

Research on power equalization using a low-loss DC-DC chopper for lithium-ion batteries in electric vehicle

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Abstract. In the near future, electric vehicle is entirely possible to replace traditional cars due to its zero pollution, small power consumption and low noise. Lithium-ion battery, which owns lots of advantages such as lighter and larger capacity and longer life, has been widely equipped in different electric cars all over the world. One disadvantage of this energy storage device is state of charge (SOC) difference among these cells in each series branch. If equalization circuit is not allocated for series-connected batteries, its safety and lifetime are declined due to over-charge or over-discharge happened, unavoidably. In this paper, a novel modularized equalization circuit, based on DC-DC chopper, is proposed to supply zero loss in theory. The proposed circuit works as an equalizer when Lithium-ion battery pack is charging or discharging or standing idle. Theoretical analysis and control method have been finished, respectively. Simulation and small scale experiments are applied to verify its real effect.

1. Introduction

The electric car, due to its zero pollution and small power consumption and low noise, is inevitable trend in the development of automobile industry. Recently, lithium-ion batteries have been widely equipped in different electric vehicles (EV) all over the world. Main advantages of this emerging battery include high energy density, no memory effect, and very low self-discharging. These features support the storage cell to obtain more safety, longer lifetime and lighter weight. To achieve the high power requirements, a large number of lithium-ion battery cells are applied and connected to each other in series [1]. Because of the difference on chemical and electrical characteristics, imbalance among these batteries obviously exists and leads to repeated charge and over discharge. It generates bad influence on energy storage capacity and battery lifetime [2-5]. Therefore, an equalization circuit is necessary for lithium-ion battery packs.

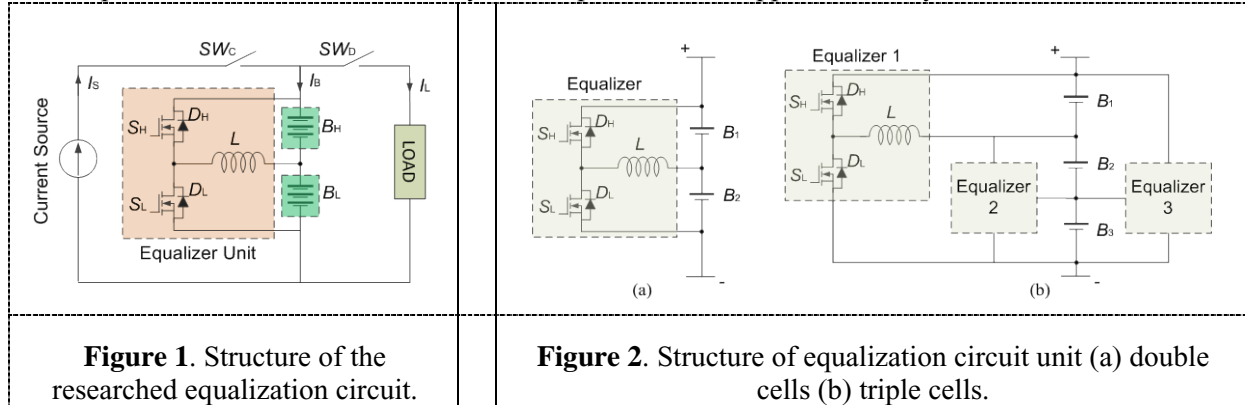
Numerous equalization circuits have already been developed, such as individual dc-dc converter, the bidirectional dc-dc converter, the switched capacitor [6-8]. Some of them can solve the imbalance problem. However, these are also suffered from long equalization time, complex circuits, control difficulty, or low efficiency when there are a large number of batteries [9-11]. This paper discusses a concept of modularized equalization for series-connected battery packs by using a low-loss DC-DC chopper. Basic principle can be described as:

- Charging state: Lower SOC batteries are charged and high power ones are bypassed.
- Discharging state: Higher SOC batteries are discharged and low power ones are bypassed.



- Standing idle state: Energy flows from high power batteries to low ones through inductor.

The mentioned modularized equalization circuit, as shown in Figure 1, can be charged by switching SWC or discharged by operating SWD. Equalizer unit includes double switches and an inductor, which works as a storage device. In theory, there is no energy consumption during the process of power regulation. To confirm its performance, theoretical analysis and control method have been developed. Simulation and four battery cells experiments are applied to verify its real effect.

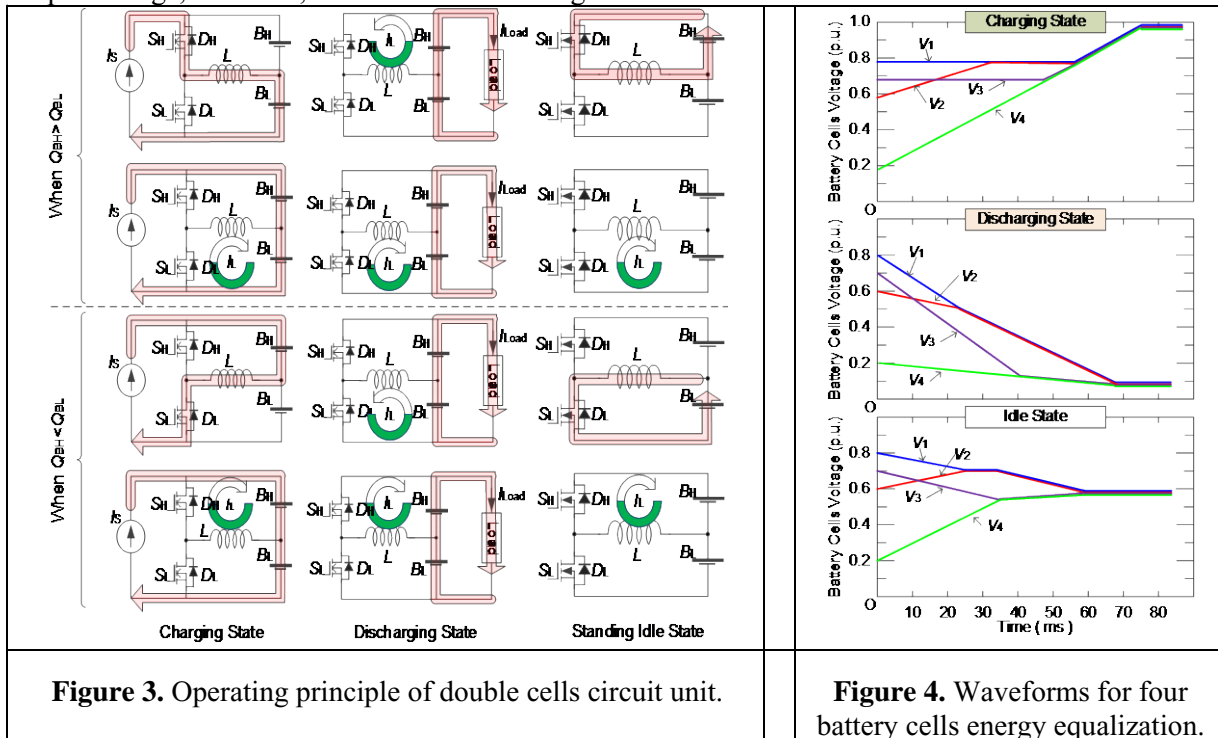


2. Low-loss DC-DC chopper used to realize energy equalization

In practice, running process of DC-DC chopper should be thought about on different states, respectively. This section discusses the circuit structure, operating principle and waveforms.

2.1. Circuit structure

In Figure 1, series-connected cells are divided into two parts, BH and BL. The number of cells included in BH or BL can be odd or even number. Smallest unit of these two parts has only one cell. Figure 2 shows two kinds of equalization circuit unit with double cells or triple cells. An expected output voltage, therefore, can be achieved through the combination of these units.



As we see, only one equalizer needed for double cells unit but three ones used in triple one. Inductor or switches in each equalizer is designed to satisfy power transmission requirements and not keep the same parameters. B_H or B_L includes several circuit units, which these number also maybe odd or even, revealed in Figure 2. Then B_H or B_L is divided into two parts again just like Figure 1. Additional equalizers can be increased between some circuit units in the adjacent position.

2.2. Operating principle

Current path, as Figure 3 shown, is displayed on different states when B_H and B_L have only one cell. If SOC of B_H is larger than B_L ($Q_{BH} > Q_{BL}$), equalization principle is introduced as follow:

- For charging state, B_H is bypassed when S_H keeps running to reduce energy charged for B_H . In other words, length of charging time is regulated to equalize B_H and B_L by controlling S_H .
- For discharging state, lower battery outputs less energy for load. It means that L is charged during S_H is opened. Inductor L is discharged and supplies a part of load current when S_H is not working. Therefore, the current supplied by B_L is decreased.
- For standing idle state, S_H is turned on to release energy stored in B_H as it higher than B_H . And B_L adopts the power stored in the inductor when S_H is turned off.

Detail process is revealed on the top of Figure 4 and another condition is also thought about. Similar principle is explained in case of $Q_{BH} < Q_{BL}$ with the difference S_L controlled only but not S_H .

For a battery pack with four series-connected cells, equalization process can be described based on the concept discussed above and shown in Figure 4. $V_1 \sim V_4$ means voltage of each cell. There are two circuit units and each one consists of double cells and an equalizer. A third equalizer is equipped between the two circuit units. Form the curves in Figure 4, V_1 and V_2 or V_3 and V_4 firstly reach the same voltage point before all of these are equalized.

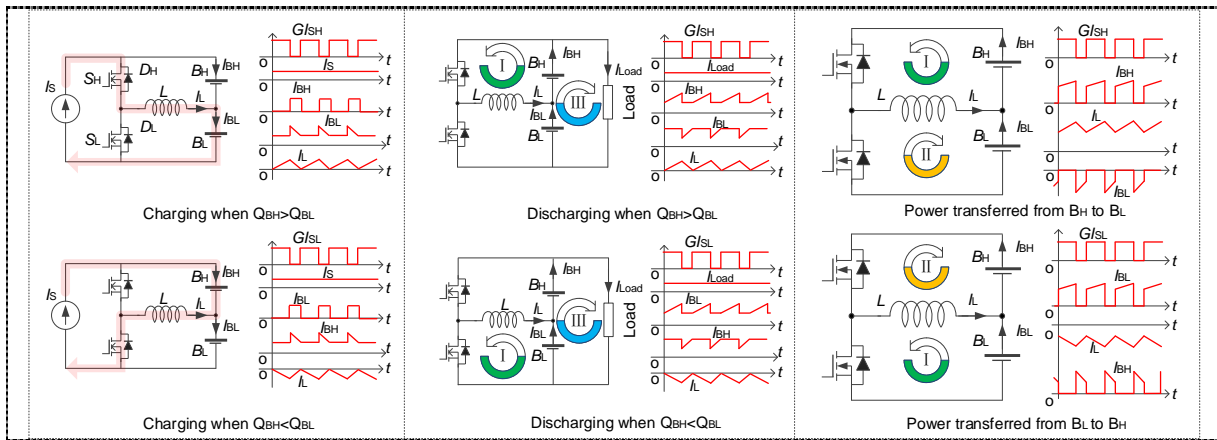


Figure 5. Waveforms of each state for double cells circuit unit.

2.3. Waveforms and mathematic model

Generally speaking, terminal voltage is an important factor for SOC evaluation of Lithium-ion batteries. It is also a key standard for energy equalization. Voltage of each cell is defined as V_i ($i=1, 2, \dots, 2n$). Then each voltage of circuit unit is $V_j + V_{j+1}$ ($j=1, \dots, 2n-1$) and voltage of x circuit units is $V_k + \dots + V_{k+x}$ ($k=1, \dots, 2n-x$). Figure 5 presents the equalization control process of battery packs. In a circuit unit, each cell's current of different states is formulated as follow:

$$\text{Charging State} \begin{cases} i_{BH} = 0 & \& i_{BL} = I_{CS}, & t \in [0, DT) \\ Q_{BH} > Q_{BL} & i_{BL} = i_{BH} + I_{CS} - V_{BL} \cdot (t - DT) / L_1, & t \in [DT, T] \end{cases} \quad (1)$$

$$\text{Discharging State} \begin{cases} i_{BH} = i_{BL} + V_{BH} \cdot t / L_1 & \& i_{BL} = I_{Load}, & t \in [0, DT) \\ Q_{BH} > Q_{BL} & i_{BL} = i_{BH} - [(V_{BH} + V_{BL}) \cdot DT - V_{BL} \cdot t] / L_1, & t \in [DT, T] \end{cases} \quad (2)$$

$$\text{Standing Idle State} : \begin{cases} i_{BL} = 0 & \& i_{BH} = V_{BH} \cdot t / L_1, & t \in [0, DT) \\ Q_{BH} > Q_{BL} & i_{BL} = [(V_{BH} + V_{BL}) \cdot DT - V_{BL} \cdot t] / L_1, & t \in [DT, T] \end{cases} \quad (3)$$

Where, L_1 means the inductor in circuit unit, and corresponding equations can be easily deduced in the case of $Q_{BH} < Q_{BL}$. For double circuit units or n double circuit units, all circuit units are divided into two parts just like B_H and B_L . They also satisfy the above equations.

3. Strategy for system equalization control

For the circuits revealed in Figure 2, two kind of strategies, including modularized equalization control (MEC) and energy averaging control (EAC), are developed to realize system equalization control. MEC has the advantage on accuracy but suffer with slower response. To the contrast, EAC has the opposite characteristics.

3.1. Modularized equalization control

Each branch of battery packs can be divided into N double cells and M triple cells circuit units. By using modularized equalization control, every circuit unit is self-regulated at first. Then adjacent circuit units start to transfer electric power when the double cells' SOC reach a same value. Therefore, four circuit units can be equalized after the former two and the latter two finished equalization. In conclusion, MEC is actually hierarchical control and Figure 6 shows its schematic.

In any circuit unit, V_A , V_B and V_C are cells voltage. Output voltage of this unit is $V_A + V_B + V_C$ and each cell's voltage equals to $(V_A + V_B + V_C) / 3$ after it equalized. Double cells unit only have V_A and V_B . Total equalization times can be described as follow:

$$\begin{cases} P(x) = \text{int}[x], e.g. P(\frac{10}{3}) = 3 \\ P_i = \text{int}[\frac{M+N}{2^{i-1}}], P_1 = M+N \\ T_{MEC} = \sum_{i=1}^D P_i \& \text{int}[\frac{M+N}{2^{D-1}}] = 1 \end{cases} \quad (4)$$

Where $P(x)$ is an aliquot function, P_i is the equalization times for each stage, T_{EMC} is the total times.

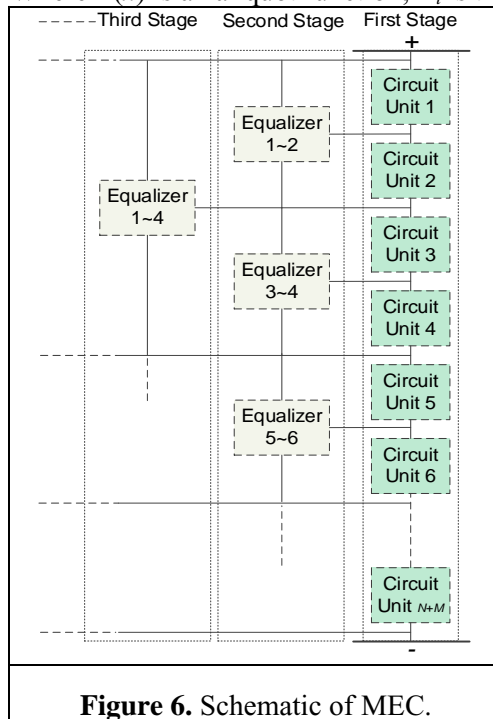


Figure 6. Schematic of MEC.

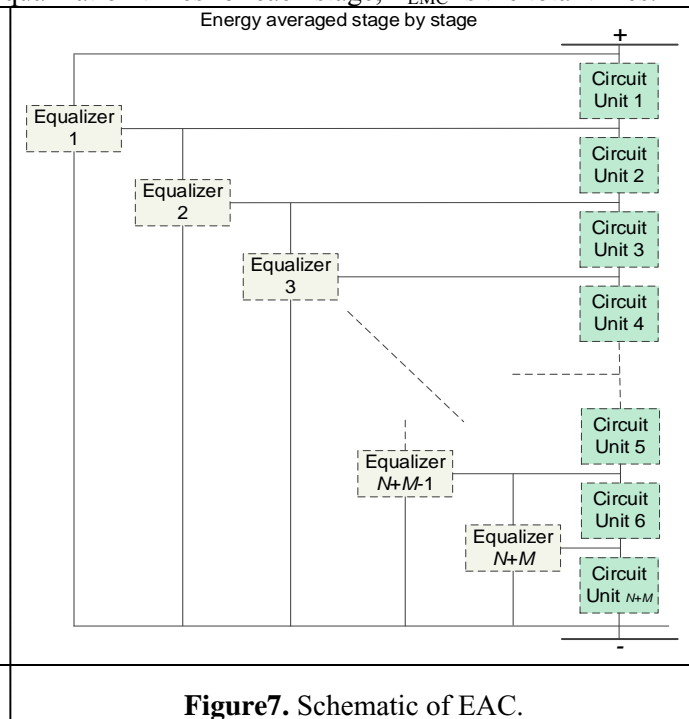


Figure7. Schematic of EAC.

3.2. Energy averaging control

For the same branch with $M+N$ circuit units, excess energy stored in unit τ is directly transferred to unit $\tau+1$ to $M+N$ (or unit $\tau-1$ to 1) by using energy averaging control and as shown in Figure 7. The maximum value of total equalization times can be described as follow:

$$T_{EAC-max} = (M + N) + 0.5(M + N) \quad (5)$$

3.3. Hybrid equalization control

Both of MEC and EAC have obviously features on control accuracy and response speed. A hybrid equalization control (HEC) is developed to improve control accuracy and promote response speed simultaneously. In HEC, only stage one and stage two are controlled by MEC. EAC is applied to the rest stages. So the total equalization times can be described as follow:

$$T_{HEC-max} = (M + N) + 0.5(M + N) + 0.25(M + N) \quad (6)$$

Furthermore, charging and discharging times of a single cell, not only each circuit, is reduced a lot compared to MEC or EAC. Then process of battery packs equalization is improved and it works more safety due to less loss and cooling difficulty.

Table 1. Characteristics of the simplified model

Category	Parameters	Values
Equalizers	MOSFETs, S_H or S_L $\times 14$	20 A, 100 V
	Inductor, $L \times 7$	100 μ H
Batteries $\times 8$	Cell's Rated Voltage, V_0	3.2 V
	Cell's Rated Capacity, Q	3000 mAh
Control Variables	Frequency, f	10 kHz
	Reference Error Voltage, ΔV_{REF}	10.0 mV
	Charging Stop Voltage, V_{max}	3.6 V
	Discharging Stop Voltage, V_{min}	2.5 V

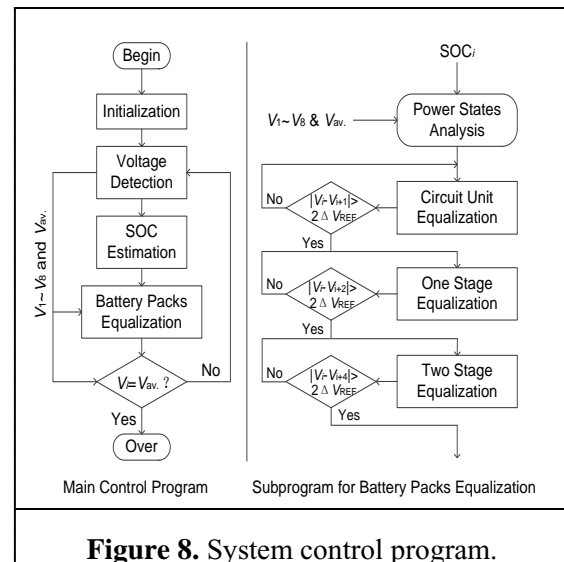


Figure 8. System control program.

4. Verifications

The concept of batteries equalization discussed above is validated using a simplified eight cells circuit in this section. Parameters and control method are designed for the experimental circuit. Then simulation and experiment results have been completed, respectively.

4.1. Small-scale equalization circuit design

A small-scale model, including seven equalizers and eight battery cells, has been established and main parameters are displayed on table 1. Applying the HEC strategy, detail running process is revealed in Figure 8. The left side is main program and the right one is subprogram.

4.2. Performance verification

Simulation and experimental verifications have been finished, respectively. To any circuit unit in the case of $QBH > QBL$ on different states, current waveforms comparison has been shown in Figure 9 (left part is simulation results, right part is experimental results). These results are obviously consistent with the theory analysis shown in Figure 5. Table 2 reflects the effect of voltage equalization for the eight series-connected battery cells. It also supports the equalization concept proposed in this paper.

Dissipated power loss, compared to traditional circuit which usually connects a resistor, has been discussed during the process of SOC regulation in practical application. Loss types mainly include line loss, loss of semiconductor devices, resistor loss and inductor loss (coil resistance). Comparative

analysis, as revealed in Figure 10, has been completed to verify the effect of loss reduction. Obviously, the saving loss has been moved to other battery cells but not consumed by resistor.

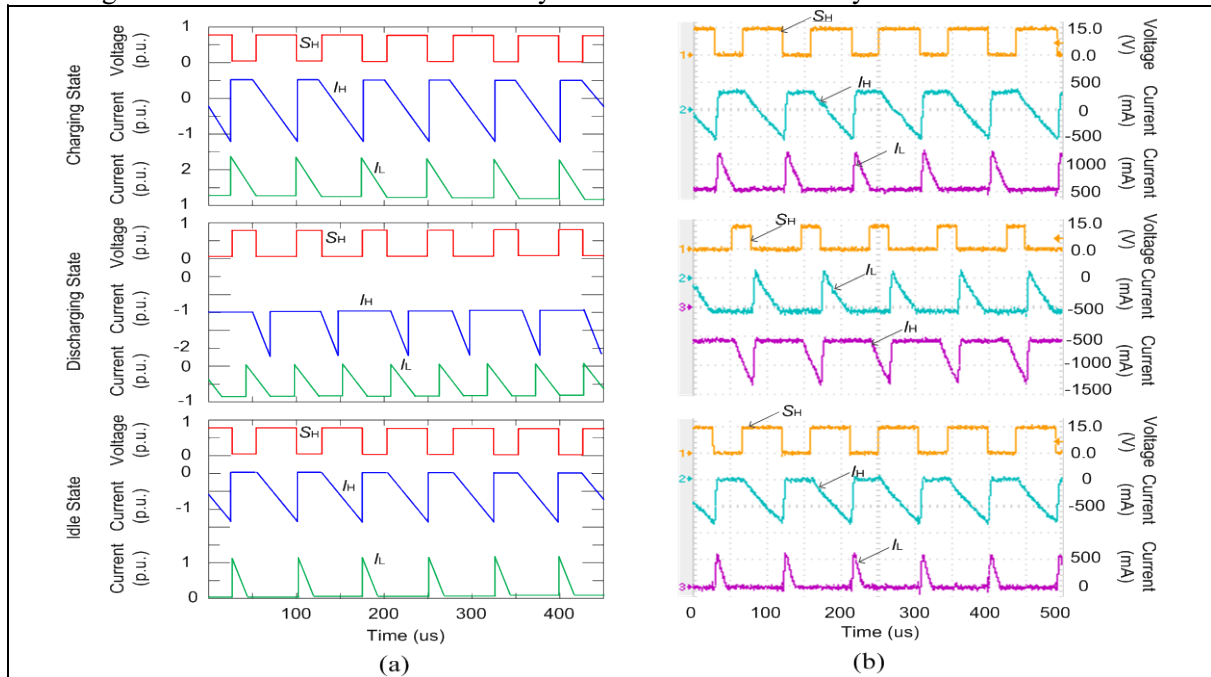


Figure 9. Verification results (a) By simulation (b) By experiments.

Table 2. Experimental results of equalization process.

Battery Cells	Charging State/Time point, ms					Discharging State/Time point, ms					Standing Idle State/Time point, ms				
	0	10	20	30	40	0	10	20	30	40	0	10	20	30	40
B_1	2.90	3.20	3.35	3.50	3.60	2.90	2.80	2.75	2.60	2.50	2.90	2.70	2.70	2.80	2.95
B_2	2.50	3.10	3.37	3.50	3.60	2.50	2.50	2.50	2.50	2.50	2.50	2.70	2.70	2.80	2.95
B_3	2.60	3.12	3.36	3.50	3.60	2.60	2.60	2.60	2.55	2.50	2.60	2.70	2.70	2.80	2.95
B_4	2.80	3.20	3.38	3.49	3.60	2.80	2.79	2.75	2.60	2.50	2.80	2.70	2.70	2.80	2.95
B_5	3.10	3.30	3.45	3.56	3.60	3.10	3.00	2.80	2.62	2.50	3.10	3.30	3.25	3.10	2.95
B_6	3.50	3.60	3.70	3.60	3.60	3.50	3.00	2.80	2.62	2.50	3.50	3.30	3.25	3.10	2.95
B_7	3.00	3.20	3.35	3.58	3.60	3.00	2.90	2.80	2.63	2.50	3.00	3.20	3.25	3.10	2.95
B_8	3.40	3.50	3.57	3.62	3.60	3.40	3.00	2.80	2.61	2.50	3.40	3.20	3.25	3.10	2.95

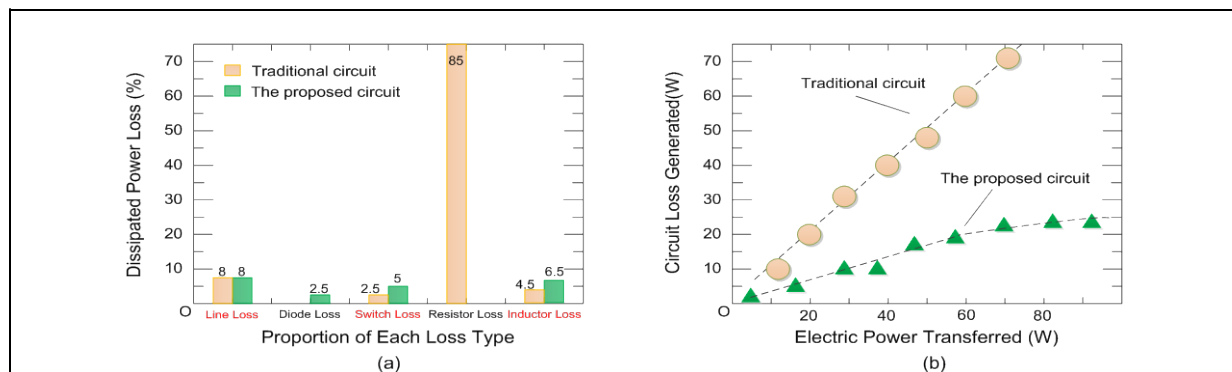


Figure 10. Power loss analysis by comparison (a) Loss proportion (b) Loss reduction effect.

5. Conclusion and future works

This work, applied a DC-DC chopper, plans to decrease the loss of energy equalization for lithium-ion batteries in electric vehicle. Advantages of the researched method include simple circuit structure, high accuracy and less loss. Stability of energy control effect has been verified by simulation and small-scale experiments. SOC estimation technique, which is also important as well as equalization circuit, must be developed in the future.

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