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Citation: Zhan, Huaxia, Pickert, V., Xiang, Xin, Lu, Xiang, Lambert, S.M. and Wu, Haimeng (2016) A cascaded transformer-based equalisation converter for series connected battery cells. In: 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016), 19/4/16 - 21/4/16, Glasgow, United Kingdom.

URL: <https://doi.org/10.1049/cp.2016.0140> <<https://doi.org/10.1049/cp.2016.0140>>

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A cascaded transformer-based equalisation converter for series connected battery cells

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Keywords: EVs, voltage equalisation, cascaded multi-winding transformer.

Abstract

Hybrid electric vehicles (HEVs) and electric vehicles (EVs) have increased in popularity as they use rechargeable battery as energy source instead of petrol, furthermore, help to reduce the release of greenhouse gases. Generally, for applications such as EVs and HEVs, a battery pack may consist of hundreds individual cells batteries in order to meet voltage and energy capacity requirements. However, due to individual chemical characteristics and manufacturing tolerances each cell in a pack will have a slightly different capacity. The capacity of a cell also changes over time as the cell ages. During charging and discharging this leads to unbalanced voltages across the battery pack, and unchecked could result in over-charging/over-discharging for certain cells. This in turn can lead to cell and pack failure or even fire. Therefore, as part of the battery management system a process for voltage equalisation of cells throughout the stack is essential. This paper proposes a new cascaded multi-winding transformer based equalisation circuit topology which, compared to more traditional multi-winding transformer-based topologies is simpler in transformer construction and is therefore far easier to manufacture. The topology concept and operating principals are discussed followed by simulation results for the proposed system. In addition accelerated equalisation speed compared to existing solutions is demonstrated.

1 Introduction

With the recent commercial release of a number of mass produced hybrid electric vehicles, (HEVs) and electric vehicles (EVs) have increased in popularity. Owing to its power and energy density and good cycle behaviour lithium-ion batteries are used in the majority of mass produced EV and HEVs. As the penetration of Li-ion powered vehicles into the world fleet increases the scale of production means that lithium-ion batteries will benefit from a maturing production technology and higher volumes resulting in lower manufacturing cost.

The voltage level for a single Li-ion battery cell is limited to between 3.7V and 4.1V. In most (H)EV battery systems the standard battery pack voltage is in the range of 300-600V [1, 2]. There is therefore a requirement for a large number of

cells to be connected in series to form a battery pack with an adequate nominal voltage.

Due to manufacturing tolerances and changes in battery chemistry due to aging effects the capacity of each cell within a battery pack is unique. This results in the charging/discharging profiles of each battery cell not being precisely the same. As during charging and discharging a series connection of cells each cell is charged by the same current level a variance in cell capacitances across the stack results in mismatches of cell voltage across the stack often termed an unbalanced state. Continued charging of mismatched cells in a pack can lead to over-charging or over-discharging of cell, reducing the power-to-volume ratio of the battery system, and in worse case, placing the whole system in risk of a catastrophic fault. Therefore, a method for voltage equalisation is necessary to guarantee safety and improve efficiency in a battery management system.

A number of different circuits have been proposed in literature to accomplish voltage equalisation [2-9]. Based on different methods to deal with the energy management of a battery pack, balancing circuits can be divided into two categories: dissipative methods and non-dissipative methods. In dissipative equalisation circuits, an energy absorbing unit such as a resistive load is switched into a parallel connection with the cell controlled by a micro-processor. This has the effect of discharging the cell's energy into the load and dissipating it as heat. This equalisation method has been widely used in low-power system, due to the simple circuit structure and circuit control, and low cost. However, these circuits obviously exhibit low efficiency since the energy abstracted from higher voltage cells has totally been wasted. Besides this, during the cell's stored energy being transferred into heat, the temperature in battery pack has to be carefully managed to avoid significant increases in the temperature of the battery pack which can also lead to safety issues with the pack. Non-dissipative equalisation circuits have better performance in energy efficiency. With the employment of an energy transfer medium, equalisation energy can be rearranged to cells within a pack. In [10], switched inductors are used as an energy transfer medium. Energy is transferred between neighbouring cells by controlling two groups of switches alternatively. This central control method is quite simple, but the equalisation time for this circuit is long especially with longer stacks of battery cells since energy can only be transferred between neighbouring cells. This technique also relies on the voltage difference between the

cells to drive the equalisation current. Since the difference are very small equalisation currents are consequently also very small. Equalisation circuits based on buck-boost converters are introduced in [11-14]. Energy can only flow between neighbouring cells in both directions, thus this equalisation scheme suffers from a similar problem when the stack is long. Nevertheless, the buck-boost converter equalizer shows advantage in respect of modularity. In [15] a flying inductor equalisation circuit is proposed. In this topology the number of power electronic devices has been dramatically reduced and hence the cost of the system is significantly lower. Another advantage is that the energy flow path is not limited to neighbouring cells, indeed energy can be transferred from one cell to any target cell in the pack. The control of such a system is, however, clearly more complex. The other main circuit schemes are transformer-based equalisation circuits. Various topologies which incorporate transformers with multiple windings either on the secondary or the primary are studied in [4, 5, 16]. In basic schemes the transformer can operate in either flyback or forward mode. In the flyback configuration there is only one active switch which significantly reduces the cost and the control complexity of the system. The forward mode allows a greater degree of control and can be more efficient and faster for a static system however the complexity of the control as well as the cost of significantly more active semiconductor devices is noteworthy.

The principle disadvantage to multi-winding transformer methods is that in whatever configuration the transformer requires a discrete windings for every cell in the system. This reduces modularity for a given converter product and makes the construction of the transformer extremely complex since each secondary must exhibit identical electromagnetic characteristics in order to properly perform a balancing operation. Achieving this is difficult when considering many tens if not hundreds of windings around a single transformer core and the cost developing such a bespoke arrangement and manufacturing it correctly to specification may be prohibitively costly. Further improvements to the multi-winding topologies have been proposed in literature however the problem with the multi-winding transformer manufacture remains [17, 19 & 20]. Other topologies utilise single transformers for each cell which can result in a large number of transformers [16, 18 & 21]. Developments have also been made in achieving the common mode isolation through solid state multiplexing of the cell stack [17] however, these require large numbers of semiconductor switches.

This paper introduces a new circuit topology which is based on a cascaded version of the multi-winding flyback transformer equalisation circuit but crucially with far fewer windings per transformer core. The proposed circuit outperforms the traditional flyback topology in equalisation rate to as well as having a greater simplicity of the constituent magnetic components.

Section II explains the operational principles for both the traditional flyback transformer equalisation topology as well

as the circuit proposed in this paper. There is also a discussion around the explanation of improved equalisation rate in comparison to the traditional method. In section III the results of a simulation model of the proposed circuit are presented. Finally, section IV includes a conclusion to this work and proposes future work on the topic.

2 Proposed Cascaded Transformer-based Equalisation Converter

2.1 Flyback Transformer-based Equalisation Circuit

The traditional equalisation circuit based on a multi-winding flyback transformer is shown in Fig.1. The circuit employs a multi-winding transformer as the energy transmission medium as well as the common mode isolation between different voltage levels of the cell stack.

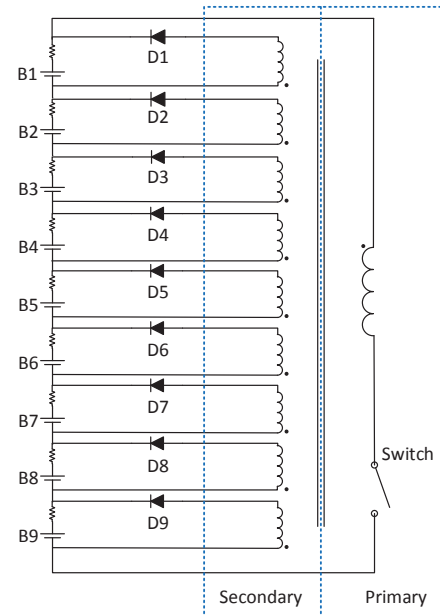


Fig.1. Flyback converter equalisation circuit

There is only one active switch in the topology which is placed on transformer primary winding which and controlled by a PWM pulse. When the switch is turned on, the whole battery pack is voltage is connected across the primary winding. Due to the secondary windings being reverse coupled to the primary winding via the transformer core the diodes in each of the secondary circuits are forced into reverse bias and no current flows in the secondary windings. Energy is stored in the transformer core. For the simplest explanation the transformer is assumed to have no leakage. Therefore the voltage across the transformer primary winding is the terminal voltage of the battery pack. Assuming the magnetising inductance of the transformer primary is L_m , the peak primary current \hat{i}_p (assuming discontinuous conduction) is given as,

$$\hat{i}_p = \frac{V_{pack}}{L_m} T_{on} \quad (1)$$

where T_{on} is the on-time for the primary side switch. The energy stored in the transformer in one switching period is:

$$W_{Lm} = \frac{1}{2}L_m(\hat{i}_p)^2 = \frac{1}{2}L_m\left(\frac{V_{total}}{L_m}T_{on}\right)^2 \quad (2)$$

$$= \frac{1}{2}\frac{V_{total}^2}{L_m}T_{on}^2 \quad (3)$$

When the primary side switch is turned off the winding polarisation is reversed, the diodes in the secondary circuits are forward biased and current flows in the secondary windings. The nature of all of the secondary windings being on the same core dictates that the secondary circuit with the lowest cell voltage has the highest current and the secondary with the highest cell voltage has the lowest current. In this way, equalisation energy is abstracted from the whole battery pack and redistributed to the whole pack again with the highest energy flow to the lowest voltage cell. After repeated operations a balanced voltage level condition is achieved across the pack and the primary switching can cease. This multi-winding transformer equalisation shows advantages over other proposed circuits particularly relating to the simple control and self-regulating equalisation. However, the multi-winding transformer becomes a complicated component which is difficult to manufacture when the number of cells is very large. Therefore, a new cascaded multi-winding transformer based equalisation circuit is proposed in this paper where there are a maximum of three coils on a single transformer core.

2.2 Operational Principle for Proposed Converter

Fig.2 presents the proposed new cascaded transformer-based equalisation circuit. For the sake of comparison, a battery pack of nine cells has been selected, The performance of the proposed system will be compared to the traditional flyback transformer based equalisation topology as described in section 2.1. In the example given in Fig.2, cells in the battery pack have been divided into groups of three, and a 1P9S (one primary, 9 secondary winding) transformer has been replaced by four 1P3S transformers. The four transformers are connected in cascaded architecture. The topology may be split in to several cascade levels, in the case of nine cells there are three levels as shown in Fig 2. Transformer (a) couples level one to level two where the primary winding connects to the whole battery pack via the switching device and the secondaries connect to primary windings of transformers (b), (c) and (d) which couple levels two to three. There are therefore nine secondary windings in level 3 each of which have the same arrangement with the reverse polarisation and diode as per the traditional flyback converter. Transformer (a), coupling levels one and two is wound with primary and secondary windings forward coupled, it therefore operates in forward mode. Transformers (b), (c) and (d) are wound inversely and as such perform in a flyback arrangement. The operational principle of this circuit is similar to traditional flyback transformer based equalisation scheme and can be broken down to three stages: the magnetizing period ($T_0 -$

T_1), the demagnetizing period ($T_1 - T_2$) and the non-conduction period ($T_2 - T_3$). The equivalent circuits with the current flow during these stages are shown in Fig. 3, along with idealized waveforms which are shown in Fig. 4.

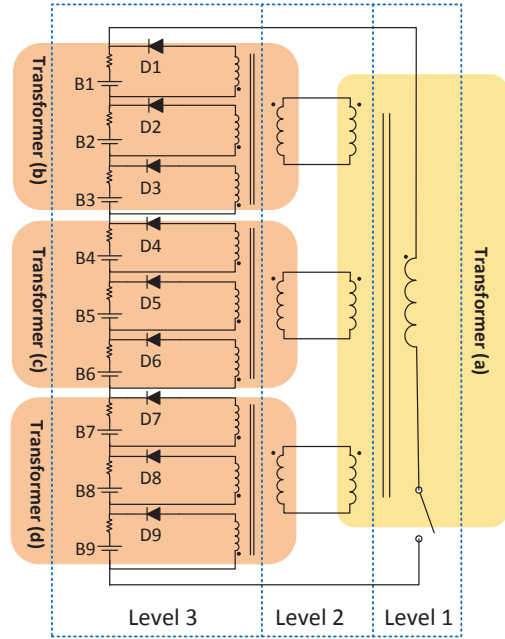


Fig.2. Proposed cascaded transformer-based equalisation converter circuit.

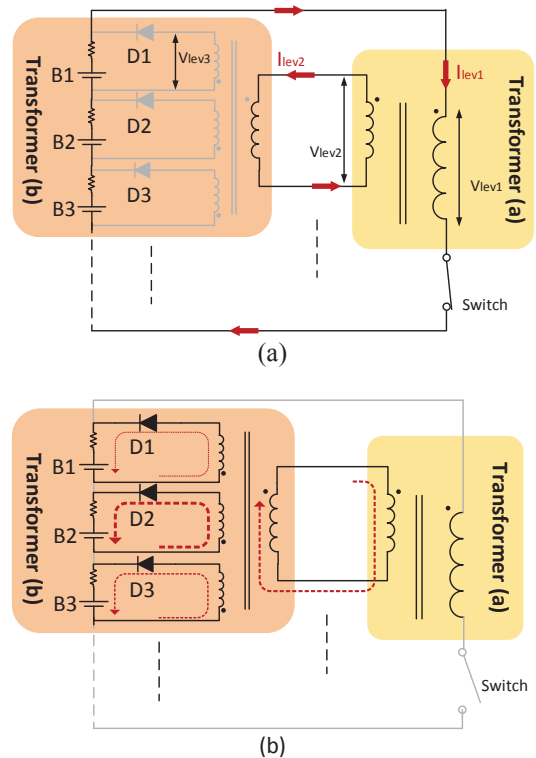


Fig.3 Equivalent circuit with current flow for (a) magnetizing period; (b) demagnetizing period.

Magnetising period ($T_0 - T_1$)

When the PWM pulse is high the switch is turned on. During this period magnetising current flows from battery pack to the primary of transformer (a) in level one. Moreover, there is a current flow in the primaries of transformers (b), (c) and (d) in level two due to the windings being positively coupled between level one and two. Current is rising in the primaries of all four transformers but no current flows in the secondaries in transformers (b), (c) and (d) in level three because these windings are inversely wound and the diode in the secondary circuit is reverse biased. The principle is identical to the operation of the flyback converter however the three stage two-three transformers' primaries are coupled via the secondaries of transformer (a) which is in turn coupled to the primary side in level one. Therefore, all of the four transformer cores are magnetized and stored with energy during this period.

De-magnetising period ($T_1 - T_2$)

The switch is turned off at the beginning of this interval. As soon as the switch is turned off all of the voltages on the various transformers change polarity, the diodes in level 3 become forward biased and the energy stored in all of the transformers is cascaded through the system. At each level the energy flow is self-regulating based upon cell voltages. In this way energy is transferred from level one to the transformer primaries in level two corresponding to the lowest average cell voltage in level three. This mode continues until the flux in each core falls to zero and no current flows in the system.

Non-conducting period ($T_2 - T_3$)

Within this period the switch remains turned off. There is no current flow throughout the circuit. When a non-conducting period exists the circuit is operating in discontinuous conduction mode (DCM) which reduces losses in the transformer.

During one magnetizing period, transformers in two stages are storing energy. For transformer (a) stored energy can be calculated as per equation (1)-(3).

$$W_{Lm1} = \frac{1}{2} \cdot \frac{V_{total}^2}{L_{m1}} \cdot \Delta T_{on}^2 \quad (4)$$

$$N_p : N_s = n : 1 \quad (5)$$

$$\frac{\Delta I_{Lm1}}{3\Delta I_{Lm2}} = \frac{N_s}{N_p} = \frac{1}{n} \quad (6)$$

$$\Delta I_{Lm2} = \frac{n}{3} \Delta I_{Lm1} \quad (7)$$

$$W_{Lm2} = \frac{1}{2} L_{m2} \cdot (\Delta I_{Lm2})^2 = \frac{n^2 V_{total}^2 L_{m2} \Delta T_{on}^2}{18 L_{m1}^2} \quad (8)$$

Therefore, within the MOSFET turns on and off in one time, the energy which has been stored in transformers are:

$$W_{Lm} = W_{Lm1} + 3W_{Lm2} \quad (9)$$

$$= \frac{1}{2} \cdot \frac{V_{total}^2}{L_{m1}} \cdot \Delta T_{on}^2 + \frac{n^2 V_{total}^2 L_{m2} \Delta T_{on}^2}{6 L_{m1}^2}$$

Compare equation (9) to the former on from traditional flyback transformer based equalizer, it is obviously that more energy can be abstracted from battery pack and rearranged to various cells within one switching period. Therefore, for a certain amount of equalisation energy, balanced voltage level will be achieved in a shorter time with utilization of the cascaded transformer-based circuit.

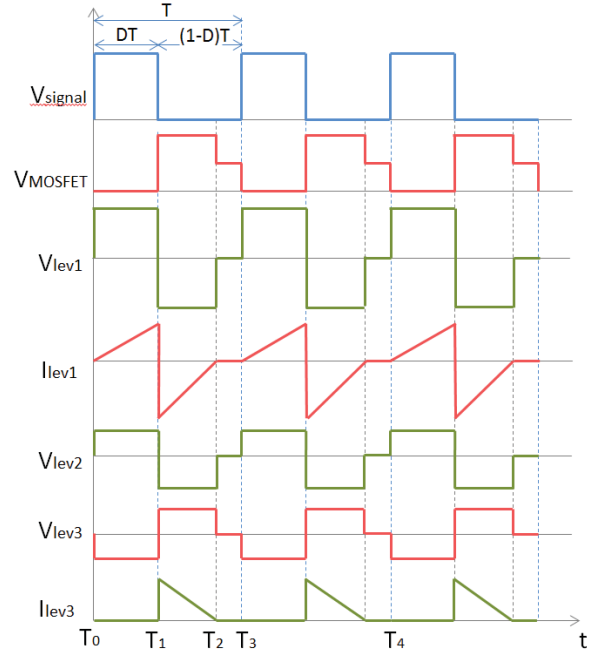


Fig.4. Idealized waveforms of proposed circuit during operation.

3 Simulation Results

A simulation has been carried out to validate the performance of the cascaded transformer based voltage equalisation circuit. As a means of comparison the traditional flyback transformer based equalizer as in Fig. 1 has been simulated using corresponding circuit components. The simulated battery packs for both the simulation circuits have identical initial charge conditions. Each battery pack has nine cells under consideration, which have equal capacity, but their initial voltages are in range of 3.0V-3.7V. Parameters for battery pack had been shown in the Table below:

Table 1 - Parameters for Objective Battery Pack

Cells	B1, B4, B7	B2, B5, B8	B3, B6, B9
Capacitance (F)	1	1	1
Initial Voltage (V)	3.0	3.3	3.7

For speed of equalisation the cells have been replaced with pure capacitances and the capacitance has been set to 1F.

For the flyback transformer based equalisation circuit, voltage across the transformer primary winding is the total voltage of

nine series connected cells, while each secondary windings are connected to one single cell. Hence, the turns-ratio N for the transformer is selected as 9:1. In the other circuit with cascaded transformer, since nine cells are under consideration as well, the voltage ratio between whole pack and single cell stays as 9:1. However, the voltage would step down twice through the two-stage structure. Therefore a turns ratio has been set at 9:3:1 (from level 1:2:3) in the cascaded transformer based circuit. The switches in these two simulations are driven by the same PWM control which is a 10 kHz, 0.4 duty cycle signal. The 40% duty cycle is to ensure the converter operates in discontinuous mode as the control for the purposes of this initial simulation demonstration is open loop.

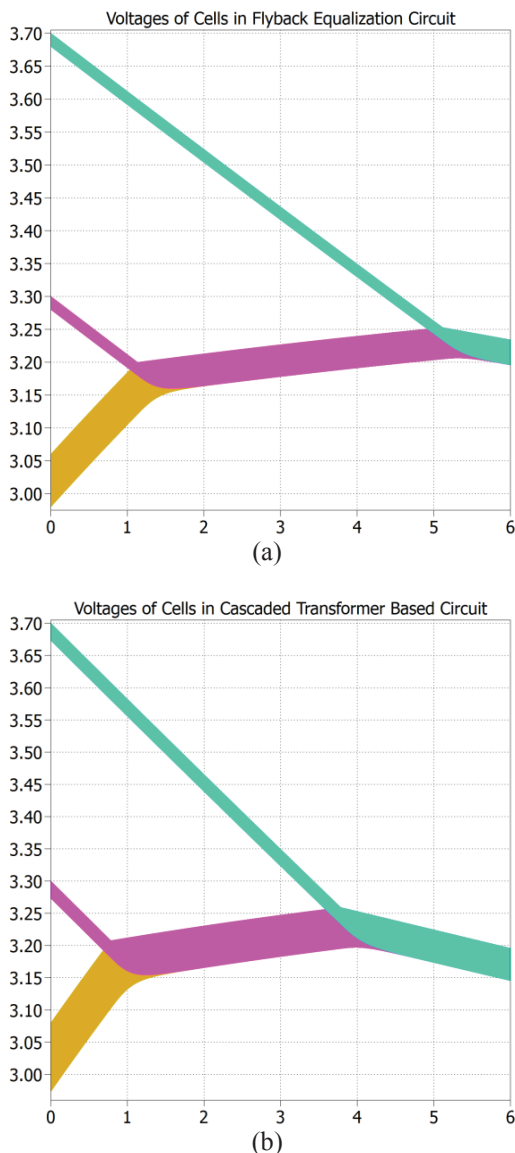


Fig.5 Equalisation performance for (a) traditional flyback based converter, (b) proposed cascaded transformer-based circuit

Fig.5 presents the voltage waveforms for both of the two equalisation circuits considered in this paper. Fig.5(a) presents the equalisation performance of the traditional

flyback transformer based equalisation circuit. Equalisation occurs after 5.7 seconds. Fig 5.(b) presents the equalisation performance of the proposed cascaded equalisation converter. In this case the equalisation time is about 4.3 seconds, which for the case of this simulation is an almost 25% improvement compared to the traditional flyback circuit. This result have proved the theory presented in last section that the new circuit shows better performance in equalization rate.

4 Conclusion

A new cascaded transformer based voltage equalisation circuit has been proposed in this paper. Compared to the conventional flyback transformer based equalisation topology, the new circuit retains the advantages of extremely simple control and high equalisation rate, moreover, the proposed topology significantly reduces the complexity of the wound components limiting the total number of windings per core to four. Furthermore, the proposed circuit has been shown to increase the equalisation speed by utilizing cascaded transformer, which means more energy storage components in circuit.

Nevertheless, the size of the magnetic components of these two topologies has not been investigated as part of this paper. It is uncertain that which transformer structure has smaller size and lower loss, one of 1P9S or four of 1P3S. In some applications this is an important consideration whereas in others the cost and component complexity improvements of the cascaded system may be of greater importance. The authors intend further work on the cascaded topology including further design and simulation iterations as well as realisation in hardware where performance will be measured against the simulated work.

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