Average Modeling of the Switched-Passive-Network Equalizer for Effective Large-scale Battery Simulation

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ABSTRACT

Switched-passive-network equalizers are the most promising equalization techniques for series-connected battery cells. Because the switching period is much smaller than the chemical time constant of the battery, the equalization process cannot be effectively simulated by the traditional circuit simulation software. This paper presents the average models of the two most common topologies: the switched-capacitor, and the switched-resonance equalizers. By applying the average models to the simulations, the equalization process of a large-scale battery pack can be executed. The simulation results are compared with the results of a real-time simulation system, which is very expensive and optimized for heavy computations. It is proved that the average-model-based simulations have almost accurate as the results obtained from the real-time simulator while the execution time is very fast. Besides, the proposed method is very simple and cost-effective for equalizer development.

Keywords: Average modeling, switched-passive-network, real-time test, large-scale battery simulation.

1. INTRODUCTION

Battery equalization is a critical function in the battery management system (BMS) to reduce the impact of battery inconsistency. The importance of the equalization methods is emphasized in second-life battery applications when the cell's characteristics become seriously mismatching [1]. The first step of the equalizer development is an operating simulation to assess the performances. Although the conventional software can simulate the transient and switching waveforms of the circuit well, the completely process of charging, discharging, or balancing operations takes a long execution time and suffers from the memory limitation of the computer.

There are two approaches to overcome the memory limitation. Firstly, a hardware-in-the-loop (HIL) test system can be used to emulate the equalizer circuit and battery [2]-[3]. It helps the simulations can be executed in real-time to assess the performance of the equalizer in a large-scale battery pack. However, the HIL system has a limited number of cores to ensure the real-time process. Besides, the cost is another barrier to popularize the HIL system. Secondly, the capacity of the battery can be scaled down to reduce the simulation time. However, the battery characteristics are changed accordingly since battery capacity is reduced. (Different OCV-SOC curve and impedance.)

By the way, the switching elements can be replaced by an average model. For example, the switched-capacitor (SC) [4] and switched-resonance (SR) [5] equalizers can be emulated by an impedance block in Fig. 1. Since the voltage of the two battery cells is mismatched, there is a current flow from the higher-SOC cell to the lower one. The charge transfer mechanism is similar to the operation principle of both SC and SR equalizers.

This paper presents the average models for the SC and SR equalizer and applies them to the classical structure of SC and SR equalizers. The detailed models of the SC and SR are presented in Section 2 and verified in Section 3. Finally, the conclusion is made in Section 4.

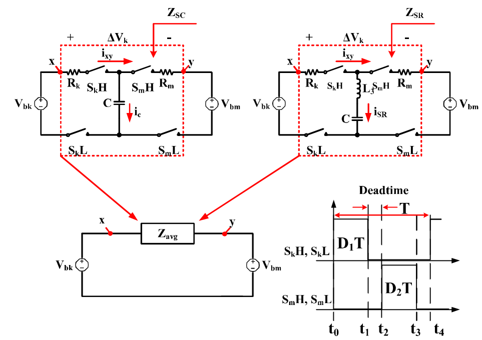

***Fig. 1**: Average model of the switch-capacitor and switched-resonance equalizers.*

2. PROPOSED METHOD

To execute a long-time simulation, switching components should be replaced by average models (AM). If the SC and the SR equalizers can be emulated by single impedance unit, energy is transferred from the higher voltage battery cell to the lower one until the voltage deviation is equalized. The configuration of the average model is dependent of the equalizer's structure. In this paper, the average models of the SC and the SR cells are applied for two classical structures in Fig. 2. The calculation of the average impedance is presented as follows.

2.1. Switched-Capacitor Equalizer

According to the analysis in [4], the apparent power of the equalizer is calculated by

$$\tau_1 = R_1 C \tag{1}$$

$$\tau_2 = R_2 C \tag{2}$$

$$S = I_{c\_rms}^2 \frac{1}{f_s C} \frac{exp\left(\frac{D_1}{f_s\tau_1}\right) exp\left(\frac{D_2}{f_s\tau_2}\right) - 1}{\left[exp\left(\frac{D_1}{f_s\tau_1}\right) - 1\right]\left[exp\left(\frac{D_2}{f_s\tau_2}\right) - 1\right]}, \tag{3}$$

where R_1 and R_2 are the total resistances of the left-hand and right-hand sides of the switching cell; I_{c_rms} is the rms current flow through the equalizing capacitor; f_s is the switching frequency of the equalizer; C is the equalizing capacitance of the circuit; D_1 and D_2 are the duty cycle of the equalizer in two phases. The apparent power of the AM also is calculated by

$$S = I_{c\_rms}^2 Z_{SC}, \tag{4}$$

where Z_{sc} is the equivalent impedance of the SC equalizer. Hence, the impedance of the SC equalizer is calculated by

$$Z_{SC} = \frac{1}{f_s C} \frac{exp\left(\frac{D_1}{f_s\tau_1}\right) exp\left(\frac{D_2}{f_s\tau_2}\right) - 1}{\left[exp\left(\frac{D_1}{f_s\tau_1}\right) - 1\right]\left[exp\left(\frac{D_2}{f_s\tau_2}\right) - 1\right]}. \tag{5}$$

If $D_1 = D_2 = D$ and $\tau_1 = \tau_2 = \tau$, Z_{sc} becomes

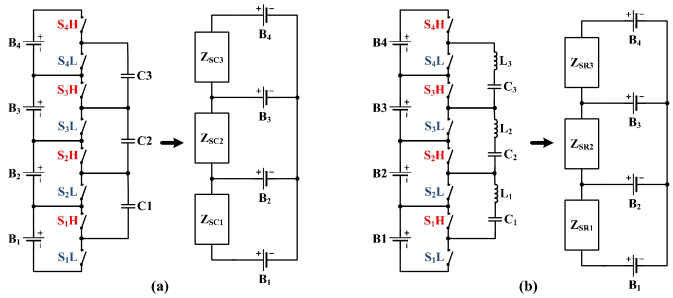

Fig. 2: *Switching cells and its average models: (a)switched-capacitor equalizer; (b)switched-resonance equalizer.*

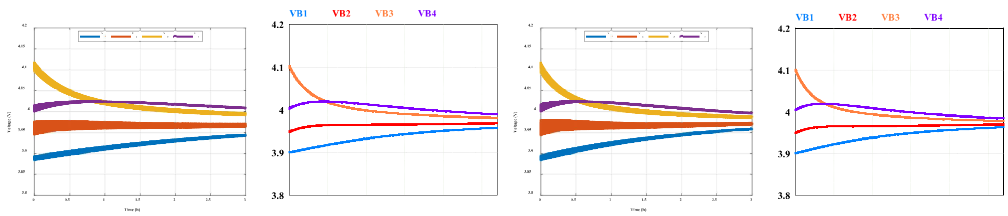

Fig. 3: *Simulation results of the average model vs real-time simulator: (a) real-time simulator of SC equalizer; (b) average model of SC equalizer; (c) real-time simulator of SR equalizer; (d) average model of SR equalizer*

TABLE 1: *SIMULATION SETUPS*

	SC-E	***SR-E***
Real-time simulator	f_s = 20kHz C = 2200uF R = 0.1Ω D = 0.45	f_s = 15kHz C = 200uF L = 0.47uH R = 0.1Ω
Avg. Imp. on PSIM	Z_{SC} = 0.45Ω	Z_{SR} = 0.36 Ω
Init SOC	$SOC_{1,2,3,4}$ =70, 80, 95, 85	

$$Z_{SC} = \frac{1}{f_s C}\frac{1 + exp\left(\frac{-D}{f_s \tau}\right)}{1 - exp\left(\frac{-D}{f_s \tau}\right)}\,. \tag{6}$$

2.2. Switched-Resonance Equalizer

Similarly, the average impedance of the SR can be calculated by the following equations [5].

$$\beta = \frac{R}{2L} \tag{7}$$

$$\omega_r = \sqrt{\frac{1}{LC} - \beta^2} \tag{8}$$

$$Z_{SR} = \frac{1}{f_s C}\frac{1 + exp\left(\frac{-\beta\pi}{\omega_r}\right)}{1 - exp\left(\frac{-\beta\pi}{\omega_r}\right)} \tag{9}$$

where L, C, and R are the resonance inductance, capacitance, and total circuit resistance, respectively; ω_r is denoted as the resonance angular frequency.

3. VERIFICATION

To verify the average models, simulations for four series-connected 18650 Li-ion battery cells (3.6V/2.6A) are executed on PSIM. On the other hand, the equalizers are emulated on a real-time simulation system as a reference. The setups on PSIM and real-time systems are summarized in Table I.

The equalization process is stopped after 3h simulation time to assess the performance. The voltage profiles of the simulations are illustrated in Fig. 3 to compare the results on the PSIM and the real-time simulation system. Although the final voltage deviation on PSIM simulation is slightly smaller than the real-time simulation, the behavior of the equalizers is almost the same. On the other hand, the HIL system requires 3h execution time to finish the equalization process, while the model-based simulation only requires 1 minute. Hence, the average model of the SC and the SR equalizers can be used to assess the performance of the equalizers during a long equalization process.

4. CONCLUSION

This paper introduces the average models for the SC and SR equalizer cells to assess the performance of the equalization methods. By replacing the switching components with the average models, simulations of a large-scale battery system is possible without resorting to expensive HIL system. The simulation results show the similarity between the real-time simulation results and the simulation on PSIM. Thus, it is expected that the average model can be an effective method to develop the battery equalizer with reduced the simulation time.

ACKNOWLEDGMENTS

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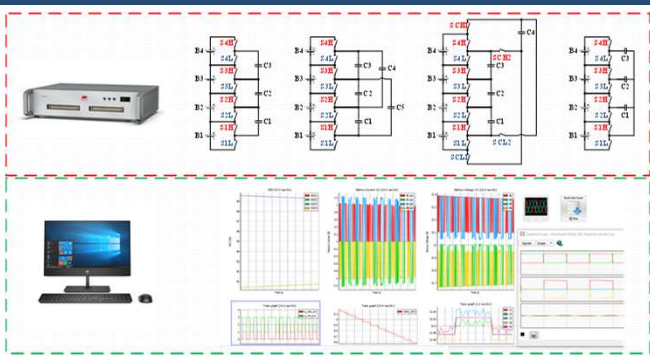
Summary

- **Equalizer** is required to **eliminate the cell inconsistency**.
- Simulation is the first step in the development process of the equalizer.
- **Traditional simulation software** cannot simulate **a long equalization process** due to the **limitation of memory**.
- **Average modeling** of the **switched-passive-network** is proposed to **simulate** the equalizing process of a **large capacity battery pack** with the advantages:
  - It can be applied for a **long equalization process**.
  - It only requires a **short execution time** to finish the simulation.
  - It shows the **similarity** in term of **equalization performance** to the **real-time simulator.**

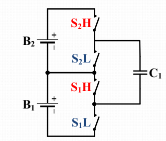
Research Motivations



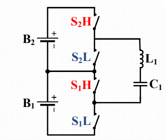
- **Real-time simulator system (RTSS)** can simulate the **equalization process** of the battery **accurately** and **vividly**.
- **RTSS** has a **limit number of core** that **limit number of components** in the simulation.
- **RTSS** is quite **expensive** that prevent **its popularization**.
- **Traditional simulation software** as PSIM or Plecs **cannot simulate** a **long equalization time** due to **the limited memory of PC**.
- **Capacity** of the battery **can be scaled-down** but the **operation of equalizer becomes not correct**.

Average Modeling of Switched-Passive-Network

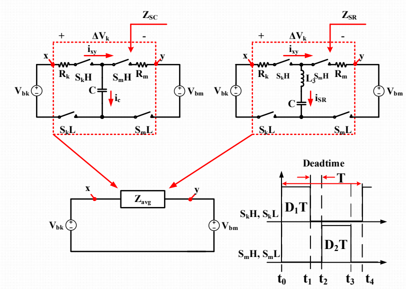
❖Average modeling – The concept



Switched-Capacitor Equalizer



Switched-Resonance Equalizer



Concept of Average Modeling

- **Switching components** is replaced by **average model.**
- **Switched-capacitor** and **switched-resonance equalizers** can be emulated by an **impedance unit**.
- **Operation principle** of **average model** and the **actual equalizer** are similar.

❖Average impedance of Switched-Capacitor equalizer

- **Apparent power of the equalizer:**

$$\tau_1 = R_1 C \tag{1}$$

$$\tau_2 = R_2 C \tag{2}$$

$$S = I_{c\_rms}^2 \frac{1}{f_s C} \frac{exp\left(\frac{D_1}{f_s\tau_1}\right)exp\left(\frac{D_2}{f_s\tau_2}\right)-1}{\left[exp\left(\frac{D_1}{f_s\tau_1}\right)-1\right]\left[exp\left(\frac{D_2}{f_s\tau_2}\right)-1\right]} \tag{3}$$

- **Apparent power also can be calculated by:**

$$S = I_{c\_rms}^2 Z_{SC}, \tag{4}$$

- **Average impedance of SC-E**

$$Z_{SC} = \frac{1}{f_s C} \frac{exp\left(\frac{D_1}{f_s\tau_1}\right)exp\left(\frac{D_2}{f_s\tau_2}\right)-1}{\left[exp\left(\frac{D_1}{f_s\tau_1}\right)-1\right]\left[exp\left(\frac{D_2}{f_s\tau_2}\right)-1\right]} \tag{5}$$

- When $D_1 = D_2 = D$ and $\tau_1 = \tau_2 = \tau$, Z_{sc} becomes

$$Z_{SC} = \frac{1}{f_s C} \frac{1+exp\left(\frac{-D}{f_s\tau}\right)}{1-exp\left(\frac{-D}{f_s\tau}\right)} \tag{6}$$

❖Average impedance of Switched-Resonance equalizer

- **Similar to SC-E, average impedance of SR-E is calculated by**

$$\beta = \frac{R}{2L} \tag{7}$$

$$\omega_r = \sqrt{\frac{1}{LC} - \beta^2} \tag{8}$$

$$Z_{SR} = \frac{1}{f_s C} \frac{1+exp\left(\frac{-\beta\pi}{\omega_r}\right)}{1-exp\left(\frac{-\beta\pi}{\omega_r}\right)} \tag{9}$$

Simulation Results

TABLE 1: SIMULATION SETUPS

	SC-E	SR-E
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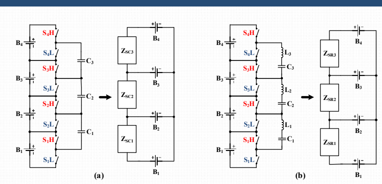
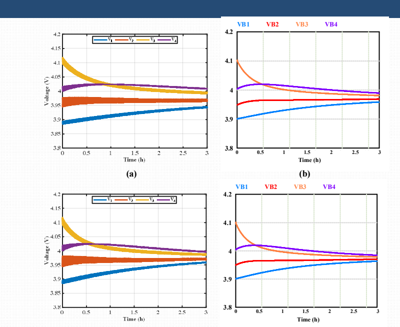


Switching cells and its average models: (a)switched-capacitor equalizer; (b) switched-resonance equalizer.

- **Average model** is implemented **on PSIM for 4 series battery string** and is compared with a **RTSS**.
- **Voltage profile** of **average model** and **RTSS** are similar.
- **Average model** just requires **1 min.** to simulate **3h long equalization process** while **RTSS** took **3h.**



Simulation results of the average model vs real-time simulator: (a) real-time simulator of SC equalizer; (b) average model of SC equalizer; (c) real-time simulator of SR equalizer; (d) average model of SR equalizer

Conclusions

- **Average models** for the **SC-E and SR-E** are proposed to **assess the performance of the equalization method**.
- **Average model-based simulation** reveal a **similar voltage profile** with the **real time simulation system**.
- **Average model-based method** just requires **1 min**. to finish the simulation of **3h long equalization process**.

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