Energy Conversion
Circuit Laboratory

# Novel Battery Equalizer-Charger Symbiosis Structure based on Three-Port DC-DC Converters

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***Abstract*—In electric vehicles and battery energy storage systems, hundreds of battery cells are grouped into battery modules and they are connected in series to make a battery pack for effective energy management. In addition to the conventional cell balancing within a module, module equalization within a pack is also required, but another external circuit makes cost and volume issues. This paper proposes a novel battery equalizer-charger symbiosis structure to mitigate the problem. A bi-directional three-port converter is presented and six possible operation modes are suggested, where the secondary port serves as a pack-charger and the tertiary port is docked to a switch-matrix to balance the battery modules. The test results from the real-time simulation for 5 battery modules are implemented to verify the performance of the proposed structure. It found that the SOC levels of modules are equalized within $0.5\%$ in our tests.**

***Index Terms*—Battery equalizer-charger, three-port converter.**

## I. INTRODUCTION

In general, a battery pack in EV or SL-BESS consists of hundreds of cells connected in series and parallel. For effective maintenance, a group of cells constitutes a module, and a group of modules constructs a pack. Therefore, the operation and hardware of the pack charger and equalizer are usually separated as shown in Fig. 1. While the equalizer ensures the consistency of the cells and modules, the bi-directional converter charges or discharges the whole battery pack. For high power handling, the isolated full-bridge converter family is mostly utilized for the charger [1], [2].

Various equalizer structures are introduced in [3]–[5]. Based on the operating schemes, they are classified into passive and active methods. The passive balancing methods are more popular in the industry due to their simplicity and low-cost [6]–[8]. However, they have low efficiency and speed due to the energy dissipation scheme. Hence, passive balancing methods are only suitable for the purposed of cell balancing inside a module. On the contrary, the active methods have a high performance due to the energy regenerative scheme. By utilizing the inductors [9], [10], transformer [11], [12], or capacitors [13]–[15] as an energy carrier, energy of the high-voltage cell can be transferred to the lower-voltage cell. But in the system that is already equipped with a charger and cell equalizer, the extra component count, board size and cost impose a big barrier to their commercialization.

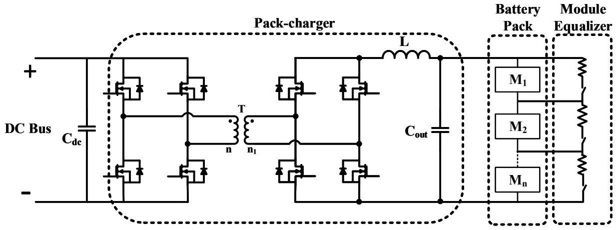


Fig. 1: Conventional structure: charger and external equalizer.

Since the cost is a big disadvantage, the battery pack is divided into multiple battery modules, which consist of a standard number of cells. The active equalizers are adopted to balance the cells inside each module while the battery modules are equalized by the passive methods or bypass switches scheme. In view of cost and volume, this solution is ineffective. Thus, an enhanced integrated equalizer-charger is required, which can balance the energy between modules while the whole battery pack is charged or discharged.

In order to overcome the limitations of conventional methods, a novel battery equalizer-charger symbiosis structure is proposed in this paper. Since the equalizer is integrated into the bi-directional converter to coordinate the operations of the charger and equalizer. The proposed topology and control flowcharts are shown in Section II. To design the optimal value of balancing and charging currents, an operating current analysis is made in Section III. The performance is verified in Section IV and the conclusion is made in the final section.

## II. PROPOSED STRUCTURE AND OPERATION PRINCIPLE

### A. Three-port Converter Architecture

The concept of the symbiosis structure is illustrated in Fig. 2(a), where the equalizer for the battery module is integrated into the bi-directional converter to form a three-port structure. The primary and secondary port of the converter connects to the DC bus and the battery pack and the bi-directional energy flow can be achieved. Besides, the tertiary port of the converter is docked to a switch-matrix as in Fig. 2(b) to equalize the modules. By cooperating operations of three ports, the battery modules can be equalized and charged/discharged at the same time. Observed that the battery cells inside the modules are

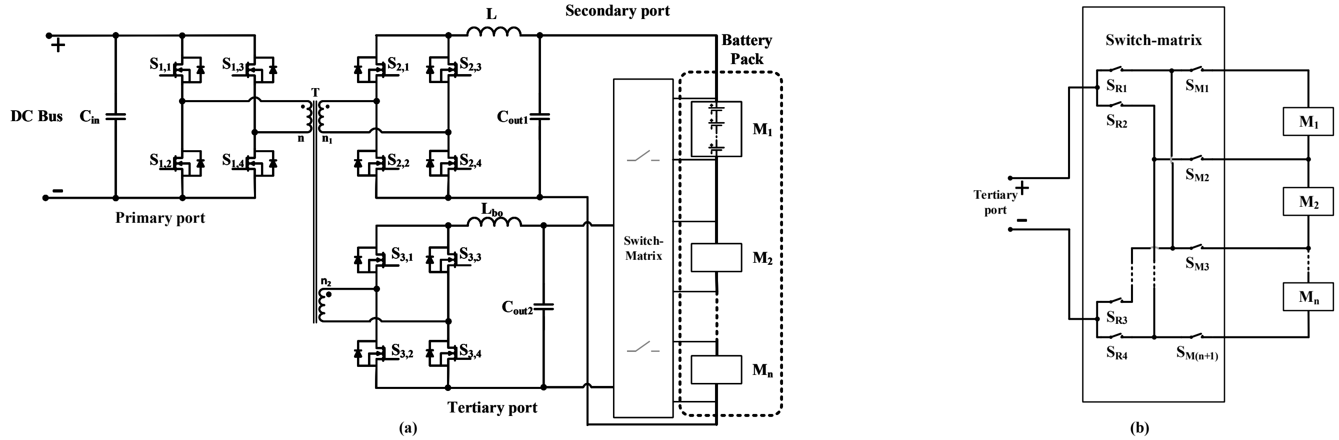


Fig. 2: Proposed symbiosis structure: (a) Three-port converter architecture; (b) switch-matrix structure.

TABLE I: Operation Modes

| **Mode** | **Operation Description** | **Energy flow** | |
|---|---|---|---|
| | | **From** | **To** |
| I | CC pack-charging + module-balancing | DC bus | Battery pack, battery module |
| II | Module-balancing | DC bus | Battery module |
| III | CV charging | DC bus | Battery pack |
| IV | Idle time, Self-balancing | Battery pack | Battery module |
| V | Pack-Discharging | Battery pack | DC bus |
| VI | Discharging process + module-balancing | Battery pack | DC bus, battery module |

monitored and equalized by the individual battery management scheme.

### *B. Operation Principle*

Due to the bi-directional three-port architecture, the operation of the symbiosis system is flexible. The symbiosis system can serve either as a self-equalizer in idle time or as a battery charger with equalization function in non-idle time. Table I summarizes the operation modes of the symbiosis system: Mode I to III are operations in charging process, Mode IV is implemented while the battery pack is in idle time, and Mode V, VI describe operations in discharging process:

- **Mode I**: In charging process, the battery pack is charged by CC (constant current) method. The secondary port of the converter charges the whole battery pack with a constant-current, $I_{pack}$. Besides, the tertiary port delivers an extra balance current, $I_{bal}$, to the lowest SOC battery module. The ratio between $I_{pack}$ and $I_{bal}$ will be discussed in Section III.
- **Mode II**: When any battery module reaches the CV (constant voltage) threshold first, the CC pack-charging process is stopped. The module-balancing is still maintained with a constant current, $I_{bal}$.
- **Mode III**: After all the module voltages reach the CV threshold, the DC-DC converter changes the control from CC to CV charging operation. In CV charging, only the battery pack is charged by the secondary port of the converter, and the tertiary port is deactivated.
- **Mode IV**: In the idle time, the primary port is deactivated, the DC-DC converter serves as a module-equalizer that delivers energy from the pack to the module through the switch-matrix.
- **Mode V**: In pack-discharging process, the battery pack discharges to the DC bus through the secondary and primary ports, and the tertiary port is deactivated.
- **Mode VI**: If the SOC difference between battery modules becomes larger than a threshold level, $SOC_{th}$, the stored energy in the battery pack flows from the secondary port to the tertiary port, charging the minimum SOC module to retain the balance.

In fact, various control strategies in [16], [17] can be applied to the proposed structure. However, only the charging and self-balancing processes are discussed in this paper. The flowcharts of the charging and self-balancing processes are shown in Fig. 3, where the lower SOC battery modules are charged by the tertiary port and the whole pack is charged by the secondary port as Fig. 3(a). At the beginning, the module voltages are measured to estimate the SOCs. The charging process consists of 3 stages according to the SOC conditions. In the first stage, the whole battery pack is charged by $I_{pack}$. In the second stage, during the pack-charging operation, the SOC measurement is

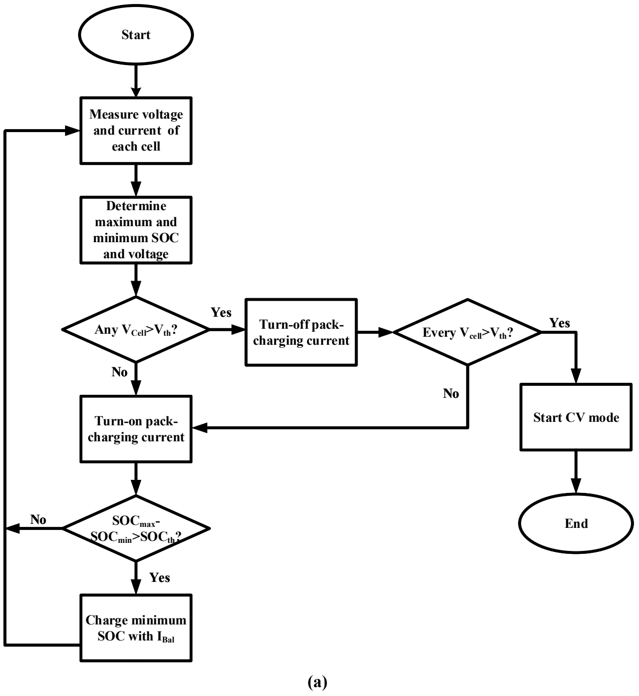


Fig. 3: Control flowchart: (a) Charging process, (b) Self-balancing process.

updated every sampling time to identify the minimum SOC module and the minimum SOC module is connected to the converter and is charged by $I_{bal}$. In the third stage, when all the modules reach the threshold voltage $V_{th}$, the converter operation is changed to CV mode and keeps charging until the end of the charging process.

On the other hand, the self-balancing process recycles the energy of the battery pack to charge the lower-SOC module as Fig. 3(b). Energy is transferred from the battery pack to the minimum SOC module through the secondary and tertiary ports of the converter. After a holding time, $T_{hold}$, the SOC level of modules are scanned again. Since the SOC levels are varying during the equalization process, another SOC comparison dynamically configures the switch-matrix to choose the minimum SOC module. Thus, the SOC levels of the modules are gradually equalized until the SOC difference becomes lower than $SOC_{th}$.

## III. PERFORMANCE ANALYSIS

If the operations of the three bridges are not properly coordinated, they could lead to harmful effects on battery performance and safety. For example, when the charging and balancing processes are executed at the same time, the current flow in one of the battery modules, which is sum of charging and balancing current, may exceed the limited current rating, $I_{total}$. Technically, there is a trade-off: the higher balancing current increases the balancing speed while the higher charging current reduces the charging time. Therefore, the ratio of balancing current to the charging current is carefully chosen. In this section, the impact such a current ratio between the charging and balancing currents is analyzed as follows.

First of all, the state of charge (SOC) of one battery module is defined as

$$SOC(t+\Delta t) = SOC(t) + \frac{1}{C}\int_{t}^{t+\Delta t} i(\tau)d\tau, \qquad (1)$$

where $C$ is the capacity of a module and $i(\tau)$ is the inward current to the module. Denote $\alpha$ as the ratio of the balancing current, $I_{bal}$, to the total current, $I_{total}$, the balancing current is represent by

$$I_{bal} = \alpha I_{total}. \qquad (2)$$

Because the sum of $I_{bal}$ and $I_{pack}$ has to be lower than or equal $I_{total}$ and in order to minimize the charging time, the maximum available pack-charging current is calculated by

$$I_{pack} = I_{total} - I_{bal}. \qquad (3)$$

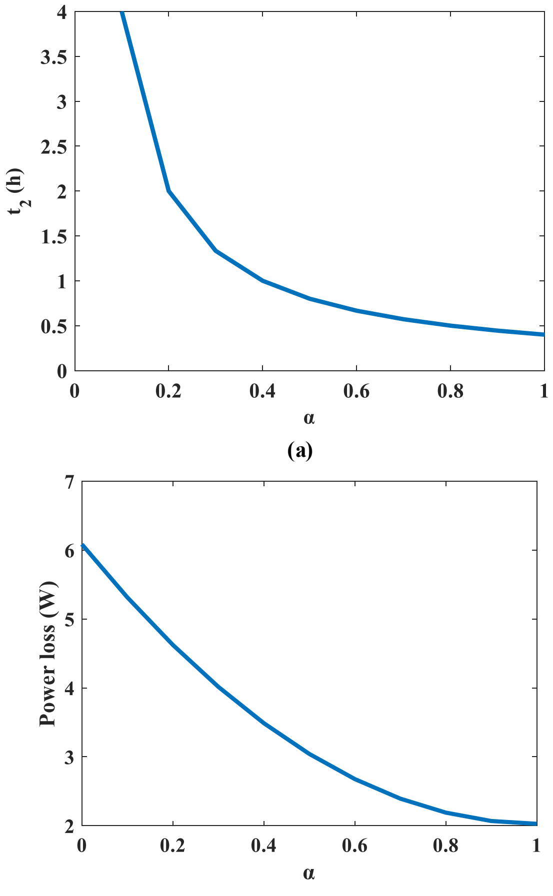
For example, consider the case of 3 battery modules with the initial SOCs of $SOC_1 < SOC_2 < SOC_3$. Assume that the secondary port of the converter charges the whole battery pack by $I_{pack}$ and the tertiary port of the converter combined with switch-matrix charges module #1 by $I_{bal}$. If we denote $t_1$ as the time taken for SOC #1 to be equal to SOC #2, the SOC level of module #1, #2, and #3 at $t_1$ are

$$SOC_1(t_1) = SOC_1(t_0) + \frac{1}{C}(I_{bal} + I_{pack})t_1, \qquad (4)$$

$$SOC_2(t_1) = SOC_2(t_0) + \frac{1}{C}I_{pack}t_1, \qquad (5)$$

$$SOC_3(t_1) = SOC_3(t_0) + \frac{1}{C}I_{pack}t_1. \qquad (6)$$

Since $SOC_1(t_1)$ equal to $SOC_2(t_1)$, the equalization time $t_1$



(a)

(b)

Fig. 4: Theoretical calculating(a) Equalization time $t_2$ vs. $\alpha$, (b) Power loss vs. $\alpha$.

is then calculated by

$$t_1 = \frac{SOC_2(t_0) - SOC_1(t_0)}{\alpha I_{total}} C. \tag{7}$$

After $t_1$, the control algorithm changes the switching pattern to alternately charge modules #1 and #2 to increase their SOC levels to $SOC_3$. Assume that $SOC_1$, $SOC_2$, and are equalized eventually at $t_2$, the SOC level of module #1, #2, and #3 at $t_2$ are

$$SOC_1(t_2) = SOC_1(t_1) + \frac{1}{2C}(I_{bal} + I_{pack})(t_2 - t_1), \tag{8}$$

$$SOC_2(t_2) = SOC_2(t_1) + \frac{1}{2C}(I_{bal} + I_{pack})(t_2 - t_1), \tag{9}$$

$$SOC_3(t_2) = SOC_3(t_1) + \frac{1}{C} I_{pack}(t_2 - t_1). \tag{10}$$

Because $SOC_1(t_2) = SOC_2(t_2) = SOC_3(t_2)$, the equalization time $t_2$ is expressed by

$$t_2 = 2[\frac{SOC_3(t_0) - SOC_1(t_0)}{\alpha I_{total}} C - \frac{1}{2} t_1]. \tag{11}$$

TABLE II: Real-time simulation setup

| Conditions | Self-balancing | | Charging | |
|---|---|---|---|---|
| | Conventional | Proposed | Conventional | Proposed |
| **Module Specification** | 20S1P, 60~84V, 2.6Ah | | | |
| **DC Bus Voltage (V)** | N/C | | 750 | |
| $I_{total}$ **(A)** | 2.6 | | | |
| **Current ratio** $\alpha$ | N/A | 1 | N/A | 0.5 and 1 |
| **Balancing Current (A)** | 0.35 | $\alpha I_{total}$ | 0.35 | $I_{total}$ |
| **Initial** $SOC_{1,2,3,4,5}$ (%) | $80, 90, 75, 65, 60$ | | $40, 15, 30, 35, 25$ | |

*N/C: Not connect

**N/A: Not applicable

If we consider a more general case of n-module. A similar analysis shows that the equalization of n-module is achieved at $t_n$ expressed as

$$t_n = n[\frac{SOC_n(t_0) - SOC_1(t_0)}{\alpha I_{total}} C - \sum_{2}^{n} \frac{1}{(n-1)(n)} t_{n-1}]. \tag{12}$$

Meanwhile, the power loss of the battery pack during the equalizing-charging process is sum of the power loss of each module and illustrated as

$$\begin{aligned} P_{loss}(t) &= nR_m I_{pack}^2(t) + R_m I_{bal}^2(t) \\ &= nR_m(1-\alpha)^2 I_{total}^2(t) + R_m \alpha^2 I_{total}^2(t), \end{aligned} \tag{13}$$

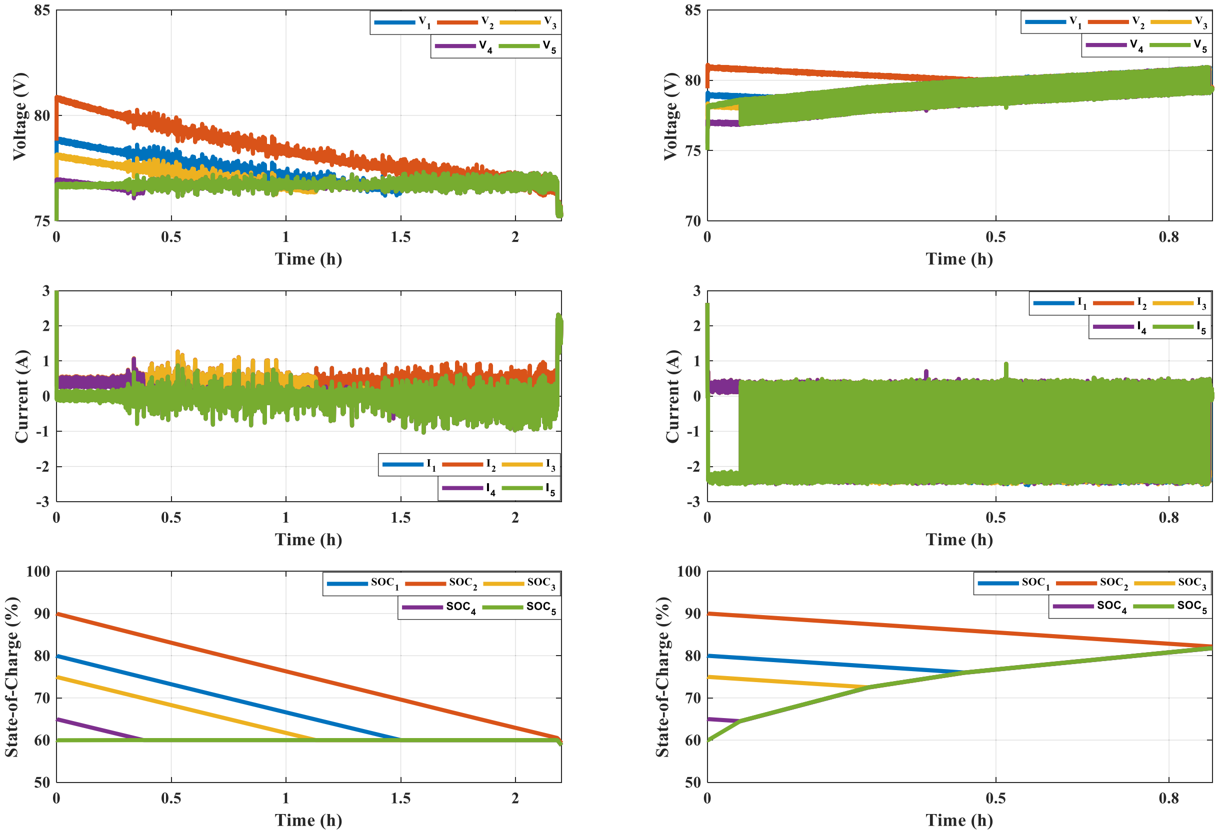
where is assumed that the internal resistance of battery modules, $R_m$, are not changed in the equalizing-charging process and they are all identical to each other. By integrating the power loss the energy loss of the battery pack during the process is determined by

$$E_{loss} = \int_0^{t_n} P_{loss}(\tau) d\tau \tag{14}$$

Assume that the number of modules is 3 and the initial SOC level of module #1, #2, and #3 are 10%, 20%, and 40%, respectively; the limited current rating of the battery, $I_{total}$, is 2.6A; internal impedance of the battery module is $0.1\Omega$. The relationship between the equalization time and the balancing current ratio $\alpha$ is plotted in Fig. 4(a), where the module balance is achieved faster as $\alpha$ becomes higher. Besides, Fig. 4(b) also shows that the power loss in the battery pack decreases as $\alpha$ approaches unity. According to Fig. 4, unity $\alpha$ provides the highest module balancing speed as well as the lowest power loss, but no pack charging is achieved.

## IV. PERFORMANCE VERIFICATIONS

To verify the performance of the proposed structure, the real-time simulations for five battery modules are implemented on Typhoon 602+ HIL system. In the tests, one battery module consists of 20 series-connected battery cells (18650-3.6V/2.6A). The performance of the proposed method is assessed in both idle and charging modes. The initial condition of the modules and the test setup are listed in Table II, where



(a) (b)

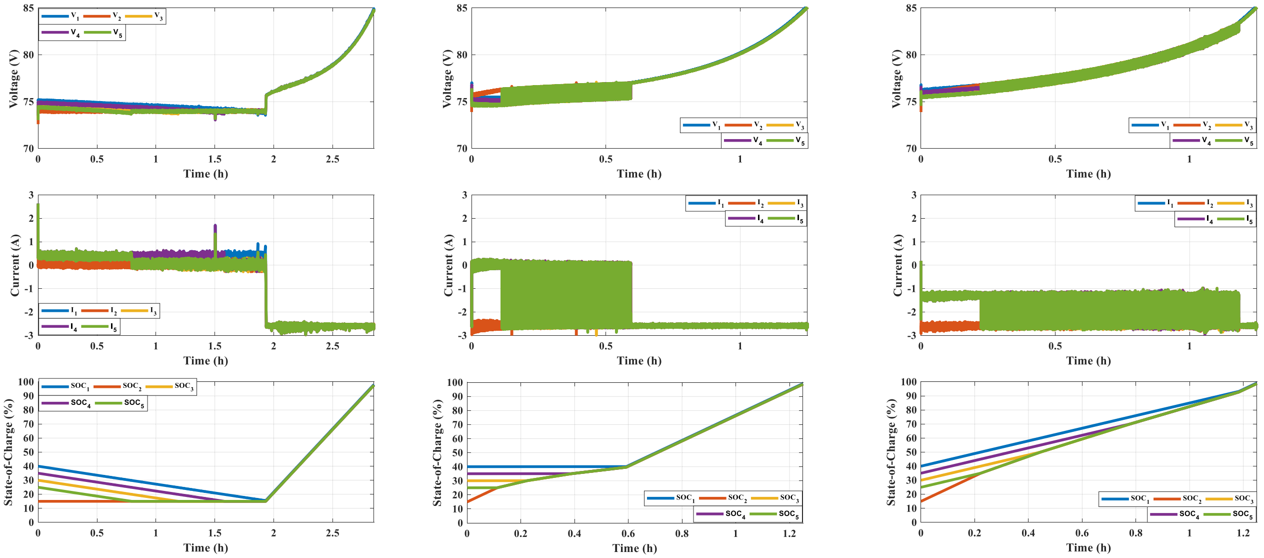
Fig. 5: Module voltages, currents, and SOC profiles in self-balancing process: (a) Conventional method, (b) Proposed method.

the initial SOC levels of the modules are set to a different level on purpose. While the battery modules are charged by a 750V DC bus in the charging process, the modules are balanced by the DC bus.

In the self-balancing process (Mode IV in Table II), the performance of the proposed method is compared to the conventional passive balancing method which is popular in industrial applications. The maximum balancing current of the conventional method is designed by 0.35A while the proposed method equalizes the modules by a constant 2.6A. The voltages, currents, and SOC profiles of the modules are plotted in Fig. 5. Due to the energy dissipation scheme, the passive method reduces the SOC level of the modules to 60%, which is the minimum of the initial SOC levels. On the other hand, the proposed method equalizes the SOC level of the modules as high as 81% retaining most of the initial stored energy after equalization. While the proposed method requires only 0.85h to equalize the SOC level within 0.5%, the conventional method needs as much as 2.2h to do the same task. Although the passive method can be reconfigured to get a higher balancing current for the faster speed, the heat sink design for the energy dissipation imposed another challenge, which clarifies that the passive balancing method is unsuitable for module equalization.

In the charging process, the conventional method is configured to balance the battery module before the execution of the pack-charging operation, since it is the most effective way to use it. On the other hand, it is possible to achieve both balancing and charging with the proposed methods. By activating Mode I in Table I, two test strategies with current ratios of 0.5 and 1 assess the performance. The voltages, currents, and SOC profiles of the modules are illustrated in Fig. 6. According to the profiles, the operation time of the proposed method is just half of the conventional method, which means that the proposed method is more effective in view of operation time. Besides, the conventional method requires more energy to fully charge the modules than the proposed method since a lot of energy is dissipated during the balancing operation.

The profiles in Fig. 6(b) and Fig. 6(c) reflect two different control strategies: In the strategy #1, the modules are equalized fully before the charging stage ($\alpha = 1$), and in the strategy #2, the charging and balancing current are equal ($\alpha = 0.5$). In this test, the operating time and energy loss during the full charging process are assessed. The energy loss is calculated by eq. (14). It is interesting to found that the total operating times for both strategies are similar but the energy loss in the strategy #2 is only 52% of that in the strategy #1. Such energy saving can be achieved due to the effective charge utilization during the cooperation of the charging and equalization process.



(a) (b) (c)

Fig. 6: Module voltages, currents, and SOC profiles in charging process: (a) Conventional method, (b) Proposed method with strategy $\#1$ ($\alpha = 1$), (c) Proposed method with strategy $\#2$ ($\alpha = 0.5$).

## V. CONCLUSIONS

This paper proposes a novel battery equalizer-charger symbiosis structure that integrates the equalization feature into the bi-directional converter. A three-port bi-directional converter is utilized where the tertiary port is docked to a switch-matrix to equalize the battery modules. Various control strategies can be adopted in the future, although only the self-balancing and charging processes are presented in this paper. The real-time simulation results obtained from 5-module battery pack system show that the SOC levels of the modules are equalized within $0.5\%$ after $0.85h$ in idle time. Because of compactness and high efficiency, the proposed structure is a good candidate for the battery module or rack equalization in EV and BESS applications.

## ACKNOWLEDGMENT

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**P_A02: Energy Storage Systems**

**P_307**

# Novel Battery Equalizer-Charger Symbiosis Structure based on Three-Port DC-DC Converters

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# Agenda

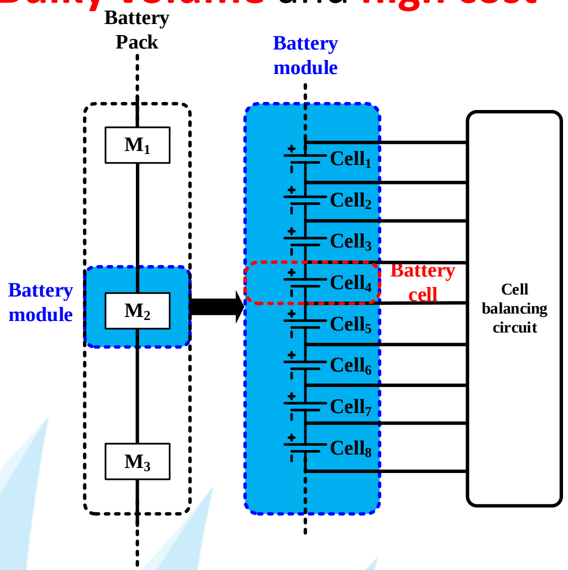
- Introduction
- Proposed structure and operation principle
- Operation analysis
- Performance verifications
- Conclusions

# Introduction (1/3)

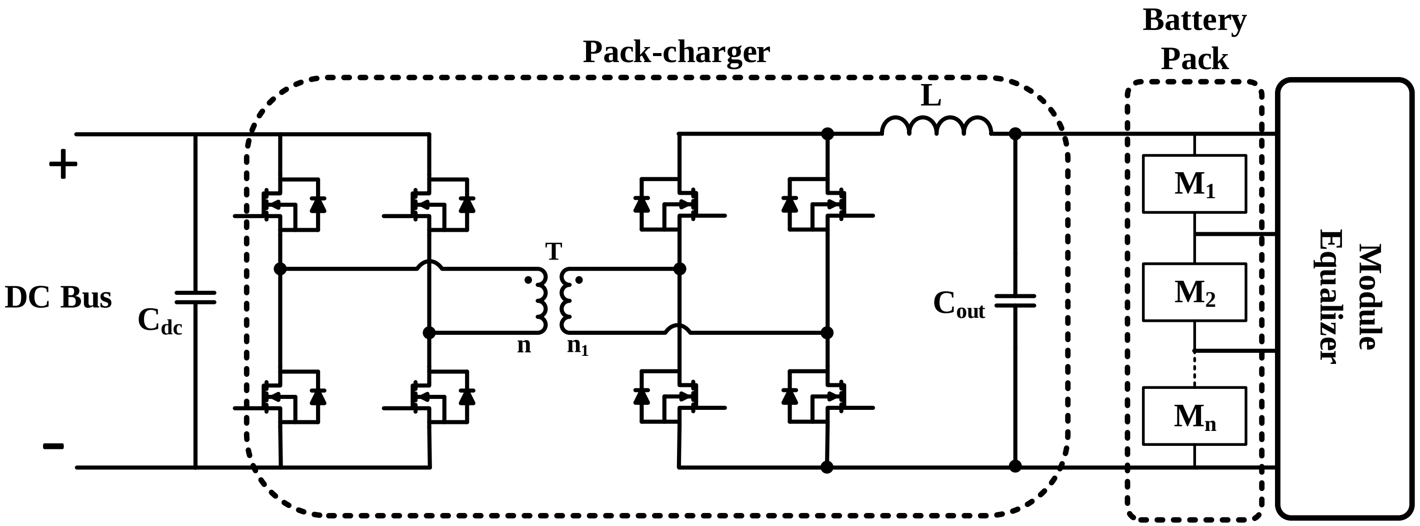
## ➢ Conventional concept – Battery pack and charger structure

- **Hundreds of cells** are configured in **series and parallel** in a battery pack.
- A **group of cells** constitutes **a module**, and a **group of modules** constructs **a pack**.
- The operation and hardware of **the pack charger** and **equalizer** are usually **separated**.

➔ **Bulky volume** and **high cost**



*Battery pack structure*

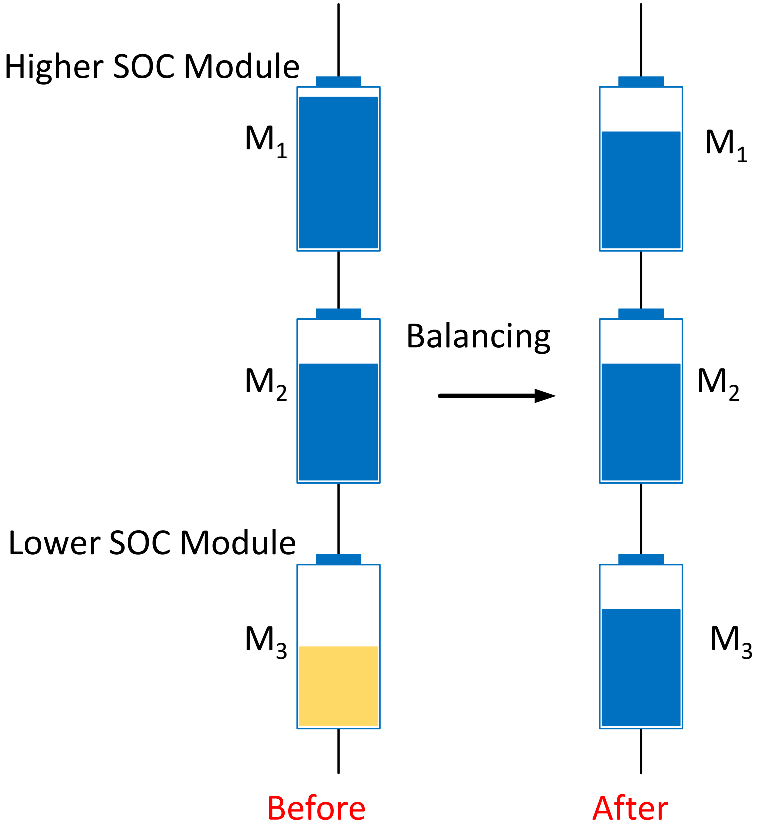


*Battery system structure*

# Introduction (2/3)

## ➢ Why do we need a module equalizer as well as a cell equalizer?

- **Cell equalizer** only provides SOC balancing **within a module**.
- However, modules within a pack suffer from **module inconsistency**.
- Module inconsistency is **caused by accumulation of difference characteristics** of cells and is further amplified by multiple connection.
- So, **the module equalization is essential in battery pack** systems with series-connected modules such as EV and ESS.
- Especially, in **ESS systems utilizing second-life battery modules**, the problem **becomes more serious**.

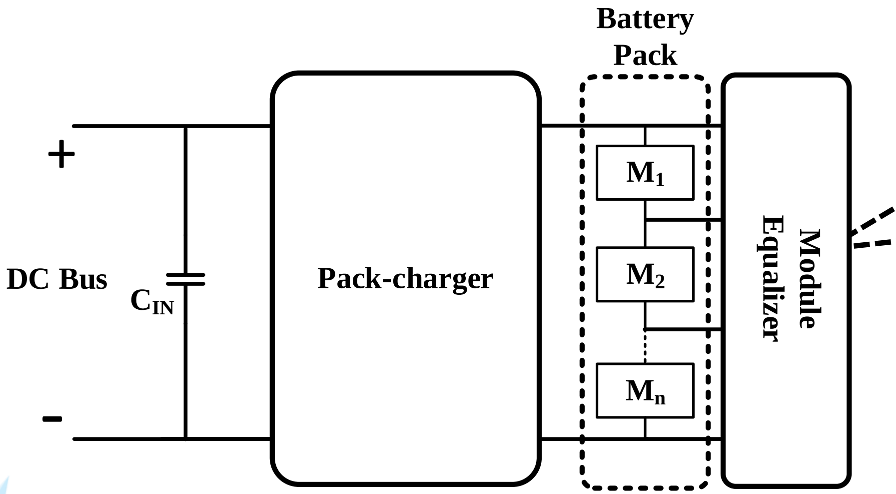


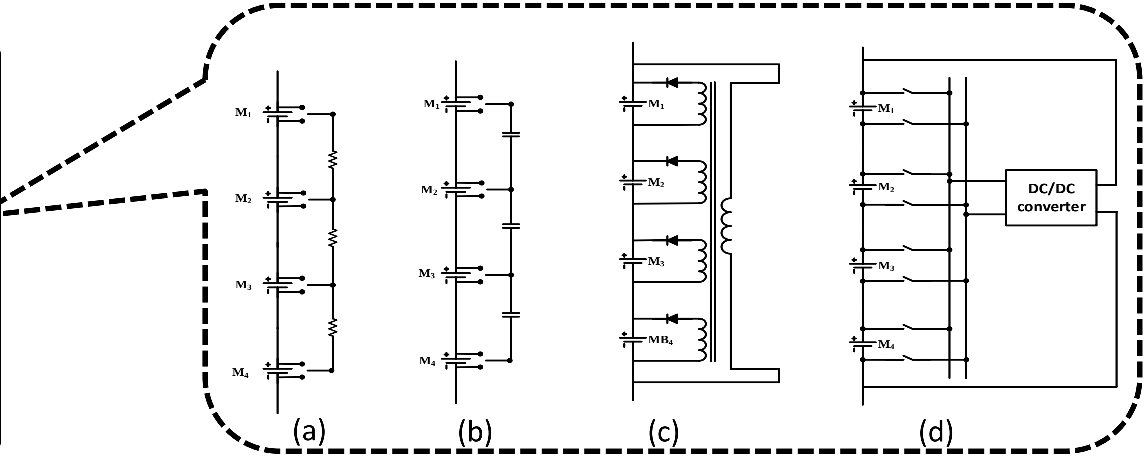
*Balancing Process*

# Introduction (3/3)

## ➢ Conventional concept – Equalizer structure

- ○ **Pack-charger** charges or discharges the whole pack while **module-equalizer** balances energy of modules.
- ○ Pack-charger and module-equalizer **are implemented separately. →** **Bulky size**
- ○ There is **no coordinated operation** between them. → **Ineffective energy management**





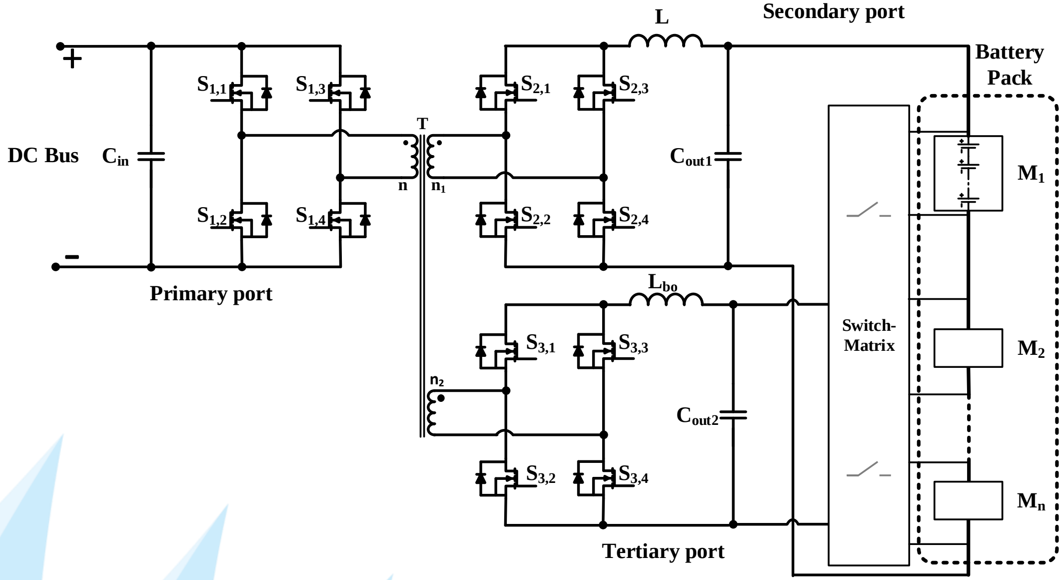
*Conventional equalizer and pack charger concept*

*Conventional equalizer structures: (a) passive; (b) active based on: switching capacitors; (c) multi-winding transformer; and (d) multiplexed dc/dc converter*

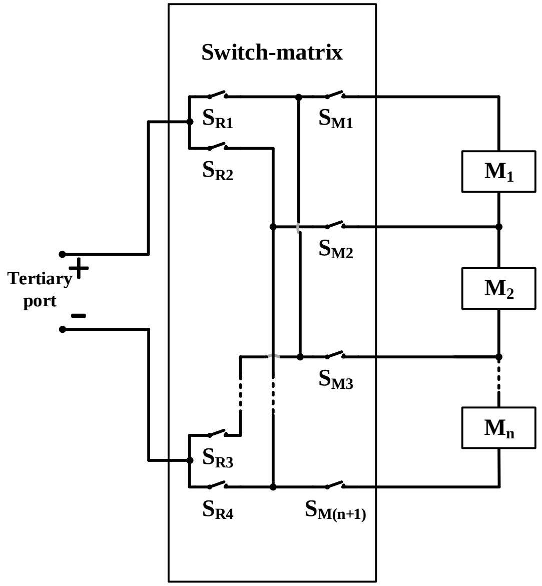
# Proposed Structure and Operation Principle (1/4)

- **Module equalizer** is **replaced by** an additional **tertiary port** in pack-charger.
  - Primary port is connected to the DC bus.
  - Secondary port is connected to the battery pack terminal.
  - Tertiary port is docked to a switch-matrix to equalize the modules.

→ **Flexibility in operation control, high performance, volume and cost reduction.**



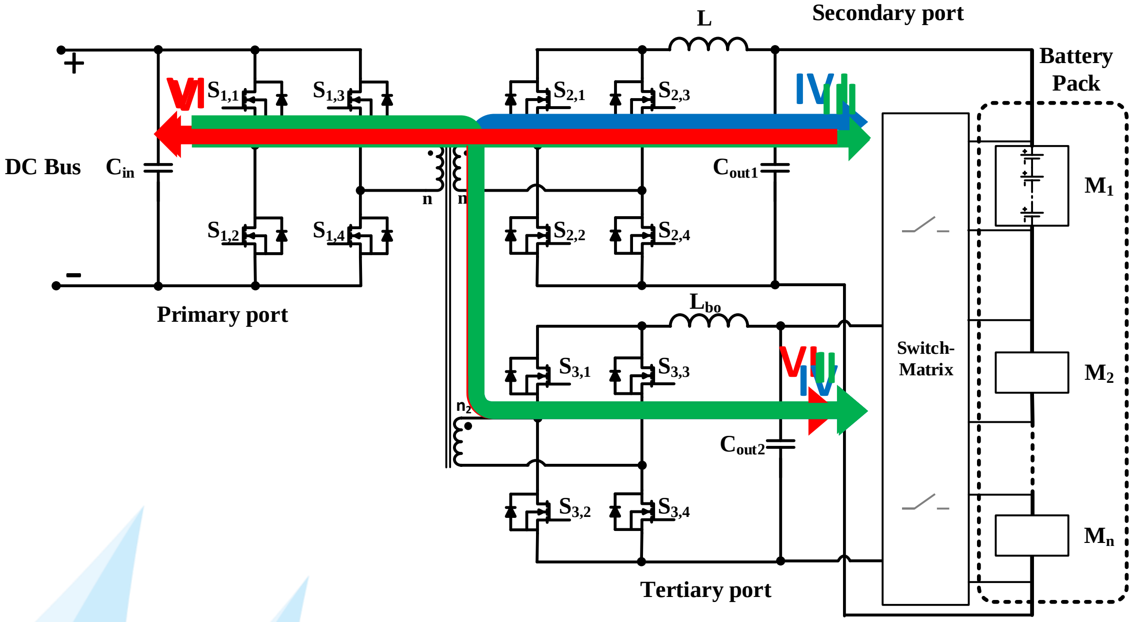
*Proposed structure*



*Structure of switch-matrix*

# Proposed Structure and Operation Principle (2/4)

- **Operation** of the symbiosis system **is flexible** due to **three-port** architecture.
- Symbiosis system can serve either as **a self-equalizer** in idle time or as **a bidirectional DC-DC converter with equalization function** in non-idle time.



*Energy flow in the symbiosis system*

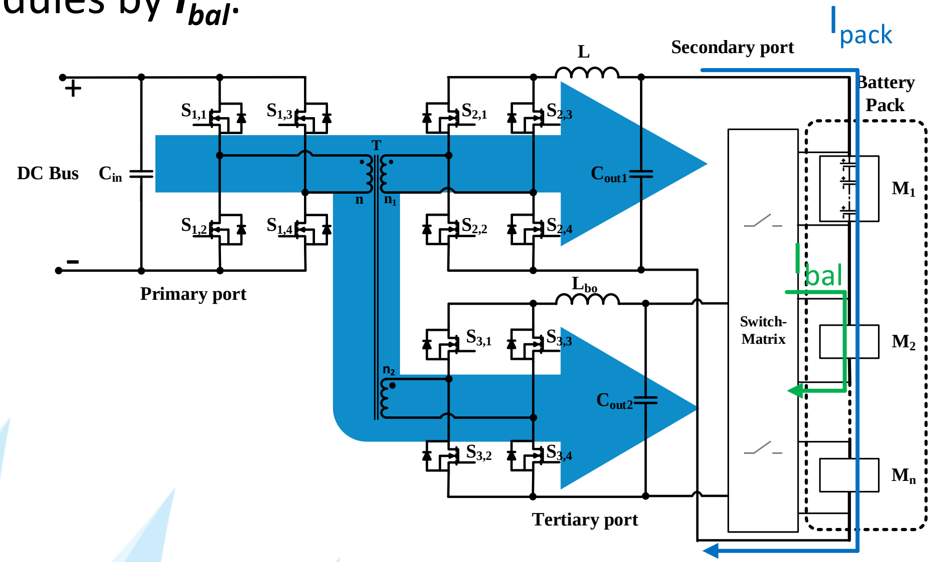
**Operation Modes**

| Mode | Operation Description |
|---|---|
| I | CC pack-charging + module-balancing |
| II | Module-balancing |
| III | CV charging |
| IV | Idle time, Self-balancing |
| V | Pack-Discharging |
| VI | Discharging process + module-balancing |

# Proposed Structure and Operation Principle (3/4)

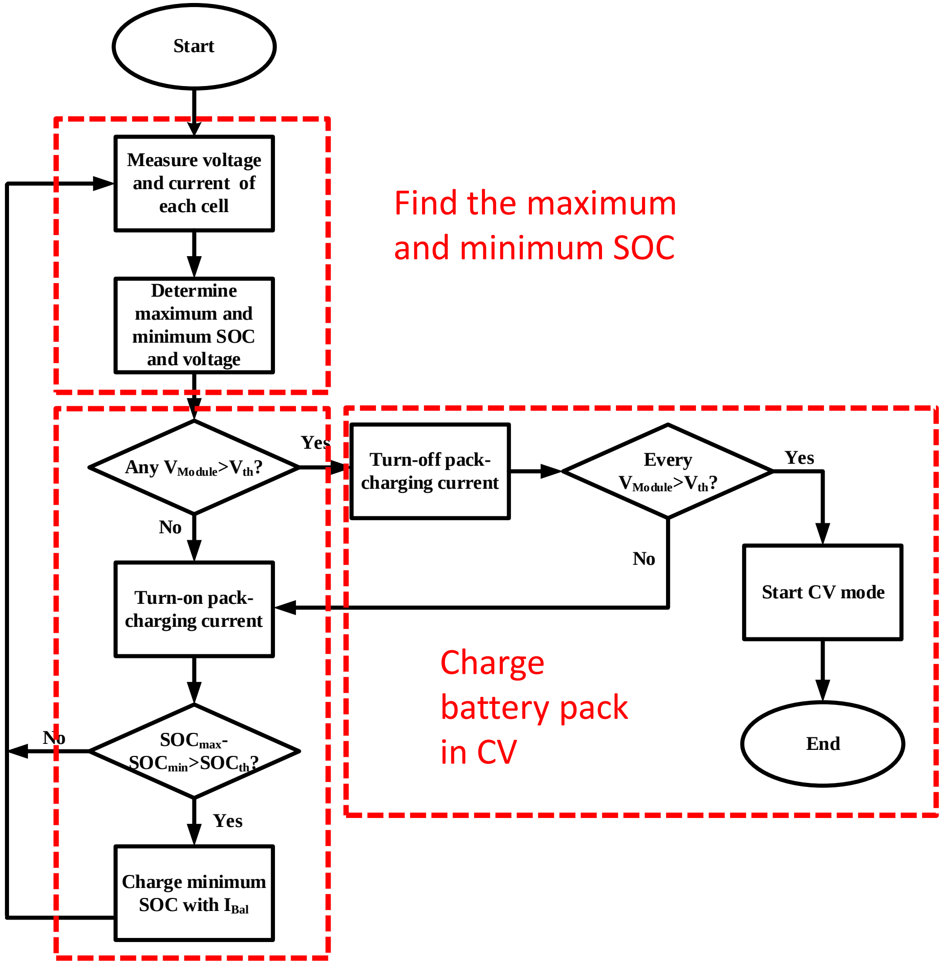
## ➢ Energy flow in charging process

- **Secondary port** supplies energy from **DC bus** to whole battery pack by $I_{pack}$.
- **Tertiary port** supplies energy from **DC bus** to one of the multiple modules by $I_{bal}$.



*Energy flow in the charging process*

Charge and equalize the unbalanced modules



Start

Measure voltage and current of each cell

Determine maximum and minimum SOC and voltage

Find the maximum and minimum SOC

Any $V_{Module}>V_{th}$?

Yes

No

Turn-off pack-charging current

Every $V_{Module}>V_{th}$?

Yes

No

Start CV mode

End

Turn-on pack-charging current

$SOC_{max}-SOC_{min}>SOC_{th}$?

No

Yes

Charge minimum SOC with $I_{Bal}$

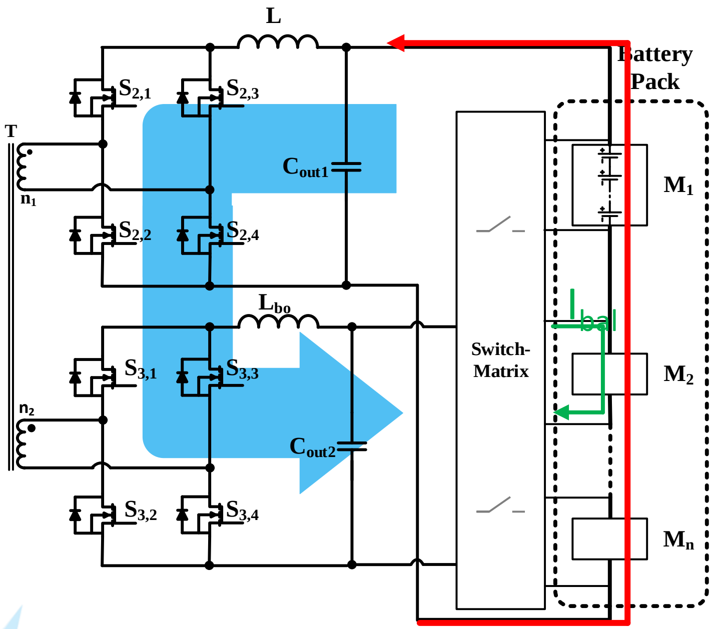
Charge battery pack in CV

*Control flowchart of charging process*

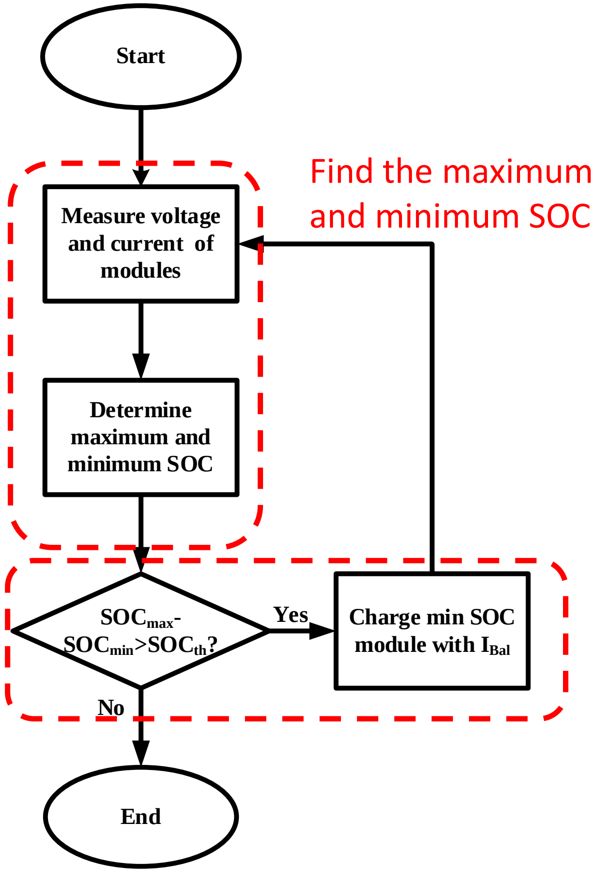
# Proposed Structure and Operation Principle (4/4)

## ➢ Energy flow in balancing process

- **Tertiary port** supplies energy from battery pack to one of the multiple modules by ***I**<sub></sub>*$I_{bal}$.



*Energy flow in the balancing process*



Find the maximum and minimum SOC

Equalize the unbalanced modules

*Control flowchart of balancing process*

# Operation Analysis (1/4)

- **Charging current analysis:** *How can we decide $I_{pack}$ and $I_{bal}$ ?*

○ Denote **α** as the ratio of $I_{bal}$ to $I_{total}$

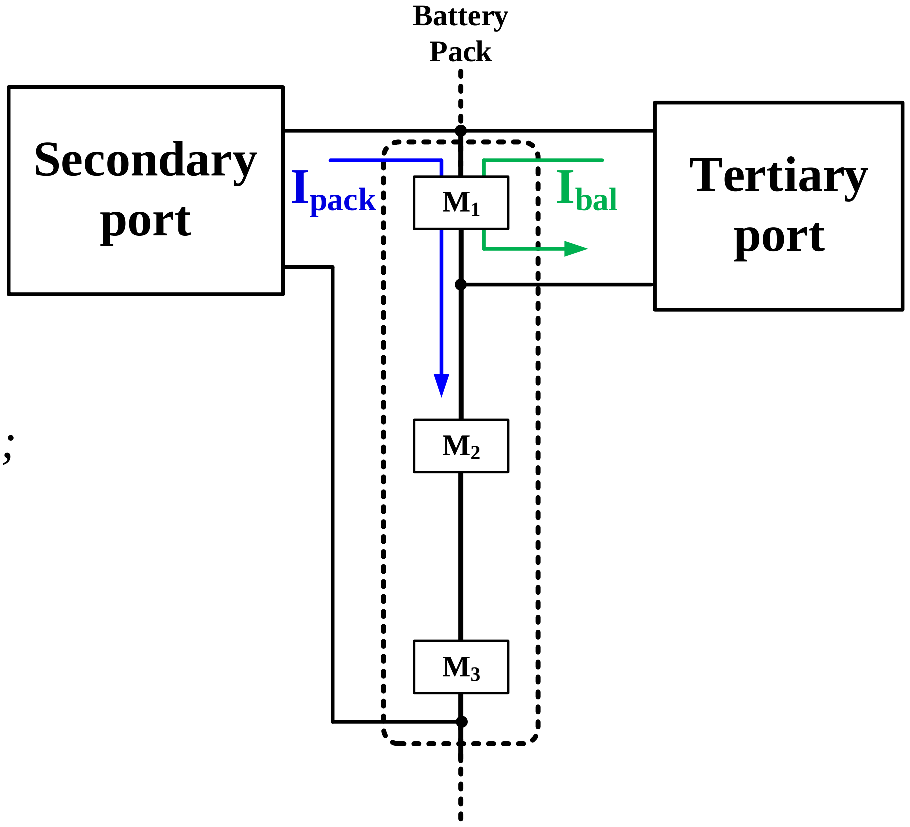
→ **Balancing current** is represented by

$$\boxed{I_{bal} = \alpha I_{total},}$$

where $I_{total}$ is sum of charging current, $I_{pack}$, and balancing current, $I_{bal}$; and it should not be larger than the maximum limit of module current.

○ **Maximum available pack-charging current** is calculated by

$$\boxed{I_{pack} = I_{total} - I_{bal} = (1-\alpha) I_{total}.}$$



*Current flow into batteries*

# Operation Analysis (2/4)

## ➢ Equalization time analysis – $t_1$

- ○ State of charge (SOC) of one battery module

$$SOC(t+\Delta t)=SOC(t)+\frac{1}{C}\int_{t}^{t+\Delta t} i(\tau)d\tau$$

where ***C*** is the module capacity; ***i(τ)*** is the inward current to the module.

- ○ ***$t_1$*** is the required time to equalize $SOC_1$ and $SOC_2$

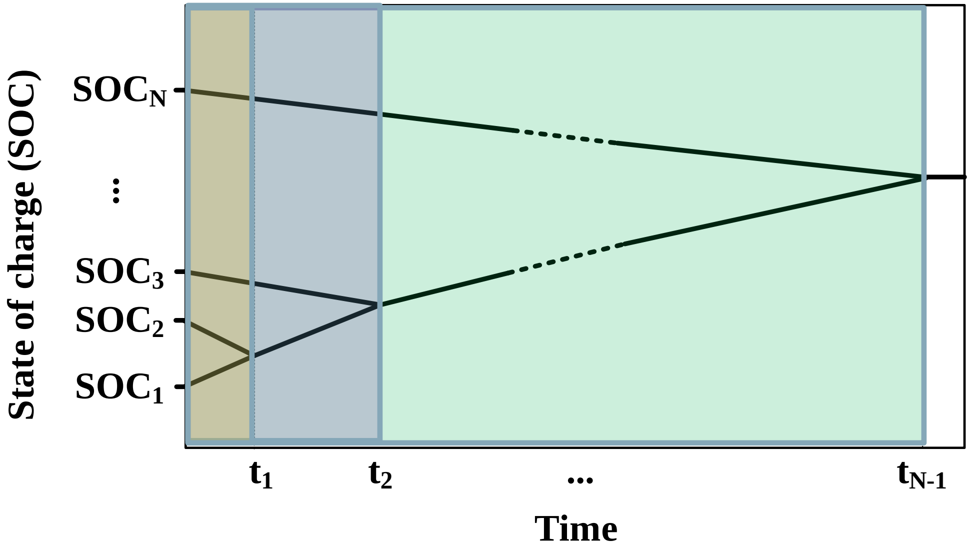
$$SOC_1(t_1)=SOC_1(t_0)+\frac{1}{C}(I_{bal}+I_{pack})t_1$$

$$SOC_2(t_1)=SOC_2(t_0)+\frac{1}{C}(I_{pack})t_1$$

$$SOC_3(t_1)=SOC_3(t_0)+\frac{1}{C}(I_{pack})t_1$$

$$\xrightarrow{SOC_1(t_1)=SOC_2(t_1)}$$

$$t_1=\frac{SOC_2(t_0)-SOC_1(t_0)}{\alpha I_{total}}C$$



*SOC curves during balancing process*

# Operation Analysis (3/4)

## ➢ Equalization time analysis – $t_2$ to $t_n$

- $t_2$ is the **required time** to **equalize SOC$_1$** and **SOC$_2$** to **SOC$_3$**,

→ **SOC level** of module **#1, #2, and #3** at $t_2$ are

$$SOC_1(t_2) = SOC_1(t_1) + \frac{1}{2C}(I_{bal} + I_{pack})(t_2 - t_1)$$

$$SOC_2(t_2) = SOC_2(t_1) + \frac{1}{2C}(I_{bal} + I_{pack})(t_2 - t_1)$$

$$SOC_3(t_2) = SOC_3(t_1) + \frac{1}{C}(I_{pack})(t_2 - t_1)$$

- Equalization time $t_2$ is calculated by

$$t_2 = 2\left[\frac{SOC_3(t_0) - SOC_1(t_0)}{\alpha I_{total}} C - \frac{1}{2} t_1\right]$$

- Generally, equalization time $t_n$ is given by

$$t_n = n\left[\frac{SOC_{n+1}(t_0) - SOC_1(t_0)}{\alpha I_{total}} C - \sum_{k=2}^{n} \frac{1}{(k-1)k} t_{n-1}\right]$$

* $n = 2, 3, \dots, N\text{-}1.$

# Operation Analysis (4/4)

## ➢ Power and energy loss:

- **Power loss** of the battery pack during the **equalizing-charging process** is calculated by

$$\boxed{\begin{aligned} P_{loss}(t) &= nR_m I_{pack}^2(t) + R_m I_{bal}^2(t) \\ &= nR_m (1-\alpha)^2 I_{total}^2(t) + R_m \alpha^2 I_{bal}^2(t) \end{aligned}}$$

where $\boldsymbol{R_m}$ is **internal resistance** of battery **modules**.

- **Energy loss** of the battery pack during the **equalizing-charging process** is calculated by

$$\boxed{E_{loss}(t) = \int_0^{t_n} P_{loss}(\tau) d\tau}$$

# Performance Verifications (1/6)

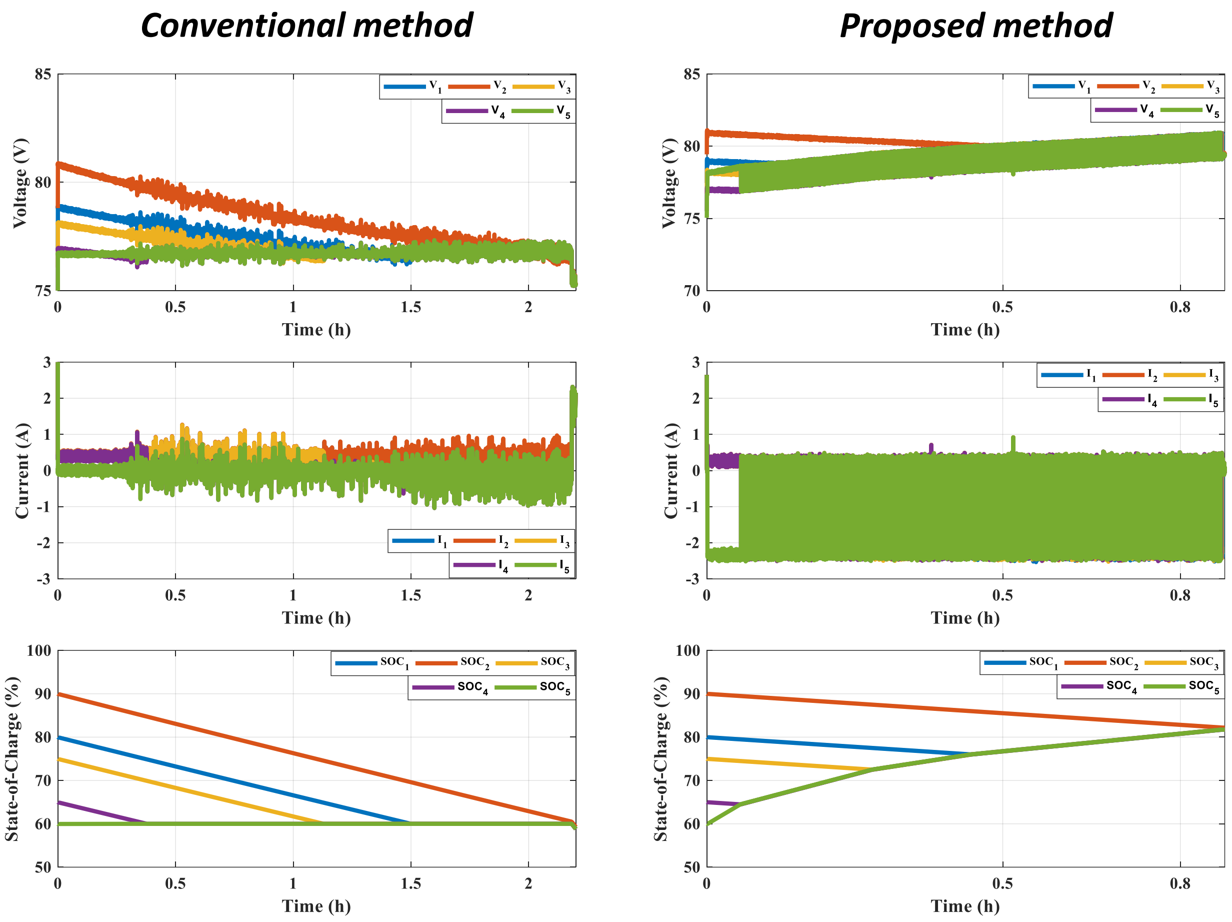
- The proposed system is compared with conventional system consisting of pack-charger and passive module equalizer.
  - Real-time simulations for **five battery modules** are implemented on **Typhoon 602+ HIL system** to verify the performance of the proposed structure.
  - One battery module consists of **20 series-connected battery cells** (18650- 3.6V/2.6A).
  - Performance of the proposed method is assessed in both **self-balancing process** and **charging modes**.

**Real-time simulation setup**

| **Conditions** | **Self-balancing** | | **Charging** | |
|---|---|---|---|---|
| | **Conventional** | **Proposed** | **Conventional** | **Proposed** |
| **Module Specification** | 20S1P, 60～84V, 2.6Ah | | | |
| **DC Bus Voltage (V)** | N/C | | 750 | |
| **$I_{total}$ (A)** | 2.6 | | | |
| **Current ratio $\alpha$** | N/A | 1 | N/A | 0.5 and 1 |
| **Balancing Current (A)** | 0.35 | $\alpha I_{total}$ | 0.35 | $\alpha I_{total}$ |
| **Initial $SOC_{1,2,3,4,5}$ (%)** | 80, 90, 75, 65, 60 | | 40, 15, 30, 35, 25 | |

# Performance Verifications (2/6) – Idle Mode

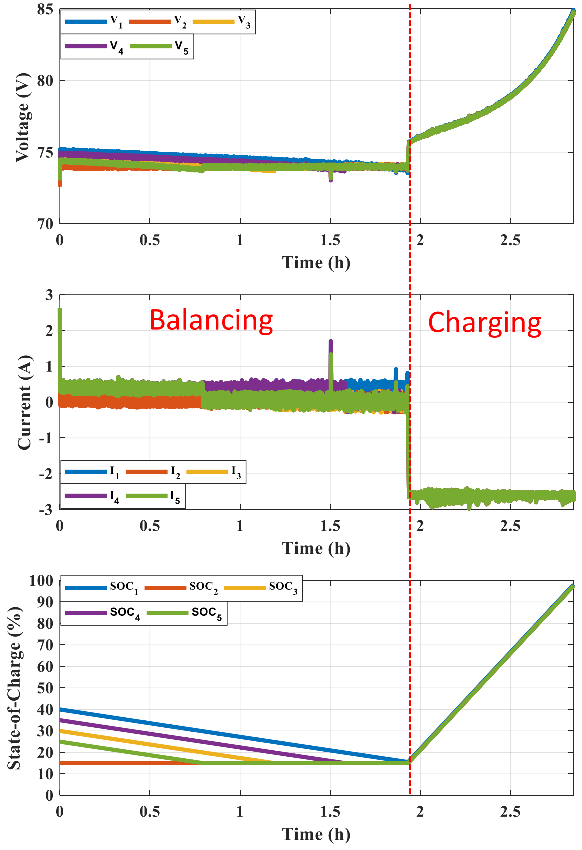
- Two methods are compared **under idle mode of operation.**
  - **Passive method** reduces the SOC level of the modules **to 60%,** which is the minimum SOC level of modules due to **dissipative operations** in the passive equalization.
  - **Proposed method** equalizes the **SOC level** of the modules at **81%** due to **regenerative operation** of the proposed method.
  - **Conventional method** requires a 2.2h longer operation time due to the insufficient balancing current.



*Module voltages, currents, and SOC profiles* ***in self-balancing process***

# Performance Verifications (3/6) – Charging Mode

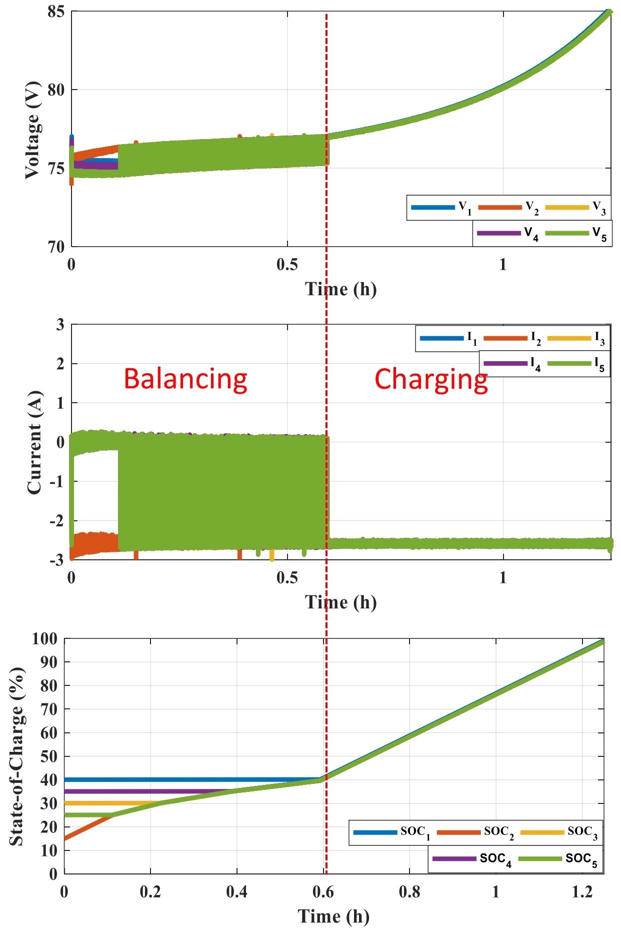
- Conventional method is tested in **charging mode of operation**.
  - Conventional method **reduces the SOC level** of the modules **to 15%** before **starting the charging process**.
  - Conventional method **takes 2h for balancing** and **1h for charging**.
  - **Operation time** is **longer** due to energy dissipation on resistors.



*Module voltages, currents, and SOC profiles of* ***conventional method in charging mode***

# Performance Verifications (4/6) – Charging Mode

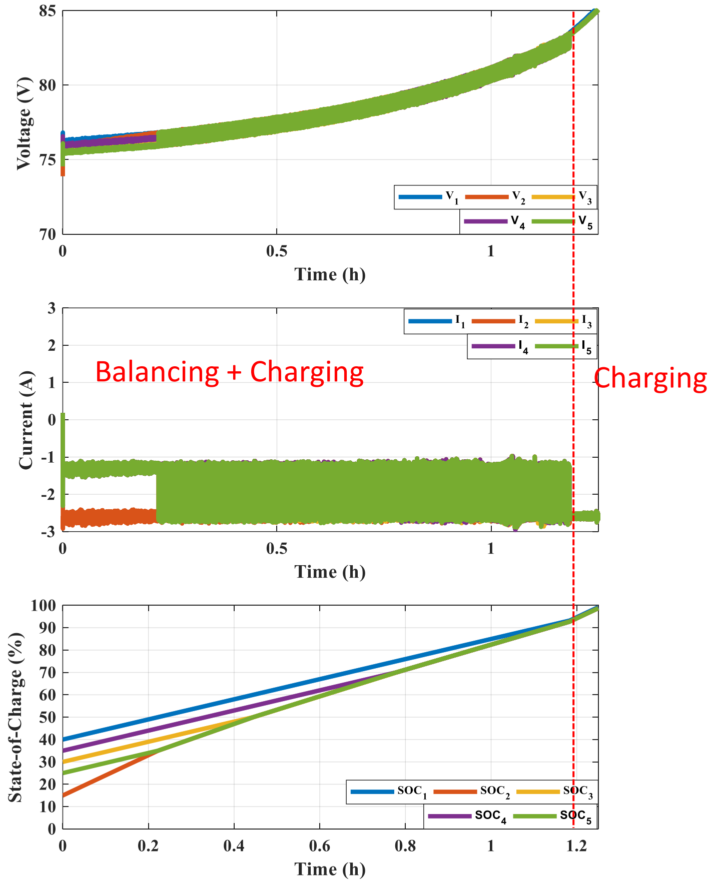
- Proposed method is tested with strategy 1 **($\alpha = 1$),** where balancing has a higher priority than charging.
- **Proposed method** balances the SOC level of the modules **to 40% before starting of the charging process.**
- **Proposed method** takes 0.6h for balancing and 0.6h for charging.
- **Operation time** is **just half of** the **conventional method**.



*Module voltages, currents, and SOC profiles of* ***proposed method with $\alpha = 1$ in charging mode***

# Performance Verifications (5/6) – Charging Mode

- Proposed method is tested with strategy 2 ($\alpha = 0.5$), where charging and balancing are operated in parallel.
  - **Proposed method conducts** the charge-equalization operation is conducted until the SOC level of the modules **to 92% before starting of the charging process.**
  - **Proposed method** takes 1.2h for balancing.
  - Charging and balancing are achieved almost at the same time.



*Module voltages, currents, and SOC profiles of*
***proposed method with $\alpha = 0.5$ in charging mode***

# Performance Verifications (6/6) – Charging Mode

- **Energy loss comparison**
  - **Proposed method can save 24.3Wh of energy** compared with conventional method.
  - In the proposed method, it is possible to **adjust α** to determine the energy loss at the price of equalization speed.
  - Energy loss when **α = 0.5 is lower by** 24.4Wh than when α = 1.
  - Further adjustment of α can **optimize the energy loss**, which will be covered in the future work.

| **Compared methods** | | **Conventional method** | **Proposed method** | |
|---|---|---|---|---|
| **C-rate (Ah)** | | 1C = 2.6 | 1C = 2.6 | |
| **Balancing current (A)** | | 0.35 | 2.6A (α = 1) | 1.3 (α = 0.5) |
| **Energy loss (Wh)** | **Charge-Equalization period** | N/A | 8.11 | 24.33 |
| | **Equalization period** | 8.09 | N/A | |
| | **Charge period** | 67.6 | 43.26 | 2.704 |
| | **Total** | **75.7** | **51.4** | **27.0** |

# Conclusions

- A novel integrated module equalizer consisting of **three-port isolated active bridge converter** is presented.
  - The primary and secondary ports exchange energy between DC bus and battery pack.
  - The primary and tertiary ports equalize modules.
- **Cooperative six modes** of operation provide **effectiveness and flexibility** in energy flow control.
  - They provide pack-charging, module-balancing, self-balancing, and pack-discharging features.
- **Real-time simulation results** for 5-modules show that:
  - Module balancing is already achieved during charging process, which is not possible in the conventional separate approach.
  - Equalization speed is **faster and energy loss is lower** than conventional method.
  - **The speed and energy loss** can be appropriately **compromised** by the adjustment of $\alpha$**.**
- **Proposed structure** is a good candidate for the **battery module equalization** in EV and BESS applications.

# Thank You for Your Listening!

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