JASAE
Journal of Applied Science and Advanced Engineering
Vol. 3 No. 2 (2025) ; p. 55 – 63

e-ISSN: 2985-7252
https://jasae.org/

Performance Optimization of Battery Balancing System Based on Multiwinding Transformer and Single Inductor with Fuzzy Logic Control Method

Yusiran Yusiran[1]*, Edi Leksono[2], Irsyad Nashirul Haq[2], and Andini Jinggan Ayumurti[2]
[1] Politeknik Negeri Batam, Indonesia
[2] Insitut Teknologi Bandung, Indonesia
*email: yusiran@polibatam.ac.id

ARTICLE HISTORY
Received: 14 April 2025
Revised: 13 July 2025
Accepted: 1 August 2025

KEYWORDS
Modularized balancing
Fuzzy logic control
Cell Balancing
Inductive Balancing
Balancing Speed

ABSTRACT– In this study, a modular battery balancing topology based on a single inductor and multi-winding transformer is proposed. In particular, the voltage equalization topology based on this modular balancer consists of cell-level equalization based on a multi-winding transformer and module-level equalization based on a single inductor. A control algorithm based on fuzzy logic (FLC) is applied to the module-level balancer with the difference between the module voltage and the module average voltage being used as the input variable and the duty cycle as the output variable. Meanwhile, the cell-level equalization utilizes a fixed duty cycle (FDC) control mechanism. The balancing process between cell and module level is done alternately so that this control method can be used on non-uniform transformers. The balancing model and FLC design were created in Matlab/Simulink 2021a and experiments using 4 cells LG HG2 18560 3000 mAh battery were carried out to verify the performance of the balancing system. The experimental results show that the FLC method can save the balancing time between modules by 31.26% compared to the FDC method. Furthermore, the proposed control system is proven to optimize the energy transfer which can reach zero voltage gap (ZVG) below 5 mV with a relatively high efficiency around 86.95%..

© Yusiran et.al.

This is an Open Access article distributed under the terms of the Creative Commons CC-BY-4.0 License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Introduction

Lithium-ion batteries are among the most widely used energy storage technologies today, particularly in applications such as electric vehicles, portable electronics, and energy storage systems. This technology offers several key advantages, including high energy density, high efficiency, long lifecycle, and a relatively smaller environmental footprint compared to other battery chemistries [1]. A single lithium-ion cell typically has a nominal voltage of 3.7 V, and to meet the required operating voltage and capacity for specific applications, multiple cells are connected in series and parallel configurations [2].

However, during the battery assembly and manufacturing process, slight inconsistencies between cells are inevitable. These variations can lead to non-uniform performance characteristics such as internal resistance, capacity, aging rates, and thermal behavior, which may cause degradation, overcharging, or over-discharging of individual cells within the battery pack [3].

To address these challenges, Battery Management Systems (BMS) play a critical role in monitoring and controlling battery operations. Among their many functions, BMS are responsible for thermal regulation, failure management, and charge balancing to maintain uniformity and extend battery life [4][5]. Cell balancing, in particular, is essential for preserving the overall health and performance of battery packs.

This research is motivated by the need to improve the speed, efficiency, and simplicity of active balancing systems, especially in modular battery configurations. Most existing balancing approaches either suffer from high energy losses or require complex and costly hardware. Therefore, this study proposes a modular active balancing system that utilizes a forward multi-winding transformer (MWT) combined with a single inductor to enhance balancing speed while minimizing circuit complexity. Additionally, a fuzzy logic control (FLC) strategy is implemented to improve adaptability and control efficiency without relying on precise mathematical models, which are often difficult to establish due to variations in battery behavior over time

Battery balancing techniques are generally divided into passive and active methods. Passive balancing dissipates excess energy from higher-voltage cells through resistors. While this method is simple and cost-effective, it is inefficient due to high energy losses and thermal dissipation, which require advanced thermal management systems [6][7][11][12]. Active balancing, on the other hand, transfers

energy between cells using non-dissipative components such as capacitors, inductors, or converters. This approach offers better energy efficiency and thermal performance, making it more suitable for high-performance battery applications [13][14].

Among active balancing methods, inductor-based and transformer-based approaches are widely explored due to their high balancing speed [24][25]. Multi-winding transformers (MWTs) are particularly promising for their ability to perform simultaneous energy transfers across multiple cells. However, these systems are often complex to manufacture, especially when a high number of windings and uniform inductance values are required [19]. To address these challenges, researchers have introduced modularization techniques that divide large transformer systems into smaller, more manageable modules.

Lim et al. [20] proposed a modular balancing strategy using magnetizing energy and pulse width modulation (PWM) to transfer energy between adjacent modules. Similarly, Shang et al. [18] implemented cross-connected secondary windings controlled by counter-PWM signals. Although innovative, these methods suffer from limited balancing speeds and difficulty in controlling current flow.

Other studies have attempted to improve modular balancing performance by adding switched capacitors, as demonstrated by Bui et al. [21]. However, these designs are constrained by limited balancing speed and high switching voltage stress. Fan et al. [22] and Duan et al. [23] introduced the use of boost converters, capacitor filters, and additional switching elements to improve energy transfer efficiency and balancing speed. While these methods have shown improvements, they require a large number of additional components, increasing system complexity and cost.

To address the challenges in controlling modular balancing systems, fuzzy logic control (FLC) has been introduced as an alternative to fixed duty cycle PWM control. FLC offers flexibility and robustness in handling nonlinear and time-varying system dynamics without requiring detailed mathematical models [27]. Studies have shown that FLC can effectively manage current flow and prevent over-equalization or cell damage during the balancing process [28][29]. Liao et al. [30] demonstrated that FLC applied to a buck-boost modular balancing system outperformed traditional control methods in terms of balancing speed and energy efficiency.

Based on these findings, this research proposes a hybrid modular balancing system that combines the simplicity of a single inductor with the high performance of a forward MWT topology, controlled by a fuzzy logic algorithm to optimize balancing speed, efficiency, and reliability.

Methodology

A. Proposed Balancing Circuits

The proposed balancing circuit, illustrated in Figure 1, integrates two balancing topologies to independently manage cell-level and module-level energy equalization. The system consists of *n* lithium-ion cells connected in series and grouped into *m* modules. As shown in Figure 1, each module incorporates a forward multi-winding transformer (MWT) for cell-level balancing, along with a freewheeling diode (D_m). Each cell is linked to the MWT's primary winding (V_{TP}) through a unidirectional MOSFET switch, enabling high-frequency switching. The secondary windings (VTS) of the MWT are paired with freewheeling diodes (D_1 and D_2) to rectify the balancing current. To facilitate direct energy transfer from higher-voltage to lower-voltage cells, the primary and secondary windings are arranged with opposite polarities, consistent with the conventional forward converter configuration.

Additionally, a single inductor (L) is placed between each module and connected with a single switch (S_{a1} and S_{b1}) in each branch to execute high frequency PWM across modules. In this paper, a limited number of batteries and modules are being set in total of 4 batteries and 2 modules to simplify the system analysis. By adding more secondary windings and modules, ideally, this balancing circuit would be functional for larger battery strings.

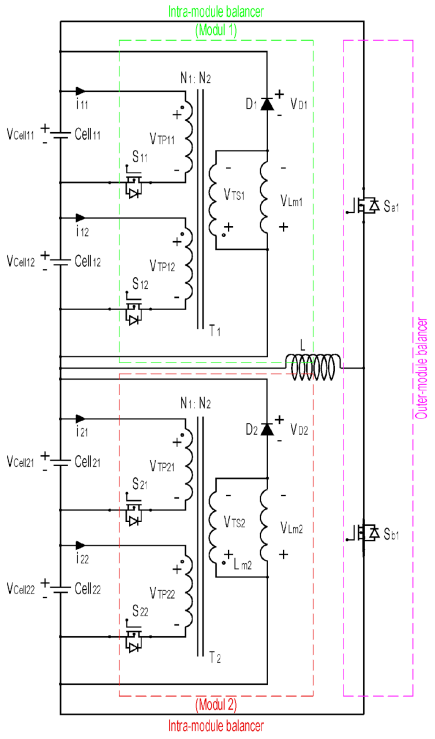
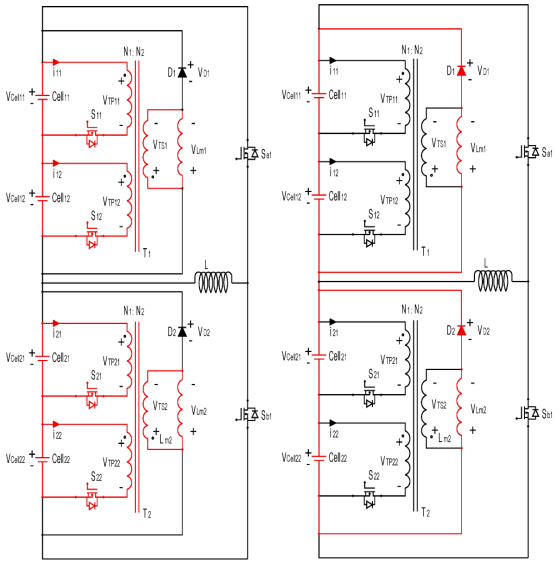


Figure 1. Multi-winding transformer and single inductor balancing circuit

A.1 Operation mode analysis in cell-level balancing

The MWT-based balancing topology operates in discontinuous current mode (DCM), which allows the inductor to fully release its stored energy during the off period. For simplification, the voltage drops across diodes and MOSFETs are neglected in the analysis. Each module comprises two cells: $Cell_{11}$ and $Cell_{12}$ in module 1 and $Cell_{21}$ and $Cell_{22}$ in module 2. The initial voltage configuration assumes a descending order, such that ($V_{Cell11} > V_{Cell12} > V_{Cell21} > V_{Cell22}$). It is assumed that energy is transferred from

the higher-voltage cell to the lower-voltage cell within the cell-level equalization process. The operation consists of two stages, as illustrated in Figure 2.



(a) (b)

Figure 2. Cell-level operation mode schematic: (a) mode 1, (b) mode 2

1. Mode 1 (t_0-t_1). During this mode, all of the MOSFET S_{11}, S_{12}, S_{21}, and S_{22} are switched on. Energy transfer occurs from the first cell to the second cell through primary windings that are connected in each cell. During this condition, according to the kirchhoff current law and the equivalent circuit of forward MWT, V_{TP} as the primary winding voltage is denoted in equation 1 [22,23]. Where L_k is denoted as the leakage inductance of the primary winding, R_{eq} as the equivalent resistance, and i is the balancing current of each primary winding.

$$V_{TP} = V_{cell} - L_k \frac{di}{dt} - R_{eq} i \quad (1)$$

Considering the secondary winding, the excitation current i_{Lm} is expressed in equation 2. With V_{TS} as the voltage of secondary winding and L_m is magnetic inductance of the secondary winding. To be exact, the excitation current that occurs at the secondary winding is the summation of the individual balancing current in each cell and primary winding that is expressed in equation 3.

$$i_{Lm}(t) = \frac{V_{TS}}{L_m} (t - t_0) \quad (2)$$

$$i_{Lm} = \sum_{i=1}^{n} i_n \quad (3)$$

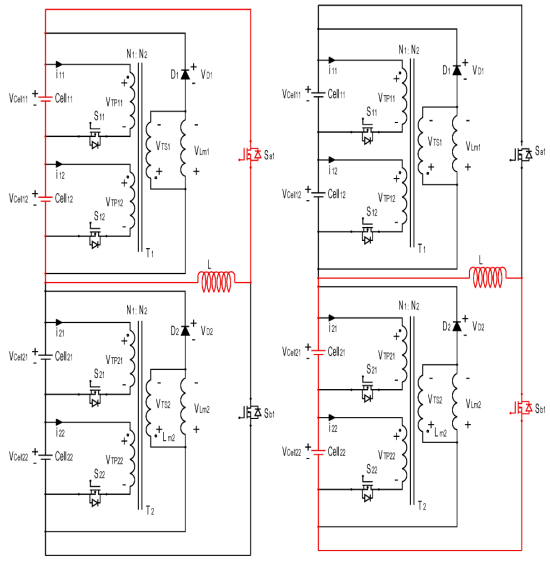
In addition, V_{Lm} is voltage that occurs across inductance magnetization in the secondary windings which follows the equation 4. During this mode, the inductance current rises from 0 to its maximum current that is dependable from the voltage difference between each cell.

$$V_{Lm} = L_m \frac{di_{Lm}}{dt} \quad (4)$$

2. Mode 2 (t_1-t_2) starts when all of the cell-level switches are turned off and the balancing current is 0. During this mode, freewheeling diodes will continuously flow the current that passes through the secondary windings to prevent magnetic saturation. The energy transfer between two cells will automatically stop and continue to mode 1 once the PWM signal is turned on.

A.2 Operation mode analysis in module-level balancing

The module-level equalizer also operates in discontinuous current mode (DCM), utilizing a distinct PWM control strategy for each switch, S_{a1} and S_{b1}. Let Module 1 and Module 2 be denoted as *M1* and *M2*, respectively, with V_{M1} and V_{M2} representing their corresponding voltages. Similar to the cell-level equalizer, the initial condition assumes that $V_{M1} > V_{M2}$.. The module-level operation is primarily divided into two stages, corresponding to the charging and discharging phases of the inductor and modules. The detailed operation mode is illustrated in Figure 3.



(a) (b)

Figure 3. Module-level operation mode schematic: (a) mode 1, (b) mode 2

1. Mode 1 (t_0-t_1). The initial charge from the battery in module 1 is transferred to the inductor when the S_{a1} PWM signal is turned on and S_{b1} is turned off. In this phase, the inductor will be in a charging condition and store the transferred energy temporarily before the PWM signal is turned off. The inductor current flow of this condition can be expressed with the equation 5 with R_{eq} representing equivalent resistance of the whole module-level balancing circuit.

$$i_{L(t_0-t_1)} = \frac{V_{M1}}{R_{eq}} \left(1 - e^{-\left(\frac{Req}{L}t\right)}\right) \quad (5)$$

2. Mode 2 (t_1-t_2) starts when S_{a1} is turned off and a

switch that connects with module 2, S_{b1} is turned on alternately. During this mode, the inductor will be in a discharging mode and the stored energy is transferred to module 2.

B. Balancing method based on fuzzy logic control

B.1 Fuzzy logic control architecture

In this study, battery voltage serves as the primary control variable for both cell-level and module-level balancing. Specific voltage thresholds are defined to minimize the zero-voltage gap (ZVG) during the equalization process. However, inherent differences in coil inductance, leakage, and internal resistance across each multi-winding transformer (MWT) and inductor complicate the regulation of balancing currents, resulting in asynchronous balancing rates and non-uniform ZVGs. To overcome these limitations, a fuzzy logic control (FLC) strategy is introduced at the module level to dynamically adapt the balancing current, thereby improving both balancing speed and energy efficiency.

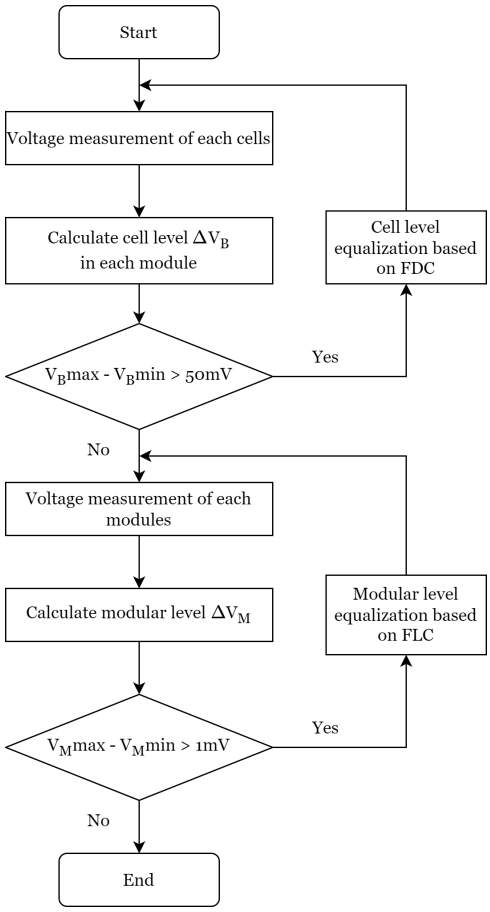


Figure 4. Proposed balancing control algorithm flowchart

Normally, the balancing current is proportional with the voltage difference between the highest voltage cell and the lowest one. The higher ZVG will significantly boost the charge transfer rate to the lowest cell. However, when the ZVG is gradually decreasing during the equalization, it is considerably difficult to optimize the equalization speed with a fixed duty cycle mechanism. Moreover, duty cycle ratio also played a prominent role in balancing current supply. In theory, higher duty cycle ratio will increase the balancing current; otherwise, the balancing current rate will decrease when the duty cycle ratio is small. Hence, taking a duty cycle adaptive control strategy through FLC can maximize the balancing speed and optimize the energy transfer between modules.

At the cell level, a conventional fixed duty cycle (FDC) control method is employed. In contrast, the module-level equalization utilizes a variable duty cycle determined by multiple input parameters, including the voltage difference between modules and their average voltage. As illustrated in Figure 4, the cell- and module-level balancing processes are executed independently and not simultaneously, enabling hierarchical and flexible control of the overall equalization system. V_{Bmax} and V_{Bmin} in Fig. 4 represent maximum and minimum cell voltage inside the module, while V_{Mmax} and V_{Mmin} show the maximum and minimum voltage of the battery module respectively. Furthermore, to ensure voltage difference between cells falls below 50 mV, cell-level balancing was done in the first place before the module-level equalization process starts. This method is proposed due to the inconsistency of multi-winding transformer properties that are considered difficult to achieve homogeneous MWT characteristics in its real application. Hence, it is expected that this method will be viable to promote FLC implementation for varied MWT characteristics.

A complete fuzzy logic control (FLC) system comprises four key components: a fuzzifier, a rule base, an inference engine, and a defuzzifier. The inference engine processes the fuzzy rule base to generate a linguistic control output, which is then converted into a crisp value during the defuzzification stage. In this study, the duty cycle serves as the output of the FLC. To ensure safe operation of the balancing system, the duty cycle is constrained within a range of 50% to 65%. Mamdani's center of area (CoA) method is employed for the defuzzification process. A simplified structure of the proposed FLC system is illustrated in Figure 5.

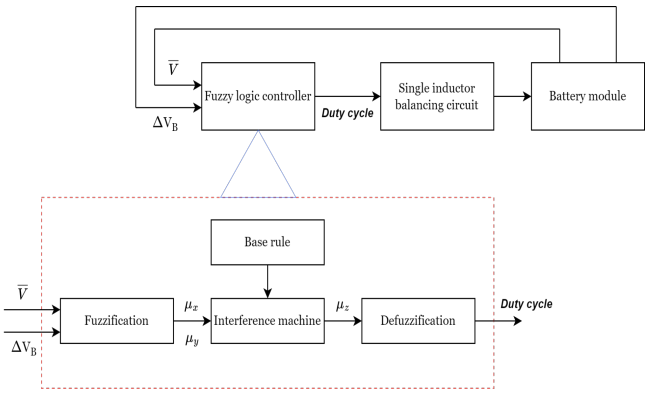
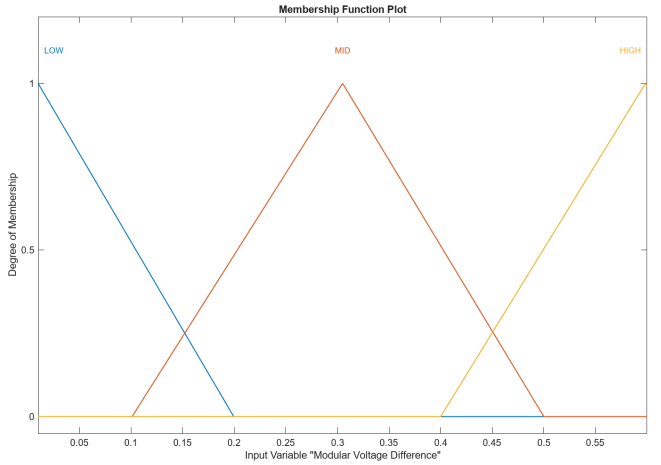


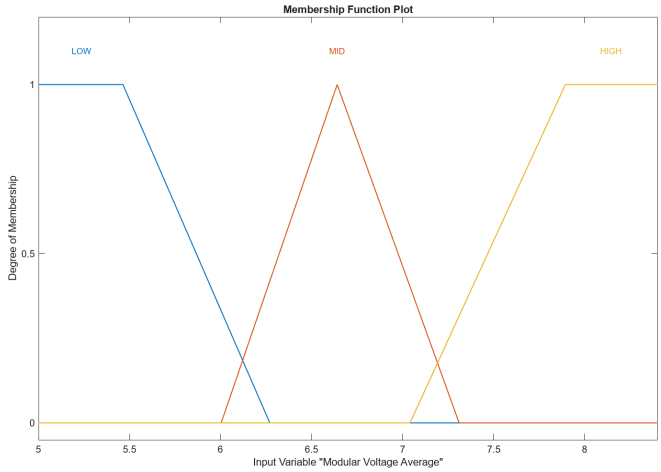
Figure 5. FLC Diagram on single inductor modular balancing

B.2 Fuzzy logic control design

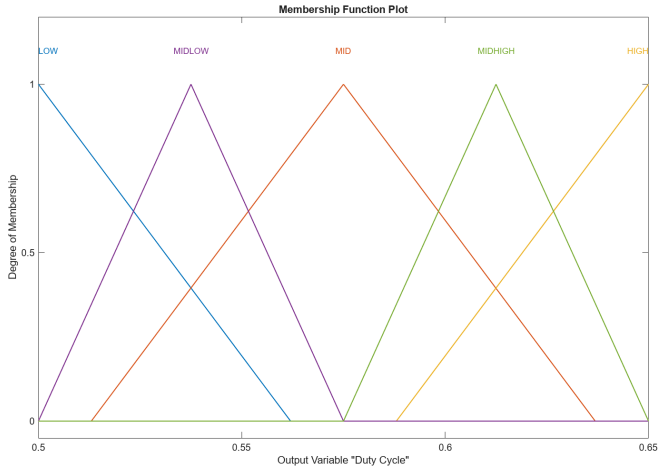
To justify fuzzy logic parameters and its rule base, the specific characteristics and specification of lithium-ion battery should be evaluated in order to give an exact estimation for fuzzy membership function



(a)



(b)



(c)

Figure 6. Membership function diagram: (a) voltage difference, (b) average voltage, (c) duty cycle

As shown in Figure 6, triangular shaped membership function is utilized for fuzzy membership function. The input variables in FLC are divided into three sub-intervals: Low (L), Medium (M), and High (H). Moreover, the output variable is divided into five sub-intervals: Low (L), Medium Low (ML), Medium (M), Medium High (MH), and High (H). Based on the lithium-ion battery specifications, the safety upper and lower limit of the battery cell is around 2.5 V to 4.2 V. For this reason, the modular average voltage is set out in a specific interval between 5.5 V to 8.4 V, whilst the modular voltage gap falls between 0 V to 0.6 V.

Table 1. Fuzzy logic base rule

		$\overline{V}$		
	Duty Cycle	L	M	H
ΔV	L	L	ML	H
	M	M	MH	H
	H	MH	H	H

In summary, fuzzy logic base rule is shown in table 1 with $\overline{V}$ and ΔV are depicted as voltage average and voltage gap respectively. This base rule is established based on experiment and can be described as follows:

1. if ΔV is high, a high duty cycle is needed to boost the balancing current and increase the balancing speed.
2. if both $\overline{V}$ and ΔV are high, a high duty cycle is required to increase the balancing current to avoid overcharging.
3. if both $\overline{V}$ and ΔV are low, a small duty cycle is utilized to reduce the balancing current to avoid over discharging.

if both $\overline{V}$ and ΔV are medium, a medium duty cycle is required to stabilize the balancing process by operating a medium current flow.

Results and Discussion

To verify the proposed system performance, a balancing prototype was built to balance 4 individual cells and 2 lithium-ion modules. In this research, two test configurations were carried out in static condition and dynamic condition. In order to evaluate the fuzzy logic control design, both FLC and FDC scenarios were tested during the static condition; furthermore, to ensure the proposed system's agility, the dynamic test condition was set out with two different scenarios – charging and discharging states. Considering the different tested scenarios, the performance parameters including balancing time and efficiency are evaluated. In this research, balancing efficiency η is calculated from the initial energy ($E_{imbalance}$) and the final energy ($E_{residue}$) after the balancing process is completed. Furthermore, the initial and final energy is equivalent to the cell's charge which can be obtained by calculating its capacitance (C_{cell}) and voltage difference before and after the equalization process. The efficiency formula is depicted in equation 6 [21].

$$\eta = \frac{E_{residue}}{E_{imbalance}} = \frac{\Sigma_{j=1}^{N} 0{,}5C_{cell}(V_{cellj}^{2\prime} - V_{min}^{2})}{\Sigma_{j=1}^{N} 0{,}5C_{cell}(V_{cellj0}^{2} - V_{min}^{2})} \; x \; 100\% \quad (6)$$

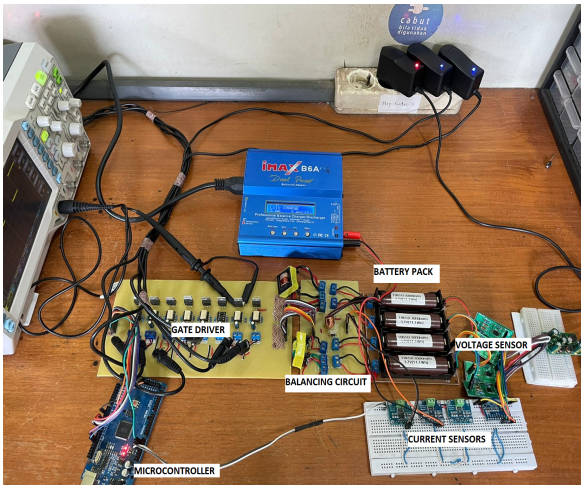


Figure 7. Prototype configuration

Figure 7 shows the prototype of MWT and single inductor balancing system. In summary, this system involved Arduino ATMega2560 as the microcontroller, lithium-ion batteries, the main balancing circuit and switching configuration, real time data logger, sensors, and battery conditioning devices. During the equalization process, a certain high frequency PWM was implemented to each MOSFET based on the MWT and single inductor requirements and characteristics. The specifications of the designed prototype are listed in Table 2.

Table 2. Prototype Specification

Module	Component	Parameter
Switching module	MOSFET	IRF540N
	Gate driver	TLP250
Balancing Circuits	MWT	Core: EE25
	Inductor	L: 0.4 mH
	Battery	LG INR18650HG2
Sensor Module	Voltage sensors	INA128
	Current sensors	INA219
Controller	Microcontroller	Arduino ATMega2560

A. Experimental result in static condition

Figure 8 presents the experimental results using fuzzy logic control (FLC) at the module level. The initial voltages of the four lithium-ion cells (Battery 1 to 4) were set to 3.401 V, 3.312 V, 3.214 V, and 3.085 V, respectively, resulting in an initial voltage difference of 306 mV. The cell-level equalizer employed a fixed 50% duty cycle for both Module 1 and Module 2. As illustrated in Figure 8, and based on the behavior observed in Figure 4, the equalization process at the module level begins approximately 200 seconds after the initiation of cell-level equalization, once the voltage difference within each module drops below 50 mV. The process concludes around 525 seconds, achieving a final zero-voltage gap (ZVG) of just 3 mV.

To validate the effectiveness of the proposed FLC algorithm, a comparative experiment was conducted using a fixed duty cycle (FDC) control method. The switching variables at the cell level were kept identical to the FLC scenario. In this case, the initial cell voltages were set to 3.375 V, 3.341 V, 3.195 V, and 3.093 V. As shown in Figure 9, the equalization process takes approximately 700 seconds; however, the final ZVG remains relatively high at around 55 mV. Since the balancing processes at both the module and cell levels occur simultaneously in this method, it becomes more challenging to coordinate the switching variables to effectively synchronize the balancing currents.

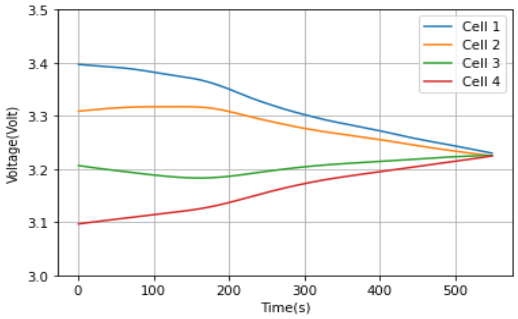


Figure 8. Voltage balance curve of FLC control method

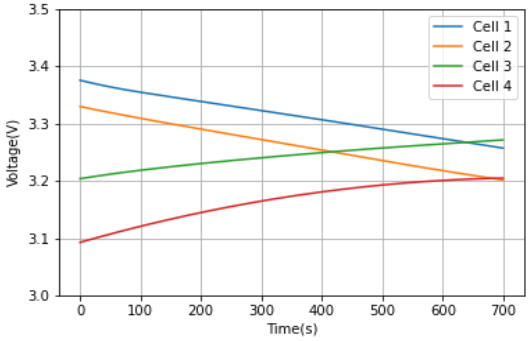


Figure 9. Voltage balance curve of FDC control method

According to the results of the comparison between the FDC control system and the proposed control algorithm, it can be proved that the proposed FLC algorithm is able to work better than the conventional or FDC algorithm. Based on the experimental result, the major downside of the FDC algorithm is that applying identical duty cycles and even combining intra-module and inter-module control systems makes overlapping often occur. The experimental result in Figure 9 clearly showed where the equalization process between modules has been completed but the ZVG in cell level still has a significant gap and has not reached the balance condition.

Figure 10 shows the equalization results with different initial voltage ranges compared with the aforementioned experiments. It can be observed that the equalization for the two imbalanced situations is well executed by the proposed

equalizer. This proves that the proposed balancing operation is independent of the cell initial voltages and positions in the series-connected battery string, showing the good robustness of the proposed equalizer.

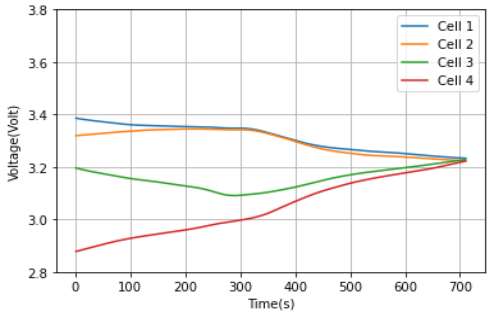


Figure 10. Experimental results for four NMC cells with different initial voltages

B. Experimental result in dynamic condition

To validate the effectiveness of the proposed balancing system in terms of dynamic equalization, Figure 11 presents the balancing results during constant current charging and discharging of the battery pack. As shown in Figure 10(a), all battery cells are charged almost uniformly using the proposed equalization method, with the maximum voltage difference significantly reduced from 222 mV to 4 mV in approximately 1600 seconds under a 0.5 A charging current. Similarly, in Figure 11(b), during discharge with a 0.2 A current load, the voltage difference decreases from 308 mV to 1 mV in around 800 seconds. These experimental results confirm that the proposed equalization scheme substantially improves both the consistency and available capacity of the battery pack during charging and discharging operations.

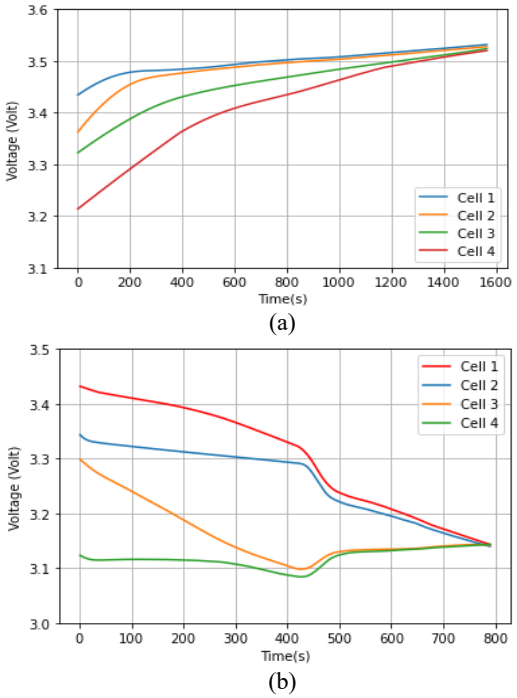


Figure 11. Dynamic balancing results for four NMC cells. (a) Battery charging. (b) Battery discharging

To more intuitively demonstrate the advantages of the proposed balancing method, a comprehensive comparison with other existing methods is presented in Figure 12 The proposed balancing topology, denoted as MWTSI-FLC, is based on a modular winding transformer (MWT) and a single inductor, combined with fuzzy logic control. For comparison, MWTSI-FDC represents a similar topology using a fixed duty cycle control instead of FLC, while MWTFC refers to the balancing topology based on MWT and capacitors, as previously discussed in [21, 29].

This comparison is based on several balancing parameters, including balancing speed, efficiency, balancing current, number of switches, and the voltage difference after the balancing process is completed. Each parameter is categorized into five performance levels, where Level 1 represents the lowest performance and Level 5 indicates the highest. The comparison results demonstrate that the proposed balancing method offers notable advantages in terms of balancing speed, balancing current, reduced number of switches/modules, and minimal voltage difference

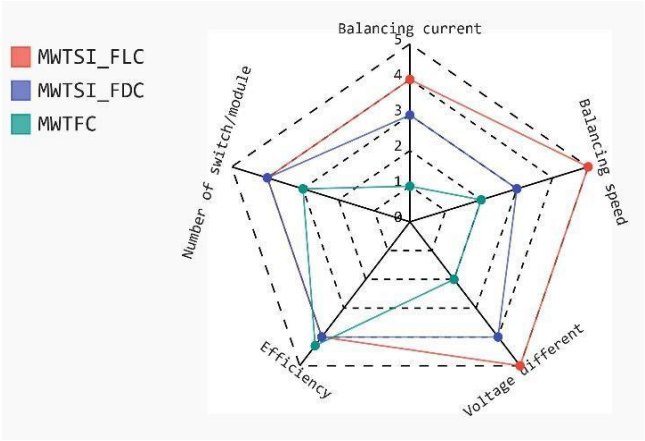


Figure 12. Comparison of the proposed equalizer with other equalizers

Conclusion

In this paper, a cell balancing topology based on a modular winding transformer (MWT) and a single inductor is proposed. This topology integrates two different balancing methods: one at the cell level using MWT, and another at the module level using a single inductor with fuzzy logic control (FLC). Experimental results demonstrate that FLC improves the module-level balancing speed by approximately 31.26% compared to fixed duty cycle control. Compared to other modularization techniques, the proposed topology significantly reduces the zero-voltage gap (ZVG) of each cell without introducing overlapping voltages during the balancing process. Additionally, the topology efficiently controls and enhances the modular balancing current using FLC, achieving an overall efficiency of approximately 86.95%. Overall, the proposed topology can simultaneously equalize both cell and module levels and effectively address the challenges posed by unequal MWT designs in modularization, leading to improved balancing performance.

References

[1] H. Tao, Z. Feng, H. Liu, X. Kan, and P. Chen, "Reality and Future of Rechargeable Lithium Batteries," 2011.

[2] J. Carter, Z. Fan, and J. Cao, "Cell equalization circuits: A review," Journal of Power Sources, vol. 448. Elsevier B.V., Feb. 01, 2020. doi: 10.1016/j.jpowsour.2019.227489.

[3] Y. Hua et al., "A comprehensive review on inconsistency and equalization technology of lithium-ion battery for electric vehicles," Int J Energy Res, vol. 44, no. 14, pp. 11059–11087, Nov. 2020, doi: https://doi.org/10.1002/er.5683.

[4] H. A. Gabbar, A. M. Othman, and M. R. Abdussami, "Review of Battery Management Systems (BMS) Development and Industrial Standards," Technologies, vol. 9, no. 2. MDPI, Jun. 01, 2021. doi: 10.3390/technologies9020028.

[5] M. M. Hoque, M. A. Hannan, A. Mohamed, and A. Ayob, "Battery charge equalization controller in electric vehicle applications: A review," Renewable and Sustainable Energy Reviews, vol. 75. Elsevier Ltd, pp. 1363–1385, 2017. doi: 10.1016/j.rser.2016.11.126.

[6] A. Alvarez-Diazcomas, A. A. Estévez-Bén, J. Rodríguez-Reséndiz, M. A. Martínez-Prado, R. V. Carrillo-Serrano, and S. Thenozhi, "A review of battery equalizer circuits for electric vehicle applications," Energies, vol. 13, no. 21. MDPI AG, Nov. 01, 2020. doi: 10.3390/en13215688.

[7] U. K. Das et al., "Advancement of lithium-ion battery cells voltage equalization techniques: A review," Renewable and Sustainable Energy Reviews, vol. 134. Elsevier Ltd, Dec. 01, 2020. doi: 10.1016/j.rser.2020.110227.

[8] Y. Chen et al., "A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards," Journal of Energy Chemistry, vol. 59. Elsevier B.V., pp. 83–99, Aug. 01, 2021. doi: 10.1016/j.jechem.2020.10.017.

[9] J. Xu, X. Mei, and J. Wang, "A high power low-cost balancing system for battery strings," in Energy Procedia, Elsevier Ltd, 2019, pp. 2948–2953. doi: 10.1016/j.egypro.2019.01.956.

[10] T. A. Abdul-Jabbar, A. Kersten, A. Mashayekh, A. A. Obed, A. J. Abid, and M. Kuder, "Efficient Battery Cell Balancing Methods for Low-Voltage Applications: A Review," in 2022 IEEE International Conference in Power Engineering Application, ICPEA 2022 - Proceedings, Institute of Electrical and Electronics Engineers Inc., 2022. doi: 10.1109/ICPEA53519.2022.9744677.

[11] Z. B. Omariba, L. Zhang, and D. Sun, "Review of Battery Cell Balancing Methodologies for Optimizing Battery Pack Performance in Electric Vehicles," IEEE Access, vol. 7, pp. 129335–129352, 2019, doi: 10.1109/ACCESS.2019.2940090.

[12] M. Uzair, G. Abbas, and S. Hosain, "Characteristics of battery management systems of electric vehicles with consideration of the active and passive cell balancing process," World Electric Vehicle Journal, vol. 12, no. 3. MDPI AG, Aug. 01, 2021. doi: 10.3390/wevj12030120.

[13] M. Gao et al., "An active and passive hybrid battery equalization strategy used in group and between groups," Electronics (Switzerland), vol. 9, no. 10, pp. 1–21, 2020, doi: 10.3390/electronics9101744.

[14] J. Gallardo-Lozano, E. Romero-Cadaval, M. I. Milanes-Montero, and M. A. Guerrero-Martinez, "Battery equalization active methods," Journal of Power Sources, vol. 246. pp. 934–949, 2014. doi: 10.1016/j.jpowsour.2013.08.026.

[15] H. S, "Overview of cell balancing methods for Li-ion battery technology," Energy Storage, vol. 3, no. 2, Apr. 2021, doi: 10.1002/est2.203.

[16] A. Farzan Moghaddam and A. Van den Bossche, "Flyback Converter Balancing Technique for Lithium Based Batteries," in 2019 8th International Conference on Modern Circuits and Systems Technologies (MOCAST), IEEE, May 2019, pp. 1–4. doi: 10.1109/MOCAST.2019.8741893.

[17] U. Abronzini, M. Di Monaco, F. Porpora, G. Tomasso, M. D'Arpino, and C. Attaianese, "High Performance Active Battery Management System with Multi-Winding Transformer," in 2019 IEEE Energy Conversion Congress and Exposition (ECCE), IEEE, Sep. 2019, pp. 1231–1236. doi: 10.1109/ECCE.2019.8912966.

[18] Y. Shang, B. Xia, C. Zhang, N. Cui, J. Yang, and C. C. Mi, "An Automatic Equalizer Based on Forward-Flyback Converter for Series-Connected Battery Strings," IEEE Transactions on Industrial Electronics, vol. 64, no. 7, pp. 5380–5391, Jul. 2017, doi: 10.1109/TIE.2017.2674617.

[19] S. Li, C. C. Mi, and M. Zhang, "A high-efficiency active battery-balancing circuit using multiwinding transformer," IEEE Trans Ind Appl, vol. 49, no. 1, pp. 198–207, 2013, doi: 10.1109/TIA.2012.2229455.

[20] C. S. Lim, K. J. Lee, N. J. Ku, D. S. Hyun, and R. Y. Kim, "A modularized equalization method based on magnetizing energy for a series-connected lithium-ion battery string," IEEE Trans Power Electron, vol. 29, no. 4, pp. 1791–1799, 2014, doi: 10.1109/TPEL.2013.2270000.

[21] T. M. Bui, C. H. Kim, K. H. Kim, and S. B. Rhee, "A modular cell balancer based on multi-winding transformer and switched-capacitor circuits for a series-connected battery string in electric vehicles," Applied Sciences (Switzerland), vol. 8, no. 8, Aug. 2018, doi: 10.3390/app8081278.

[22] S. Fan, J. Duan, L. Sun, and K. Zhang, "A Fast Modularized Multiwinding Transformer Balancing Topology for Series-Connected Super Capacitors," IEEE Trans Power Electron, vol. 34, no. 4, pp. 3255–3268, Apr. 2019, doi: 10.1109/TPEL.2018.2848364.

[23] J. Duan, M. Duan, K. Zhang, Z. Lv, and L. Sun, "Research on voltage equalization among multiple supercapacitor modules based on multiwinding transformer," International Journal of Electrical Power and Energy Systems, vol. 120, Sep. 2020, doi: 10.1016/j.ijepes.2020.106031.

[24] A. F. Moghaddam and A. Van den Bossche, "An efficient equalizing method for lithium-ion batteries based on coupled inductor balancing," Electronics (Switzerland), vol. 8, no. 2, Feb. 2019, doi: 10.3390/electronics8020136.

[25] Y. Chen et al., "An any-cell(s)-to-cell(s) equalization method with a single magnetic component for Lithium-ion battery pack," J Energy Storage, vol. 33, Jan. 2021, doi: 10.1016/j.est.2020.102071.

[26] Y. Shang, B. Xia, C. Zhang, N. Cui, J. Yang, and C. Mi, "A modularization method for battery equalizers using multiwinding transformers," IEEE Trans Veh Technol, vol. 66, no. 10, pp. 8710–8722, Oct. 2017, doi: 10.1109/TVT.2017.2702065.

[27] Y. Zheng, M. Ouyang, L. Lu, J. Li, X. Han, and L. Xu, "On-line equalization for lithium-ion battery packs based on charging cell voltages: Part 2. Fuzzy logic equalization," J Power Sources, vol. 247, pp. 460–466, 2014, doi: 10.1016/j.jpowsour.2013.09.012.

[28] X. Cui, W. Shen, Y. Zhang, and C. Hu, "A fast multi-switched inductor balancing system based on a fuzzy logic controller for lithium-ion battery packs in electric vehicles," Energies (Basel), vol. 10, no. 7, Jul. 2017, doi: 10.3390/en10071034.

[29] Y. Shang, C. Zhang, N. Cui, J. M. Guerrero, and K. Sun, "A crossed pack-to-cell equalizer based on quasi-resonant LC converter with adaptive fuzzy logic equalization control for series-.connected lithium-ion battery strings," in Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC, Institute of Electrical and Electronics Engineers Inc., May 2015, pp. 1685–1692. doi: 10.1109/APEC.2015.7104574.

[30] L. Liao and H. Chen, "Research on two-stage equalization strategy based on fuzzy logic control for lithium-ion battery packs," J Energy Storage, vol. 50, Jun. 2022, doi: 10.1016/j.est.2022.104321.