BATTERY CELL EQUALIZATION WITH THE FUZZY CONTROLLER IN THE ELECTRIC VEHICLE BATTERY CHARGING STATION

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Abstract— Electric vehicles (EVs) require an onboard battery charger unit and a battery management system (BMS) unit that balances the voltage levels for each battery cell. Thus, the proposed circuit utilises two functions in one and therefore eliminates the need of having two autarkic units reducing complexity and reduction in component count. Battery equalization, aiming at keeping the state of charge of inside cells in the same level, is of great importance to maximize the capacity of the whole battery pack and keep cells away from overcharge and over discharge damage. In this paper, based on the analysis of bi-directional converter, we have proposed a fuzzy controller to adaptively tune the equalizing current. The inputs of fuzzy controller are selected as the difference in state of charge, the average of state of charge and the total internal resistance. The overall performance of the proposed equalizer is evaluated by multi-indexes such as equalizing speed, efficiency and cell protection. The proposed circuit operates as a flyback converter and achieves power factor correction during battery charging. The constant-current constant-voltage (CC–CV) charging method is employed to charge the batteries. However, to limit the number of sensors that will be employed as a result of varying cells during charging. The battery current is estimated using a single current transducer and embedding a converter model in the controller. The operation of the circuit is presented in detail and is supported by simulation results.

Keywords— Electric vehicles (EVs), battery management system (BMS), fuzzy controller, flyback converter, constant-current constant-voltage (CC–CV)

1. INTRODUCTION

Along with the development and popularity of various portable devices, batteries as a kind of movable power sources are employed frequently in many applications and even become to one of the most important components which affect the performances of productions. Due to the electrochemical characters of battery materials, the voltage of a single cell is limited to less than so that a battery has to incorporate numbers of series-connected cells to provide necessary higher voltage. This issue is intensified more seriously in the application of electric vehicles (EVs) which usually ask for a working voltage of tens or even hundreds of volts and hence a battery consisting of around 100 series-connected cells. However, the existing technologies in battery design and production cannot keep the consistence of cell parameters such as internal resistance, charge and discharge efficiencies, the speeds of aging and degradation, and so forth. The differences will result in the imbalance of cells in the same battery package and force cells to have different state of charge (SoC), state of health (SoH) and terminal voltages. Therefore, the monitoring and control at the battery level are insufficient to manage a battery, especially vehicular battery. To reduce the complexity, the concept of multi-functional power electronics systems can be applied where only one consolidated circuit is used to conduct battery charging and battery charge equalisation. This concept involves modifying the battery charger to achieve dual functions of charging and battery management. Therefore, eliminating a separate onboard charger unit or the BMS. Several proposals have been published in the literature to include additional functionality in BMS [22, 23]. In [22], a bi-directional battery charger is proposed with a modular integrated equalisation circuit in which the battery cells are connected to the grid via a full-bridge rectifier, a DC/DC converter and a group of switches. The main drawback is that the circuit selects a cell with the lower voltage level and charges it and then terminates the charging process once the maximum voltage threshold is reached. Thus, rather than charging all cells in series simultaneously, each cell is charged individually via the converter. However, once the vehicle is unplugged, no voltage equalization across the cells can take place due to the chosen circuit topology. Another study proposes a battery charger that includes a voltage source and a non-dissipative shunt that can be customized to charge any number of batteries [24]. This non-dissipative shunt circuit consists of a pair of transistors and an inductor that is configured as a buck-boost converter to connect with each pair of batteries. In such a configuration, the circuit can be used to charge the battery as a regular EV charger when it is connected to the grid; meanwhile, it is capable of balancing cell voltages through the shunted buck-boost converters when the circuit is unplugged. However, the circuit used for voltage balancing and the circuit used for battery charging does not share any components, and as such, act as two independent circuits having different functions. Therefore, this is not truly a multi-functional power electronics system. When the vehicle is operational, that is not connected to the grid; the circuit is controlled to run as a conventional voltage equaliser. The design of such a circuit therefore provides AC/DC conversion, galvanic isolation between the grid and the battery, and charge equalisation.

The main contributions of this paper are as follows:

(1) Development of single stage charger/charge equalisation circuit using only two winding transformer.

(2) Allowing n number of cells to be added by simply modifying the cell selector.

(3) Introducing a control structure to improve the overall system performance, flexibility and provide desirable charger/charge equalisation interaction.

In addition, the control strategy for charge equalization is incorporated in the charger control algorithm. Compared with the intensive designs on equalizing circuit, the control of equalizing current is still lack of comprehensive study. The equalizing current determines the duration of equalization and usually is designed to be large when the difference in terminal voltage between the selected or neighbored pair of cells is large and to be small when the difference is mall. It also takes into consideration the terminal voltage, the higher which is, the smaller the current Is. Based on the general concepts, a fuzzy control system is proposed in [12] to real-time tune the equalizing current. However, the state causing the difference in terminal voltage and really to be equalized is the SoC. Although the open circuit voltage (OCV) can indirectly represent SoC, the small difference in OCV may be caused by a large difference in SoC due to the nonlinear and flat voltage SoC relationship. Therefore, recently [13] has proposed an equalization control method directly based on SoC estimation, where, nevertheless, SoC is only utilized as thresholds to turn on and turn off the equalization process rather than tune the equalizing current.

2. PROPOSED CIRCUIT TOPOLOGY, OPERATION AND SIMULATIONS.

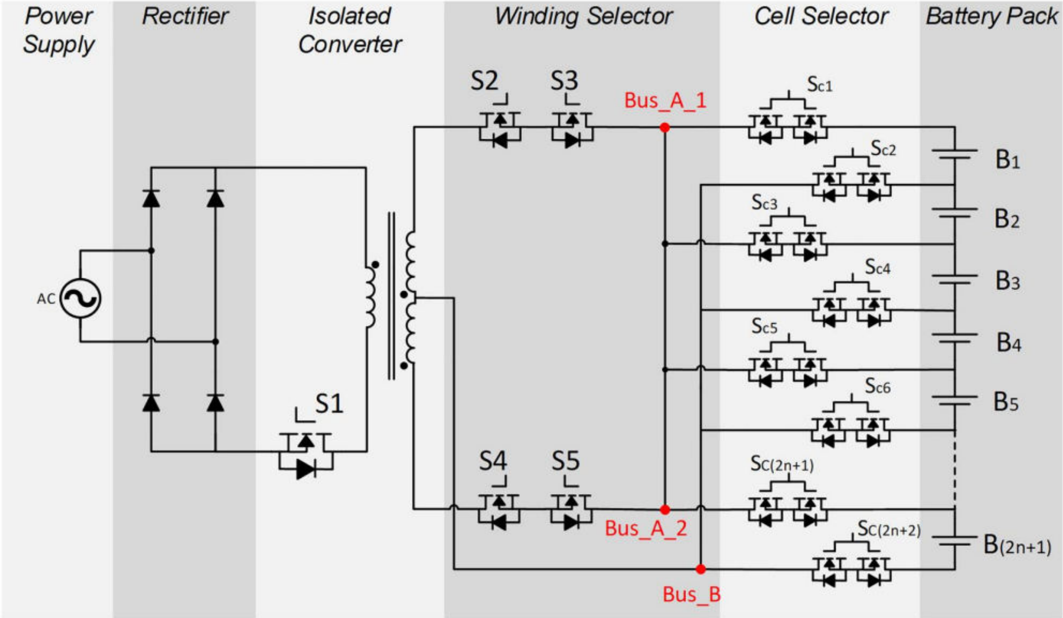


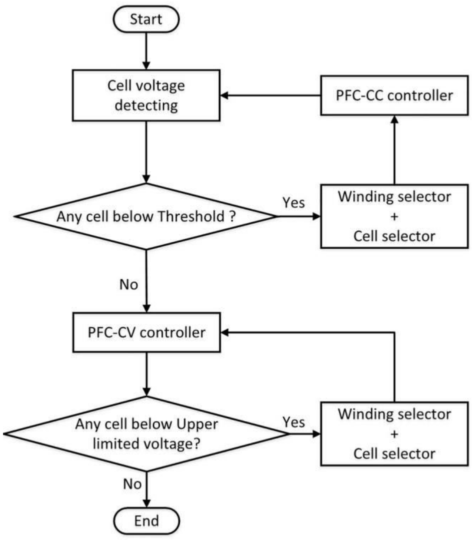
Fig1. Proposed multi-functional battery charger integrated with voltage equalization in (2n+1) battery cells

The proposed battery charger integrated with an equalisation circuit is presented in Figure 1. The circuit can be sub-divided into four parts: the rectifier, the isolated converter, the winding selector and the cell selector. For Level 1 unidirectional EV chargers, it is common to add a single-phase full-wave diode bridge rectifier to the grid-side in order to convert AC input into DC [17]. The rectifier is followed directly by an isolated converter, which consists of a three-winding transformer and a transistor that is connected in series to the primary winding. The primary winding and the two secondary windings are reverse-coupled on one magnetic core. Therefore, when power flows from the source to the batteries, irrespective of which secondary winding is involved during the de-magnetizing period, the circuit always works as a flyback converter. Meanwhile, two windings in the secondary side are connected end-to-end. When the energy is transferred between two secondary windings during voltage equalisation, the transformer operates in flyback mode as well. The winding selector comprises two pairs of bi-directional switches that are connected to the top and bottom terminals of the two secondary coils. A bi- directional switch is made up of two anti-series (back-to-back) connected transistors with their body diodes facing opposite directions, and the pair of back-to-back transistors are controlled independently. This arrangement of the winding selector makes it possible that current can go through either of the windings and is under control in both directions.

3. PFC & CC-CV CONTROLLER FOR THE PROPOSED CIRCUIT

To comply with the IEEE and the Society of Automotive Engineers (SAE) standards, it is a common practice to include a power factor correction (PFC) circuit for onboard battery chargers when they are connected to the power grid [25–28]. As the proposed circuit operates as a flyback converter during battery charging, one significant advantage of the proposed topology is the capability of achieving PFC without using additional inductors, diodes or switches. The diagram of the proposed circuit with the PFC-constant current (CC) and constant voltage (CV) controller. The controller consists of four functional blocks: the outer voltage loop, the outer current loop, the inner current loop, and the PWM modulator. PFC-CC control mode for the proposed circuit. In CC mode, the charging current could be measured from the secondary side; however, since the topology allows varied numbers of cells to be charged, placing the current transducer on the secondary side may not be optimal. Instead, by using the primary side current transducer combined with the knowledge of the transformer turns ratio, as well as the number of cells being charged, the secondary current can be estimated through embedding a converter model in the controller. In this way, only one primary current sensor is required for the entire system control. The outer control loop regulating the current level and the inner loop regulating the current envelope means the controller keeps the circuit at the CC output with a high input power factor.

The cells voltages are first measured to determine the controller whether to run in the PFC-CC or PFC-CV mode. If the voltage of any cell is under the threshold voltage, the PFC-CC controller is activated, charging the batteries at the desired C-rate.

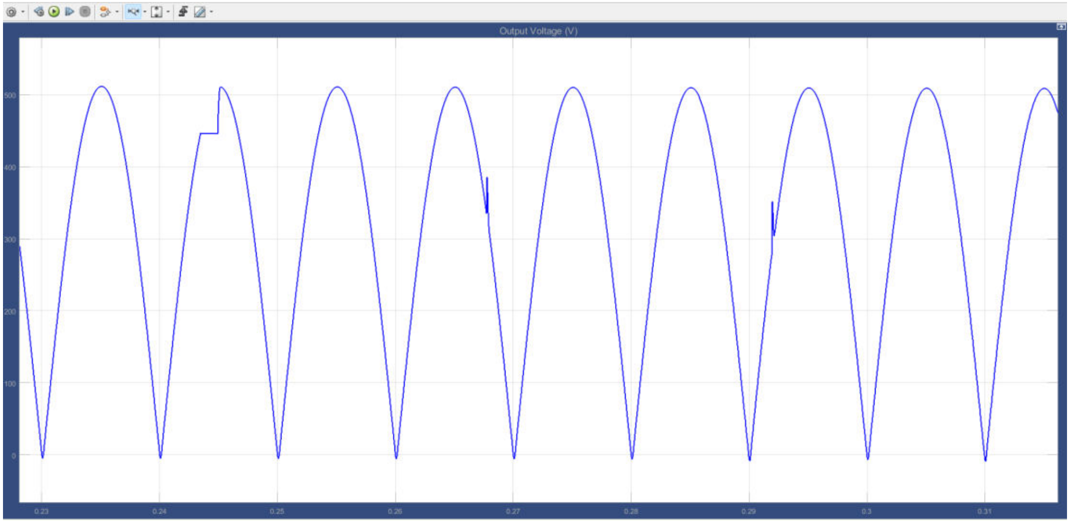


The winding selector and cells selector will work together to bypass cells that reach the threshold voltage. Once all the cells reach the threshold voltage, the controller is switched to the PFC-CV control mode to charge the cells with a decreased charging current. When individual cells reach the upper voltage limit, the winding selector and cells selector will work together to bypass the fully charged cells and make the converter to charge the rest of the cells. Thus, in time, all the cells can be charged to the same upper voltage limit. There is necessarily a hysteresis around the CC-CV decision point to avoid the controller losing stability at the threshold.

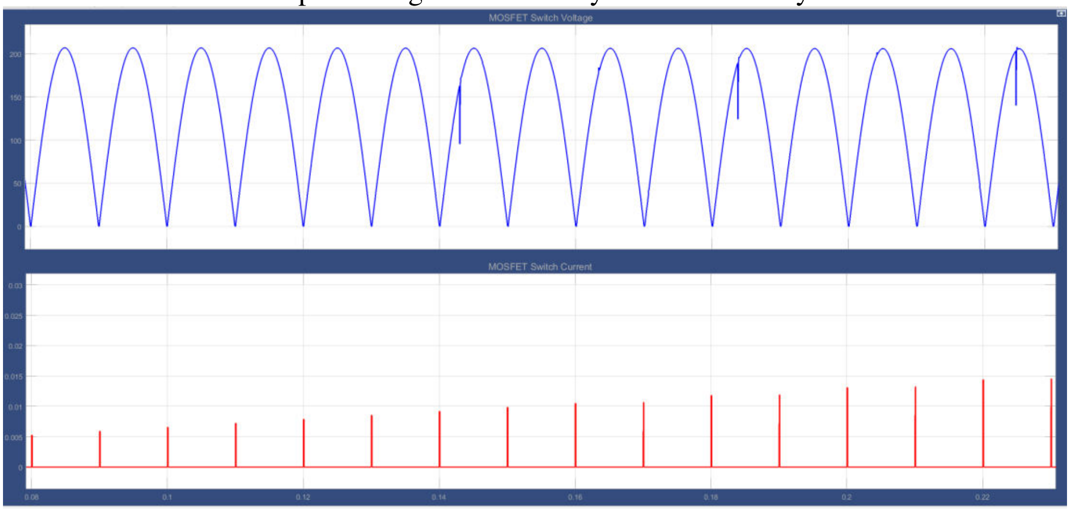
4. FUZZY CONTROL

Based on the equalizing circuit with parameters given above, equalizing process can be driven by the control frequency to MOSFET. Besides the speed of equalizing process, the performance of an equalizer is also evaluated by the equalizing efficiency and the protection of cells. Therefore, a fixed control frequency is insufficient to achieve a satisfactory overall performance. Given the states of cells, how to tune the control frequency, equally to tune the equalizing current, becomes to the key issue in equalizing system design. Implementation of Fuzzy Controller Based on the inputs proposed above, a controller should map the input vector to a control frequency, i.e. establish a function F. However, due to the lack of quantitative analysis and modeling of the relationship among these variables, it is hard to design a controller based on traditional methods. On the contrast, the inputs can easily be qualitatively classified into some levels and expressed as linguistical variables in the last subsection such as large, small and so on. Therefore, it gives strong reasons to apply fuzzy control to determine the equalizing current. A general fuzzy controller consists of the membership functions of inputs and outputs, rules database, and inference methods [18]. The inference methods are the same as the default settings of in fuzzy logic toolbox given by Matlab

5. SIMULATION RESULTS



Experimental results when charging seven cells
Output Voltage of the Battery Cells with Fuzzy



MOSFET Voltages and the Currents Fuzzy

CONCLUSION

Based on the analysis of the equalizing circuit implemented by Cukˆ converter, we have established a fuzzy controller to adaptively tune the MOSEFT control frequency and equally tune the equalizing current. The battery charging system of EVs typically requires two independent units to achieve a grid-connected charging process and voltage equalisation of battery cells with increased cost, weight and volume. This paper presents a circuit topology that can be used as both a grid charger and a cell voltage equaliser in a single circuit. Membership functions and rules database are established based on experience and knowledge of experts and the characters and abilities of cells. Simulations under various initial conditions are conducted to demonstrate availability and efficacy of the proposed equalizer. Meanwhile, the equalizing strategy among multi cells is also to be further studied. In addition, the proposed equalizer will be put into practice to test its robustness in the real conditions such as inaccurate SoC estimation and internal resistance estimation. When the vehicle is static and connected to the grid, the proposed power circuit operates as an onboard charger with functional blocks including AC/DC conversion, PFC and isolated DC/DC conversion. When the vehicle is not connected to the grid, and unbalanced voltage is detected within the battery pack, the proposed circuit operates as a standalone equaliser. The operational principle of the proposed circuit is discussed.

Selected experimental results are shown to validate the effectiveness of the proposed circuit.

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