Flyback Converter Balancing Technique for Lithium Based Batteries

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***Abstract*—In This paper, the concept of flyback converter cell balancing method for lithium based batteries in ultralight Electrical Vehicle (EV) is investigated. In electrical vehicles, Battery Management System (BMS) plays and important role, in order to achieve a reasonable life time and best performance. A cell balancing circuit is essential to equalize each battery cell as the same voltage level in a series battery cells. Among cell balancing method, flyback converter balancing method has fast balancing time. It has N secondaries for N cells. It only requires one switch and N diodes at the output for each cell. Therefore, the number of active switches are reduced, resulting in less losses and more efficient. In this paper, eight cells are investigated to be equalized. The primary is supplied by the total battery pack, which is controlled by N-channel MOSFET. The switch will be turn ON and OFF with 50% duty cycle. The simulation results are performed to testify the variability of the proposed system.**

***Index Terms*—Balancing method, BMS, EV, Flyback converter, Lithium battery, MOSFET.**

I. Introduction

In today's world, rechargeable lithium based batteries act significant role in numerous application such as electric bikes, electric vehicles uninterruptible power supplies (UPS). They are the most common electrical energy storage device in vehicles as a replacement of traditional fuel [1], [2]. Among batteries, lithium ion has some advantages such as high density, low self discharge rate, lower weight, higher safety, no memory effect [3]. However, the voltage of a single cell is low, thus battery packs are built by connecting multiple cells in series to provide required high voltage. However, the existing battery manufacturing technology cannot ensure perfectly equal cells, which results in cell imbalances. Furthermore, due to the charging and discharging process, the voltages of the cells will differ. These imbalances are a major factor to deteriorate the performance and reliability of the battery pack, because of the decrease in the usable capacity due to low voltage battery cell. Hence battery equalizers are required in order to ensure that all cells in a series connected battery string are fully charged. During past decades, many battery equalizers have been proposed in the literature [4]–[7]. The balancing processes can be divided into passive and active balancing methods. The passive balancing technique dissipate energy as a heat, with using shunting resistor or switches shunting resistor for each cell [8], [9]. The active balancing technique is used to overcome problem of the energy loss and equalizes voltages of battery cells by transferring charge from high voltage battery cells to low voltage battery cells. The capacitor shuttling balancing method is an active balancing technique. This method uses capacitors as external energy storage for shuttling the energy between the cells [10], [11]. The main advantage of capacitor types is that the circuit does not require inductive components, but on the other hand, the disadvantage of this method is long equalization time. However, switched resonant switched capacitor balancing decreases the balancing time [7]. The inductor balancing method transfers energy from a cell to other cell by using inductors and has fast equalization time [6], [12]. The transformer balancing method transfers energy from a cell to other cell by multi-winding structures [13]. It has fast equalization time, However due to nonuniform turn-ratio of secondary winding leakage inductance, the voltages of the secondary windings are not equal [14], [15]. In this paper, flyback balancing method will be investigated. The flyback is designed not only to transfer energy, but also to store it for a fraction of time in the switching period. The core of the flyback has an air gap to store energy.

II. The proposed flyback converter balancing circuit

The schematic of the proposed flyback converter balancing is shown in Fig. 2. The primary side is connected to the complete battery pack, and every battery cell is connected to the secondary windings through a diode. The secondaries are in such a way that, their polarity are opposite regarding to the primary winding. When the main switch, which is a N-channel MOSFET, is turned on, the energy will be stored in the transformer as a flux. The stored energy can not be transferred to the secondary, because the diode is reverse biased. In the next mode, when the switch is turned off, the energy will be transferred to the secondary windings. Flyback is widely used in power supplies, it has low cost, simple design, and high efficiency. The other advantages are: the primary side and secondary side are isolated, and it can provides multi-output, and positive negative output voltage selection. In order to analyze the circuit, let's consider the operational principle

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of the circuit in two modes. In mode one, when the MOSFET is ON, the primary inductor voltage is

$$V_{Lp} = V_{\text{Battery}} \tag{1}$$

$$T_{\text{(on)}} = D \times T_p \tag{2}$$

where T_p is the period, and D is duty cycle The primary current will be calculated as

$$i_{Lp} = \frac{V_{\text{Battery}}}{L} \times T_{on} \tag{3}$$

In the next mode, during OFF time, primary voltage is

$$V_{Lp} = \frac{-V_{\text{cell1}}}{n} + \frac{-V_{\text{cell2}}}{n} + \cdots + \frac{-V_{\text{cell}m}}{n} \tag{4}$$

where n is duty ratio, and m=1, 2,. . . ,8. is the cell number.

$$T_{\text{(off)}} = (1 - D) \times T_p \tag{5}$$

Also, the primary current during off, can be written as

$$i_{Lp} = 0 \tag{6}$$

By applying volt-second rule which means, the average voltage across inductor during steady state is zero, the transfer function can be driven as

$$T_{\text{(on)}} \times V_{Lp} = V_{\text{Battery}} \times D \times T_p \quad \text{during(on)} \tag{7}$$

$$T_{\text{(off)}} \times V_{Lp} = -\frac{V_{\text{cell}m}}{n}(1 - D) \times T_p \quad \text{during(off)} \tag{8}$$

$$V_{\text{Battery}} = n \times \frac{D}{1 - D} \times V_{\text{cell}m} \tag{9}$$

In order to calculate the primary current, assume one secondary for simplicity. The output voltage is 3.6V and assume 2A output current. The output power can be calculated as

$$P_{out} = V_{out} \times I_{out} = 3.6 \times 2 = 7.2W \tag{10}$$

If the diodes and switches are ideal the efficiency can be considered as 100% for simplicity, which means $P_{in} = P_{out}$. Then the average primary current can be expressed as

$$I_{P,ave} = \frac{P_{in}}{V_{Battery}} = \frac{7.2}{28.8} = 0.25A \tag{11}$$

The primary peak current of a flyback is a sawtooth waveform, therefore, the area is the area of square divided by two. The average current of primary can be expressed as

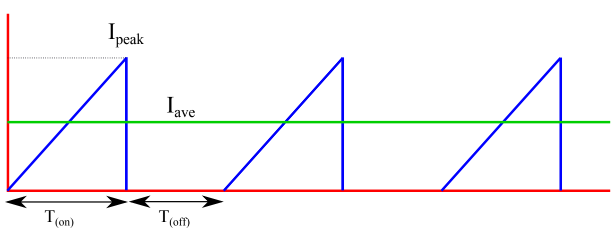

Fig. 1. Expected peak, and average current waveform of primary

$$I_{P,ave} = \frac{1}{T_p}\int_0^{T_p} I(t)dt = \frac{Area}{T_p} \tag{12}$$

$$\frac{0.5 \times I_{Peak} \times D \times T_p}{T_p} = 0.5 \times D \times I_{peak}$$

$$\text{where,} \quad D = 0.5, \quad I_{P,ave} = 0.25 \times I_{peak}$$

Now, the primary peak current can be written as

$$I_{peak} = 4 \times I_{P,ave} = 1A$$

In order to find primary inductance, the general equation of inductor voltage can be used as Eq. 13

$$V = L\frac{di}{dt} \quad \Longrightarrow L_p = \frac{V}{di}dt \tag{13}$$

$$L_p = \frac{V_{Battery}}{I_{peak}} \times T_{on} \tag{14}$$

$$T_{on} = \frac{D}{f} = \frac{0.5}{50kHz} = 10\mu s \tag{15}$$

$$L_p = \frac{28.8 \times 5\mu s}{1A} = 288\mu H \tag{16}$$

III. Simulation results

In this section, the simulation results with MATLAB are performed to verify the proposed flyback converter circuit as shown in Fig. 2. In order to simulate the circuit, the saturable multi-winding transformer is chosen with turn ratio of $a = 1 : 8$. The transformer has one primary and eight secondaries, which are in parallel with each cell. The number of secondaries can be increased or decreased with the desired numbers. The total battery pack voltage is applied to the primary side and the each secondary is connected to one cell via a diode. The switch is a MOSFET, which is controlled by pulse width modulation (PWM) signal with the frequency of 50kHz and 50% duty cycle. As compared with the forward converter structures, the flyback converters are easy to implement and has less components. In forward converters, an auxiliary winding or a supplementary circuit are necessary in order to reset the transformer to avoid saturation. This results in bulky size, more components and losses. The supplementary circuit could be RCD snubber circuit and it has low efficiency, for the reason that, the magnetic energy will be dissipated through a resistor. In addition, at the output, an extra diode and inductor is needed, this results in more circuitry and components, while the flyback type has simpler structure. In order to analyze the circuit, the operation is divided in two stages. In the first stage, when the switch is turned on, the energy will be stored in the transformer. It can not be transferred to the secondaries due to diodes which are reverse biased. In the next stage, when the switch is turned off, the stored energy will be transferred to the secondaries. This energy will charge each individual battery cells. In Fig. 3 the gate to source voltage of the MOSFET with 50% duty cycle is presented. The batteries are modeled with the capacitors with the value of 5F and voltage differences from 3.1V to 3.6V in order to apply significant voltage imbalances. The cell voltages of the battery, with imbalances after equalization, are presented in Fig. 4. As it can be seen in the figure, the cells are balanced fast in 0.02 second. The primary voltage and secondary voltages in steady state are

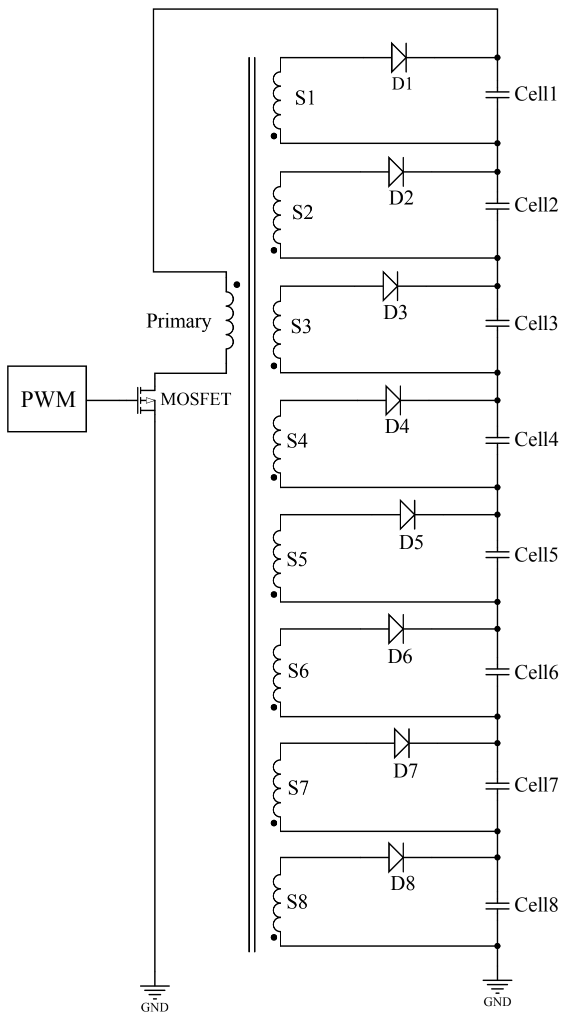

Fig. 2. Schematic of the proposed flyback balancing circuit

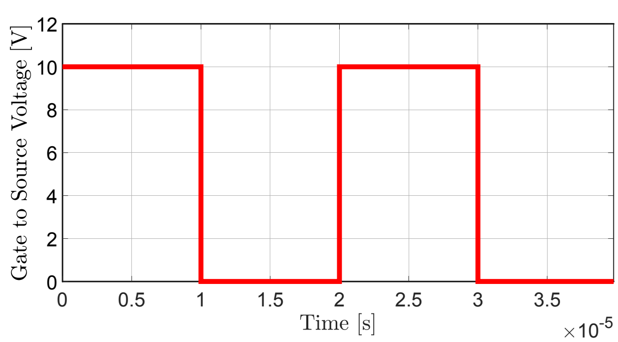

Fig. 3. Gate to source voltage (Vgs) to the MOSFET

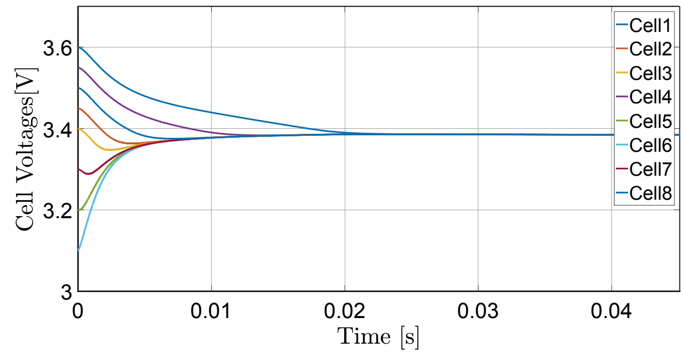

Fig. 4. Equalized cell voltages of the flyback circuit with imbalances

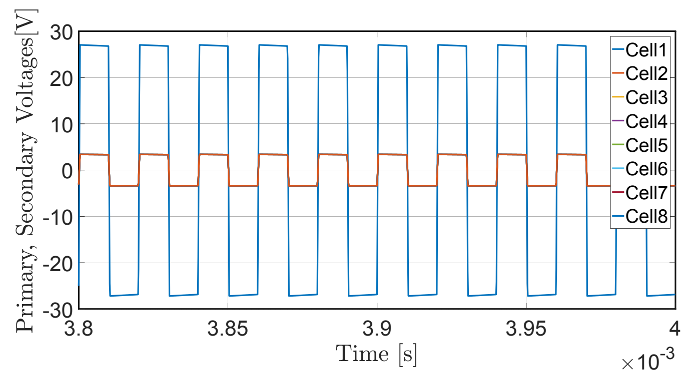

Fig. 5. Primary and secondary output voltage waveforms

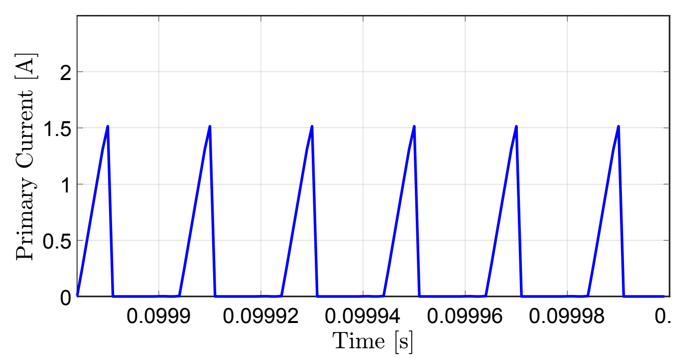

Fig. 6. Primary current waveform in steady state

presented in Fig. 5. The primary voltage is the summation of eight battery cells which is 3.6 V×8 = 28.8 V and 3.6 V for the secondary side corresponding to the battery cells. Fig. 6 presents the primary current waveform of the flyback converter circuit in steady state. It can be noticed that, during $T_{(on)}$, the primary current is rising, and during $T_{(off)}$, when the switch is not conducting, the primary current is zero. The current waveform of the cells in steady sate are presented in Fig. 7. It can be seen that all currents are in the same value which means the cells are equalized and are in the same voltage level. The cell currents waveform during transient is shown in Fig. 8. The cell current waveforms at the beginning of the period are not equal, due to the reason that, the cells are not balanced yet. Then after transient time, in steady sate, the cells are all equalized, thus the currents will be the same for each cells. In Fig. 9, the voltage waveform across MOSFET during On and OFF time is presented. It can be noticed that during ON time when the switch is turned on the voltage is zero, while in OFF time, the voltage is approximately two times that primary voltage. The switch should be chosen in such a way that, it should hold twice the input voltage.

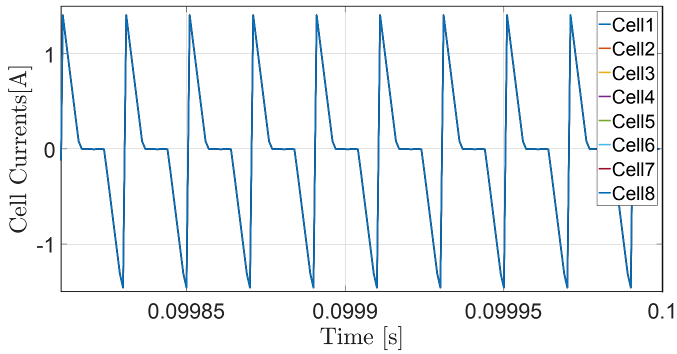

Fig. 7. Cell current waveforms in steady state

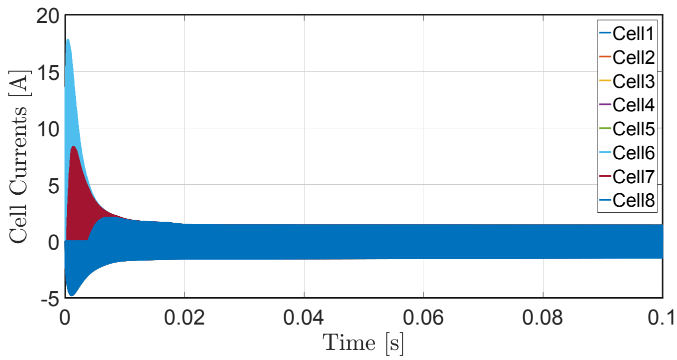

Fig. 8. Cell current waveforms during transient

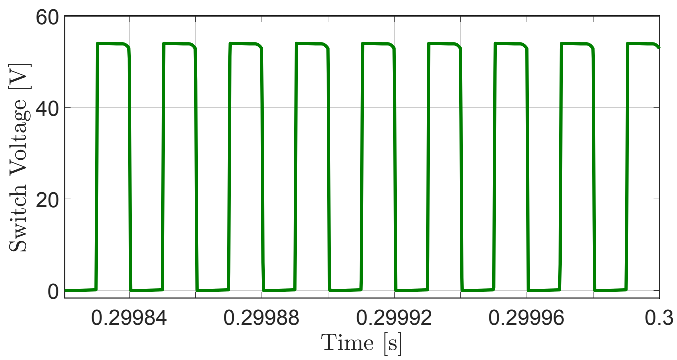

Fig. 9. Voltage waveform across MOSFET during On and OFF time

IV. CONCLUSION

The concept of active balancing technique by using flyback converter structure is investigated in this paper. This proposed circuit, equalizes eight cells in series in a battery pack. Flyback balancing has fast equalization time and easy to control and implement as compared to forward converter which requires an supplementary circuit, RCD snubber, or auxiliary winding to reset the transformer core to prevent saturation. It requires only one switches for N cells, and N diodes at output of the secondaries for each cell. The switch is a N-channel MOSFET with body diode which is triggered by a pulse width modulation (PWM) signal with the switching frequency of 50kHz and 50% duty cycle. The batteries are modeled with capacitors with the value of 5F, from 3.1V to 3.6V. The transformer has eight secondaries with saturable core. Unlike the forward converter that the energy form primary will transfer to the secondary, in flyback the energy will store in the transformer during On time and then during off time it will be transferred to the secondaries. The advantages of flyback as compared to the forward converter is that, it will not require a reset winding in primary side, and also extra diode and inductor at secondary side. Therefore, less component are easy to implement. The diodes are considered to be ideal diodes. The simulation result are presented to verify the feasibility of the circuit.

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