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A Modular Cell Balancer Based on Multiwinding Transformer and Single Inductor Circuit for a Series-Connected Battery String

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Abstract. In this research, a cell balancing topology for a series-connected Lithium-Ion battery circuit is proposed and simulated verified. In particular, the equalization topology based on this modular balancer consists of an intra-module balancer based on a multi-winding transformer (MWT) circuit and an outer module balancer based on a single inductor. This topology offers a solution to overcome the limited number of cells that can be balanced by multi-winding transformers by developing a modularization system. The speed of balancing between cells and between modules is increased by the presence of a single inductor as a balancing circuit between modules. The simplicity of the control system and the reduction in the number of components are the advantages of the proposed topology. The results showed that the zero voltage gap was reached in 5 seconds with the final voltage of each cell being 3.33 (±0.05) V

Keywords: *cell balancer; modular; multiwinding transformer; single inductor.*

1 Introduction

Unbalanced battery cell voltages can reduce storage capacity and may cause an explosion or fire. This is a major obstacle to the safe and optimal operation of battery-powered equipment such as electric vehicles. Efforts are being made to overcome the voltage imbalance between battery cells by developing a battery cell balancing circuit [1]. Evaluation of the proposed battery cell voltage balancing methods based on cost, efficiency, control complexity, energy flow, size, voltage stress and current stress on the switch. The evaluation results show that the battery cell balancing system based on multiwinding transformers has several advantages over other methods. The disadvantage of this method is that it is difficult to make a transformer with many turns so that the number of cells that can be balanced is limited. This study also noted that the number of unit series that could be applied was only 12 cells [2]

Multiwinding transformer (MWT) based modular balancing circuit has provided a solution to the limited number of cells that can be balanced. In reference [3] first proposed a modularization technique, but with the existence of a modularization technique on a MWT-based balancing circuit, a balancing strategy between modules is needed. The balancing circuit proposed in literature [3] uses a balancing strategy between modules using the concept of magnetization energy, this circuit does not require a module-level equalizer, because the flow of energy can occur automatically, but the current flowing in the secondary winding from one module to another others become difficult to control and tend to be small. Literature [2] improved the control system in the circuit proposed in reference [3] by proposing a PWM+ and PWM- control system to improve balancing performance.

The balancing method between modules using a switch capacitor was proposed in literature [4]. The results of a study on the balancing performance conducted by show that the switch capacitor-based balancing circuit has a weakness in terms of charge transfer speed. The switch capacitor based balancing method also has another problem, that is the high voltage stress on the switch [5]. Literature [6] proposed a method of balancing between modules by adding an additional winding that is serialized with a switch, additional turns and switches are required in each module, if you want to add modules you must add the number of turns and switch. This causes the use of the number of equalizer components needed to balance the voltage between modules to increase and of course has an impact on the cost and complexity of the circuit.

The results of the study on the comparison of the balancing performance of the various proposed methods show that the single inductor-based balancing method has advantages in terms of performance, namely the balancing rate that is more optimal than the switch capacitor and converter based method [5]. Based on the literature review, this research will use a single inductor based balancing method to balance the voltage between modules in a single inductor based circuit. The use of a single inductor in the MWT-based battery cell voltage balancing circuit to balance the voltage between modules will make the charge transfer rate increase, so the contribution of this research is to optimize the performance of the MWT-based modular battery cell voltage balancing..

2 Proposed Balancer

2.1 Configuration of Proposed Balancer

The topology of the balancing circuit based on MWT and a single inductor (MWTSI) is shown in Figure IV.1. There are M modules in the circuit, each module has n_i $(i = 1,2,3 \dots \dots k)$ serial cells. This topology has a cell-level balancing circuit and a module-level balancing circuit. The equalization of voltage within the module is carried out by a balancing circuit based on MWT while the equalization of voltage between modules is the work carried out by a balancing circuit based on a single inductor.

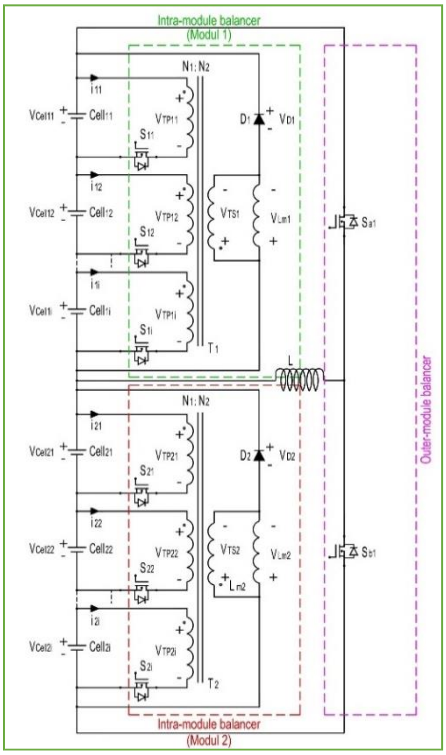


Figure 1 Proposed Balancing Circuit Topology

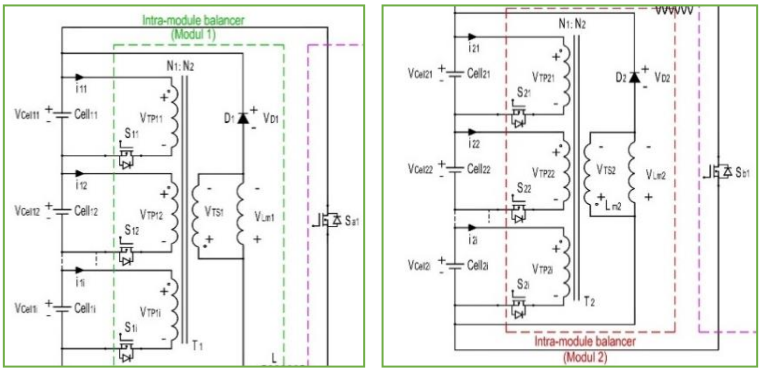
Fig.1 shows the proposed balancing system configuration. Each battery cell is connected to a switch and the primary side of the multi-winding transformer. The transformer is modeled as a single magnetizing inductance L_m on the secondary side and a leakage inductance L_e on the primary side with a turn ratio of $n_1{:}\, n_2 = 1{:}\, 1$.An inductor with an inductance L is used to balance the voltages between the modules. To simplify the analysis, according to **Fig.1** there are only 2 battery modules and in the module there are only 3 lithium ion battery cells. Although for large-scale applications it can be done by adding the number of cells and the number of modules. In practice, the number of serial units between modules is usually the same.

2.2 Operation Mode Analysis for MWTSI

An analysis of the operating mode is needed to know how the balancing balancing process occurs in the circuit, to simplify the analysis, the following assumptions are made:

1) Each module consists of 3 lithium ion battery cells.
2) Identical duty cycle D_{M1} applied to S_{11}, S_{12}, S_{13} and identical duty cycle D_{M2} applied to S_{21}, S_{22}, S_{23}
3) The relationship between the battery cell voltages $V_{B1}, V_{B2}, V_{B3}, V_{B4}, V_{B5}, V_{B6}$ is $V_{B1} > V_{B2} > V_{B3} > V_{B4} > V_{B5} > V_{B6}$
4) Battery module 1 voltage ($V_{M1} = V_{B1} + V_{B2} + V_{B3}$) is higher than battery module 2 voltage ($V_{M2} = V_{B4} + V_{B5} + V_{B6}$)

The division of module 1 and module 2 in the circuit is shown in **Fig.2**



(a) (b)

Figure 2 (a) Module 1 (b) Module 2

2.2.1 Operation mode analysis for intra-module

Mode ($t_0 - t_1$)at the time $t = t_0$, the six MOSFET switches are turned on simultaneously, the charge from the high-voltage battery cell will be transferred directly to the low-voltage battery cell. The primary transformer voltage V_{TP} is

$$V_{TPN} = V_{BN} - L_{eN}\frac{di_N}{dt} - R_{eN}i_N \tag{1}$$

Where, $N = 1,2,3,4,5,6$

The current and voltage across L_m can be determined by the Eq. (2&3)

$$iL_{m1}(t) = \frac{V_{TS1}}{L_{m1}}(t - t_0) \tag{2}$$

$$L_{m2}(t) = \frac{V_{TS2}}{L_{m1}}(t - t_0) \tag{3}$$

The relationship between magnetizing current and balancing current in each module can be expressed in Eq. (4)

$$i_{Lm1} = i_{11} + i_{12} + i_{13} \tag{4}$$

The voltage across L_m can be written in the Eq. (5)

$$V_{Lm} = L_m \frac{di_{Lm}}{dt} \tag{5}$$

Mode 2 $(t_1 - t_2)$ When S_{11}, S_{12}, S_{13} are turned off at the same time, since i_{Lm} flows continuously, the diode starts to do its work to prevent magnetic saturation in the transformer. Then V_{Lm} becomes negative and i_{Lm1} will flow into the inductor as shown in Eq. (6) and Eq. (7)

$$V_{Lm} = -(V_{B1} + V_{B2} + V_{B3}) \tag{6}$$

$$i_{Lm1} = i_{Lm1} - \frac{V_{M1}}{L}(t - t_1) \tag{7}$$

Mode 3 $(t_2 - t_3)$ When i_{Lm} becomes zero, mode 3 starts, from $(t_2 - t_3)$ no current flows in the circuit. At t_3, the operating mode switches back to mode 1.

2.2.2 Operation mode analysis for outer module

Single inductor is used in the balancing scheme of modules operating in Discontinuous Conduction Mode (DCM) to reduce the possibility of inductor saturation and to reduce voltage stress on power switches. The process of balancing techniques between modules in the inductor circuit can have two stages in the charge transfer process, namely, first the charge will be transferred to the inductor, the inductor here serves to temporarily store the charge that will be transferred later to module 2 by activating and S_{a1} and S_{a2}.

2.3 Control method

In this study, the topological control method for equalization between cells and between modules is simple and easy. All switches in the inter-balancing circuit use a switch signal with the same duty cycle value and switching frequency, as well as the outer-module balancing circuit which is controlled with a fixed value of the switching frequency and duty cycle. The voltage sensor will detect the voltage of each battery cell. If the voltage difference between cells or between modules exceeds a predetermined interval, all switches will work at the same time. In this study, open-loop control is adopted, the value of the switching frequency and duty cycle of the PWM signal is set. After a certain period of time the difference in voltage values decreases or approaches zero voltage gap (ZVG), all switches will working and the voltage equalization state has been reached. The balancing algorithm applied is voltage-based balancing. The balancing algorithm used is shown in **Fig.3**

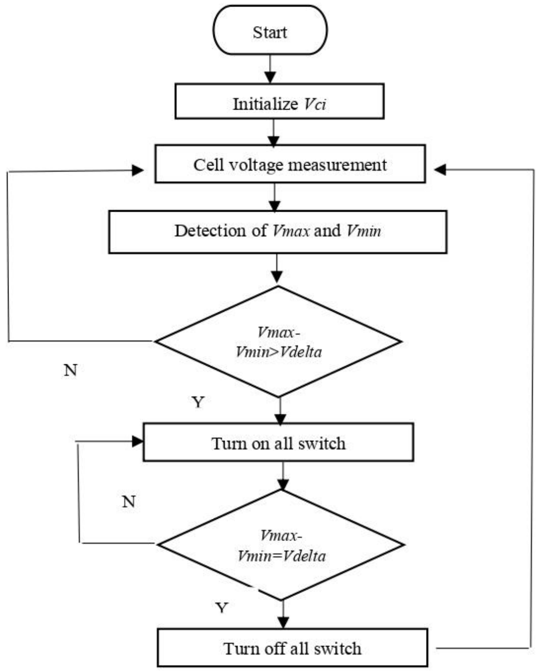


Figure 3 Flowchart of the proposed control method

3 Simulation

The simulation model of the MWTSI is established in MATLAB/Simulink software, as shown in **Fig. 4.** C_1, C_2, C_3, C_4, C_5, and C_6 are battery cells. The PWM signals are generated by the pulse generator. The main parameter of the simulation model are shown in Table 1.

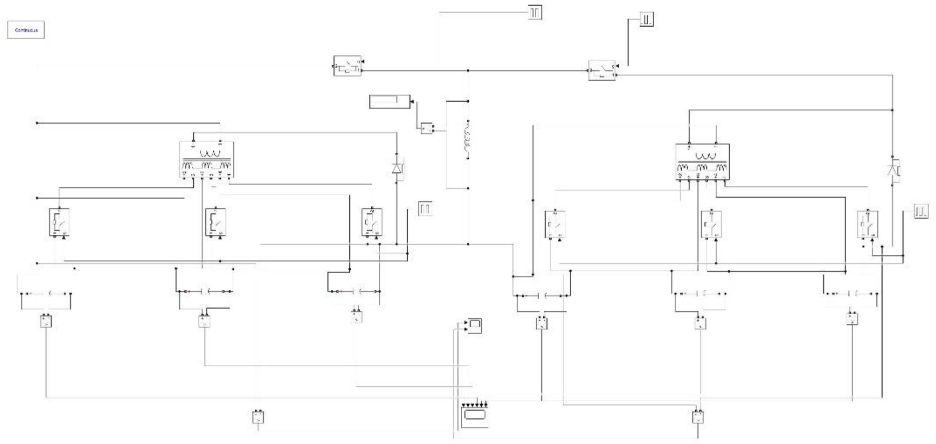


Figure 4 MWTSI Simulation Model

Table 1 Main parameters of simulation model.

Simulation parameters	Value
Transformer excitation inductance (mH)	1
Transformer ratio	1:1:1:1
Transformer winding resistance (mΩ)	1
Capacitance value (µF)	700
Initial voltage (Volt)	*C1*=3.7, *C2*=3.6, *C3*=3.5, *C4*=3.2, *C5*=3.1,*C6*=2.9
PWM frequency (kHz)	10
PWM duty cycle (intra module)	50%
PWM duty cycle (outer module)	S_{a1} = 65% S_{a2} = 45%
Inductance of inductor (mH)	0.01

4 Result and Discussion

The simulation result are shown in **Fig 5** and **Fig 6. Fig 5** show the cells voltage balancing curves. The predicted value of final voltage in individual cell is $V_f =$

$3.7+3.6+3.5+3.2+3.1+2.9=3.33\ Volt$. After 5s the voltage value $V_{B1}, V_{B2}, V_{B3}, V_{B4}, V_{B5}, V_{B6}$ of all cells in series voltage equalization basically reach the near 3.33 V (±0.05 Volt) from initial value in Table 1. From the simulation result, it can be seen that the equalization topology among cells can achieve voltage balancing. The cell voltage is higher and lower than that of high and low voltage cells at the beginning of cell discharging and charging, respectively. This condition enables the achievement of zero voltage gap (ZVG).

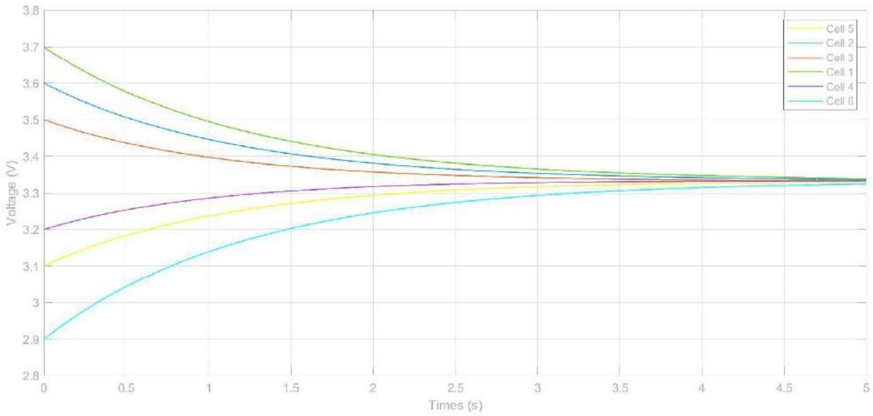


Figure 6 Voltage equalization curves for 6 cells

The equalization process consist of equalization state and reset state. During the equalization state, the PWM signals is high (50%) for intra modules and (65% and 45%) for each mosfet in outer module. The charging and discharging current of the cells varies exponentially during the balancing process, and the become zero in reset state. In reset state, the PWM signals become low and switch is off.

Fig. 6 shows the voltage equalization curve for the two modules. the initial voltage of each module is $V_{M1}=3.7+3.6+3.5=10.8$ V and $V_{M2}=3.2+3.1+2.9=9.2$ V. The predicted value of final voltage of module is 10 Volt. The simulation results show that the equilibrium condition
between the modules is reached in 5s with the final voltage of each module is 10 (±0.01) V.

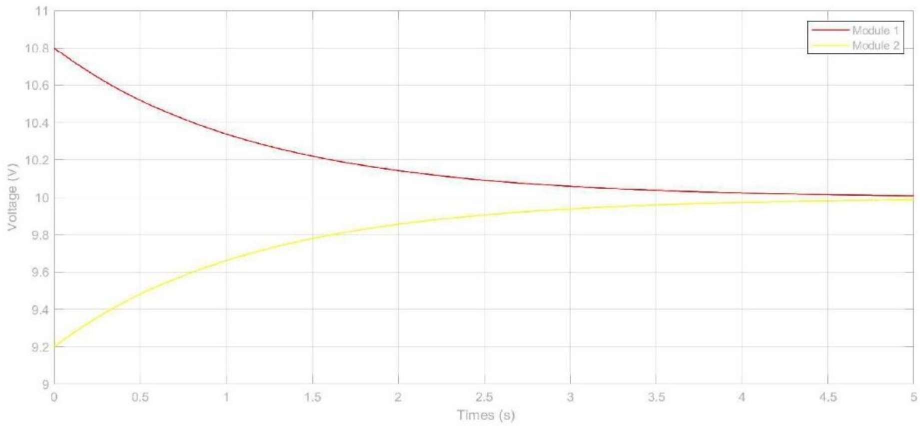


Figure 6 Voltage equalization curves for 2 modules

These results indicate that voltage balancing between cells and between modules can occur quickly. although this study has not carried out battery modeling based on empirical data, referring to previous research, battery modeling to offer a new topology can be replaced with an RLC circuit and using capacitors to facilitate the analysis process. Simulation-based validation shows that the proposed balancing circuit can increase the rate of voltage equalization between modules and between cells.

The control system using a fixed duty cycle and constant switching frequency makes this topology easier to implement. From the above analyses, it can be concluded that as long as the multi-winding transformers have the same turns ratio and the same duty cycle, i.e., D = 50%, the proposed equalizer can achieve an ideal balancing effect for a battery string.

When viewed from the complexity of the circuit and the number of components used in this circuit, it can be seen that the number of switches used to balance 2 modules is only 2 switches, when compared to the previously proposed balancing circuit which even requires 4 switches to balance 2 modules [4], or need 1 switch for each module [6]. this topology is successful in optimizing the use of the number of switches in a modular cell balancer based on MWT.

5 Conclussion

A modular cell balancer based on MWT was developed to overcome the limited number of cells that can be balanced by a multi-winding transformer, voltage balancing between modules is the main problem addressed in this study. The proposed balancing circuit can improve the balancing performance between modules and between cells without causing a significant increase in the number of components and can simplify the control system in the balancing circuit. the next work we will do is verify the circuit experimentally by building a prototype balancer

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