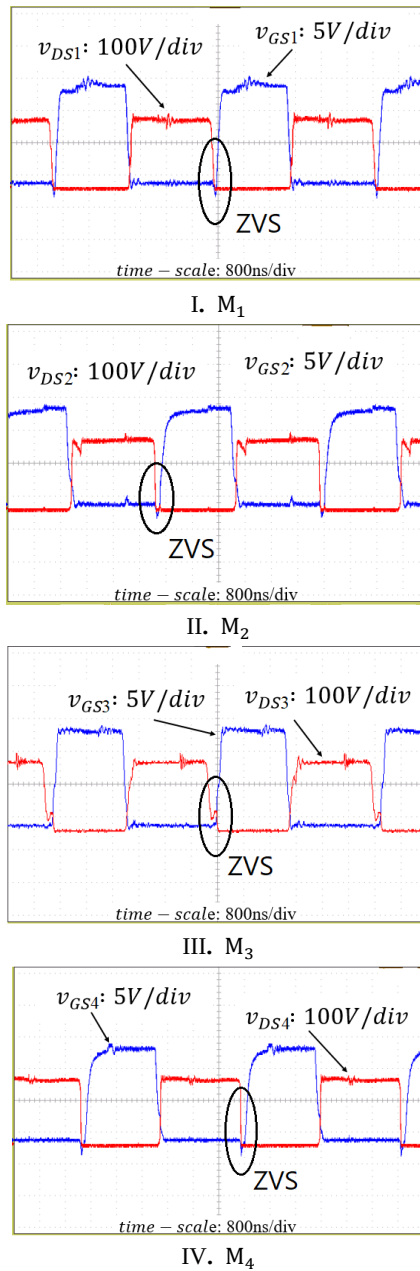


Fig.17. Different voltage waveforms of the power MOSFETs at $V_{in} = 200\text{ V}$, $I_{out} = 10\text{ A}$, and $f_s = 200\text{ kHz}$.

Regarding the abovementioned features and capabilities, some extensions for the near future are increasing the equalization speed by increasing the equalization current without the violation of power conduction losses, burst-mode operation of the converter under full charging conditions, small signal modeling and closed-loop control, and introducing novel voltage multiplier networks with lower components count for voltage balancing of high power EV applications.

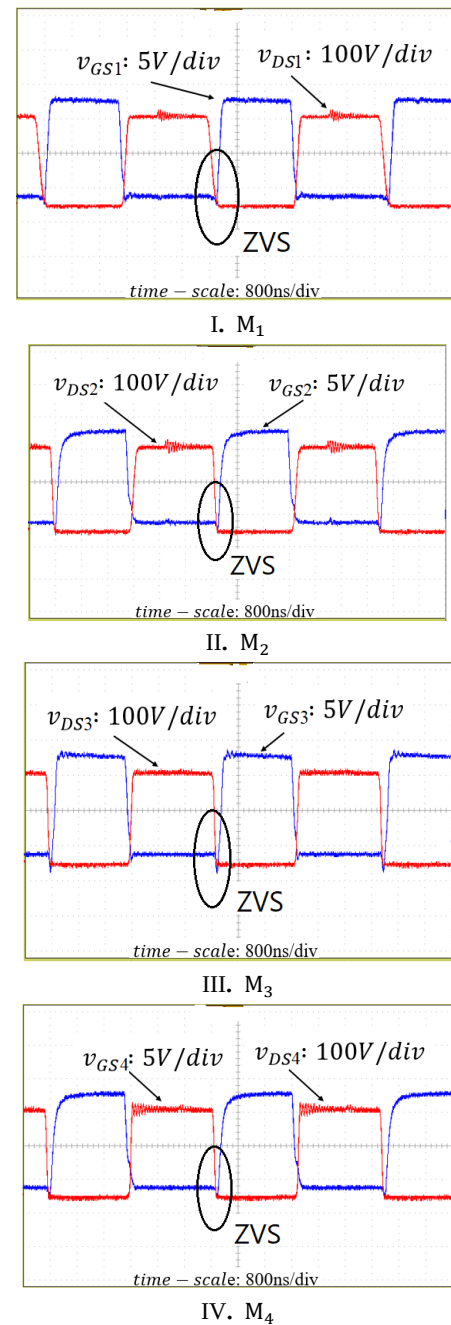


Fig.18. Different voltage waveforms of the power MOSFETs at $V_{in} = 250\text{ V}$, $I_{out} = 1\text{ A}$, and $f_s = 200\text{ kHz}$.

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