Unified Average Model of Switched-Passive-Network Equalizer for Performance Assessment in Long-term Simulations

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***Abstract*—Cell inconsistency is a big challenge for electric vehicles (EV) and energy storage systems (ESS), where large number of battery cells are connected in series. For the purpose of active balancing, switched-passive-network equalizers such as switched-inductor (SI-E), switched-capacitor (SC-E), and switched-resonance (SR-E) equalizers are more promising. During the equalizer development, simulation is the first approach to design the circuit topology. However, the traditional simulation method only can assess the equalizer performance in a short operation-time due to the PC's memory limitation. This paper proposes a unified average model of the switched-passive-network equalizers to assess the long-term performance of the equalizers. The unified average models are implemented by PSIM, and the results are compared with the waveforms by a hardware-in-the-loop (HIL) real-time simulation system. It is observed that a high similarity exists between the average simulation and the switching simulation, but the execution-speed becomes faster in the proposed method. Besides, it is also proved that energy loss during the equalization process can be assessed by the average model.**

I. INTRODUCTION

In the electric vehicle (EV) and battery energy storage system (BESS), the battery cells are connected in series to increase the voltage of the system. Usually, the cell characteristics are screened before the assembly to ensure the uniform performance [1]. However, the uniform operation of the cells are only maintained in the first few operating cycles. Since the aging patterns of the cells are different, due to the packing conditions or material tolerances [2], the operation of the cells become mismatch. The different performance of the cells, so-called cell-inconsistency, can lead the whole system to the over-charging or over-discharging conditions if the protection is missing [3]. Thus, the cell-equalizer is required to ensure the performance and safety for the series battery string.

Various cell-equalization techniques have been introduced in [4], [5], which can be classified into passive and active catalogs. To choose a good performance equalizer, simulation-based assessments are a critical step. The equalizers are implemented for multiple test conditions and scenarios such as initial voltage distribution, inconsistency characteristic, dynamic response, etc. Although the transient and switching waveform of the equalizers can be simulated by the traditional software as PSIM, Matlab, or Plecs, the long operation of the equalizer is hard to be executed due to the computer's memory limitation.

To overcome this limitation, the capacity of the battery is sometimes scaled down to shorten the execution-time. However, the battery characteristics are correspondingly changed in term of impedance and OCV-SOC relationship. Consequently, the performance of the equalizer is not property evaluated and the simulation results becomes useless. On the contrary, the hardware-in-the-loop (HIL) test system can be a promising solution to emulate the equalization in a long operating time [6], [7]. The equalization can be simulated in real-time and all operation parameters of the equalizer or battery can be monitored without any capacity scale-down action. However, the cost of HIL system is so substantial that just a few laboratory can afford to use it. Besides, the HIL system has too limited number of cores to simulate a large number of cells. It should be also noted that the real-time simulation is not an accelerated test but takes as much time as required for the real test.

In the view of DC-DC converter, the switching elements of the equalizer can be replaced by average models. Due to the sampling-time independence, the averaged models can simulate hours of equalization process just in a few seconds. In the previous research, the switched-capacitor equalizer (SC-E) [8] and the switched-resonance equalizer (SR-E) [9] can be emulated by an impedance element in the simulation. However, the equivalent impedance only approximately reflects the losses of the equalizer while the the charge sharing process between the battery cells and the energy tank (capacitor or resonance circuits) is unclearly described. Furthermore, there is a lack of one general model to describe the behavior of switched-inductor equalizers (SI-E), SC-E, and SR-E. This paper proposes a unified average model for the switched-passive-network equalizers and illustrate their applications as a tool for the equalizer development. The detail of the model is described in Section II and is verified in Section III. Finally, the conclusion is made in Section IV.

II. PROPOSED UNIFIED AVERAGE MODEL AND ITS APPLICATION

A. Unified Average Model of Switched-Passive-Network

Among the battery equalization techniques, the active switched-passive-network based methods have a high effi-

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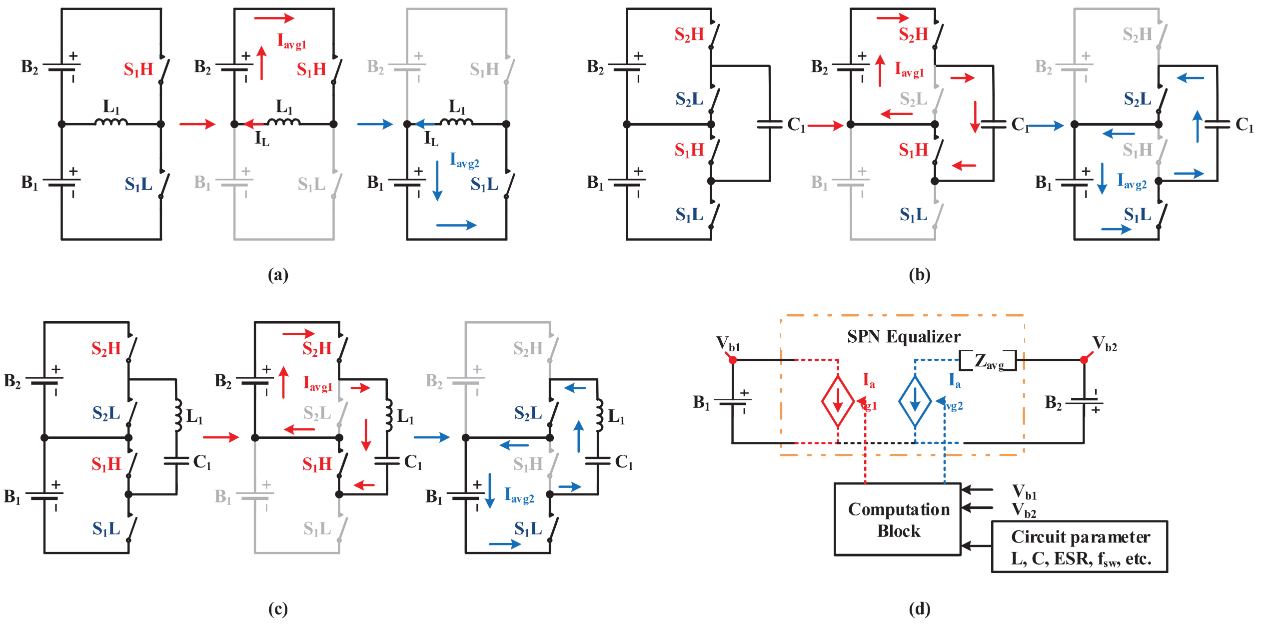


Fig. 1: Operation principle of SPN-Equalizer: (a) SI-E; (b) SC-E; (c) SR-E; and (d) unified average model of the SPN-E

ciency, small size, and control simplicity. Thus, it is more promising to be popular in the actual application. Various topology configurations were introduced but their operation principles are almost similar. One energy tank such as an inductor (SI-E), a capacitor (SC-E), or a LC resonant circuit (SR-E) serves as an intermediate energy carrier. One switches network is used to alternately connect the adjacent cells to the energy tank. Assume that the upper cell has a higher energy level, the equalization between two cells are divided into two phases.

- Phase A: the upper-switches are turned on while the lower-switches are kept off. The upper cells charge the energy tank due to the voltage different.
- Phase B: the upper-switches are turned off and the lower-switches are on to connect the energy tank to the lower cell. Due to the voltage different, energy is transferred from the energy tank to the lower cell.

By repeating the equalization process, energy is transferred from the upper cell to the lower cell gradually. The direction of energy flow is dependent on the voltage deviation between two cells and is autonomous. The operation principle of SI-E, SC-E, and SR-E are summarized as follows.

1) Operation of SI-E: As mentioned, the equalization process of SI-E is illustrated in Fig. 1(a). The switched inductor circuit operates as a buck-boost converter, where the inductor current is calculated by

$$I_L = \frac{DV_{b1} - (1-D)V_{b2}}{D^2(R_1+R_L) + (1-D)^2(R_2+R_L)} \tag{1}$$

where D is the duty ratio of the switches and R_L is the internal resistance of the inductor. In the quasi-steady state condition, the battery voltage is assumed to be constant. Thus, the average current that flows into and out of the battery cells are respectively calculated by

$$I_{avg1} =< i_L >= DI_L \tag{2}$$

$$I_{avg2} = (1-D)I_L. \tag{3}$$

where $< . >$ demotes the time average operation. To assess the losses of the equalizer, the equivalent resistance and power loss of the SI-E are expressed by

$$R_{SI} = \frac{2(V_{b1} - V_{b2})}{I_L}, \tag{4}$$

$$P_{SI} = R_{SI} I_L^2 \tag{5}$$

2) Operation of SC-E: Similarly, the operation of the SC-E is described in Fig. 1(b), where the energy tank is a capacitor unit. The detailed operation of the SC-E and SR-E is illustrated in Fig. 2 and are clearly described in [10], where the battery is modeled by one voltage source, V_{b1} or V_{b2} and one resistor, R_1 or R_2 in series. Based on the model, the average currents flowing into or out of the battery cells are calculated by

$$I_{avg1} = \frac{1}{2}(V_{b1} - V_{b2})Cf_{sw}(1 - e^{\frac{-D_1}{f_{sw}R_1C}}), \tag{6}$$

$$I_{avg2} = \frac{1}{2}(V_{b1} - V_{b2})Cf_{sw}(1 - e^{\frac{-D_2}{f_{sw}R_2C}})e^{\frac{-1}{2f_{sw}R_2C}}, \tag{7}$$

where D_1, D_2 are the duty ratio of phase A and phase B, respectively; f_{sw} is the switching frequency of the switches; R_1 and R_2 are the loop resistance including the battery resistance, internal resistance of the switches and the energy

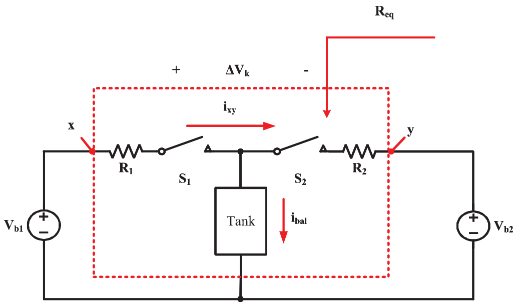


Fig. 2: Equivalent model of the SPN-Equalizer

tank. Hence, the power loss of the SC-E is calculated by

$$P_{loss} = \frac{I_c^2}{f_s C} \frac{e^{\frac{D_1}{f_s \tau_k}} e^{\frac{D_2}{f_s \tau_m}} - 1}{\left(e^{\frac{D_1}{f_s \tau_k}} - 1\right)\left(e^{\frac{D_2}{f_s \tau_m}} - 1\right)}. \tag{8}$$

where I_c is the capacitor current, τ_k and τ_m are the time constant of each equalization phase, respectively. Since the loss of equalizer can be emulated by an equivalent resistance, R_{eq}, the power loss on the equalizer circuit is expressed as

$$P_{loss} = I_c^2 R_{eq}. \tag{9}$$

By comparing (8) and (9), the equivalent resistance of the equalizer is calculated by

$$R_{eq} = \frac{1}{f_s C} \frac{e^{\frac{D_1}{f_s \tau_k}} e^{\frac{D_2}{f_s \tau_m}} - 1}{\left(e^{\frac{D_1}{f_s \tau_k}} - 1\right)\left(e^{\frac{D_2}{f_s \tau_m}} - 1\right)}, \tag{10}$$

which is a function of the duty ratio (D_1, D_2), the capacitance, C, and the switching frequency, f_s.

3) Operation of SR-E: Because the operation of SC-E and SR-E are almost similar, the operation analysis of the SR-E and the SC-E are the same. The equalization process of the SR-E can be described as Fig. 1(c), where the energy tank is a L-C resonant circuit. The average equalization current of each battery is calculated by

$$I_{avg1} = \frac{1}{2}(V_{b1} - V_{b2}) C f_{sw} \frac{(1 + e^{\frac{-\beta_1 \pi}{\omega_{r1}}})}{(1 - e^{\frac{-\beta_1 \pi}{\omega_{r1}}})}, \tag{11}$$

$$I_{avg2} = \frac{1}{2}(V_{b1} - V_{b2}) C f_{sw} \frac{(1 + e^{\frac{-\beta_2 \pi}{\omega_{r2}}})}{(1 - e^{\frac{-\beta_2 \pi}{\omega_{r2}}})}, \tag{12}$$

where

$$\beta_1 = \frac{R_1}{2L}, \tag{13}$$

$$\beta_2 = \frac{R_2}{2L}, \tag{14}$$

and C is the equalization capacitance; f_{sw} is the switching frequency; R_1 and R_2 are the loop resistance including R_b, R_{d_on}, and ESR of the capacitor. The resonant frequency can be calculated by

$$\omega_r = \sqrt{\frac{1}{LC} - \beta^2}, \tag{15}$$

if $\beta_1 = \beta_2 = \beta$. The equivalent resistance and power loss of the equalizer are expressed by

$$R_{SR} = \frac{1}{f_{sw} C} \frac{1 + e^{\frac{-\beta \pi}{\omega_r}}}{1 - e^{\frac{-\beta \pi}{\omega_r}}}, \tag{16}$$

$$P_{loss} = R_{SR} I_{avg}^2 \tag{17}$$

B. Unified Averaged Model of SPN-Equalizer

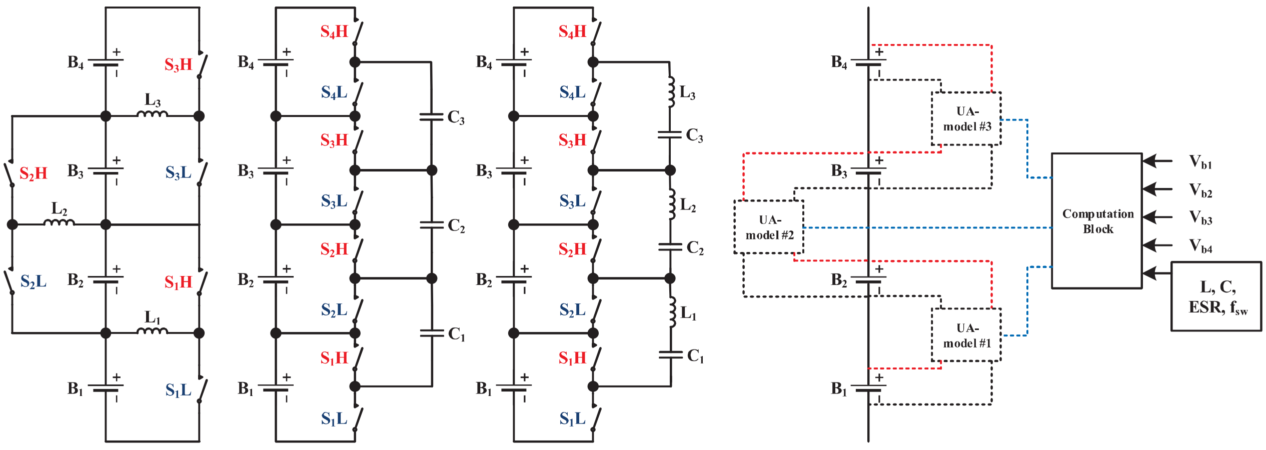
In order to provide a developing tool for the battery equalizer, an unified average model (UA-model) is proposed here. The concept of the UA-model is illustrated in Fig. 1(d), where two controlled current sources are introduced to emulate the charge transfer process during the equalization. Besides, one equivalent output resistance, Z_{avg}, is used to assess the energy loss during the equalization, where Z_{avg} can be R_{SI} as (4), R_{SC} as (10), or R_{SR} as (16). The polarity and magnitude of the current sources are a function of the voltage deviation between the cells along with the circuit parameters. The equalization is divided into multiple cycles, where the battery voltage are monitored and updated by the computation block. In the computation block, the average equalization currents of the equalizer are calculated based on the operation principle mentioned above and adjust the controlled current sources. The battery cells are charged or discharged by the corresponding constant current during one equalization cycle before the next calculated is executed.

C. Application of UA-model in Battery Equalizer Development

For a vivid demonstration of the application of UA-model to the equalizer development, the examples for the SI-E, classical SC-E, and classical SR-E are assessed as Fig. 3. One UA-model block represents one equalizer and the topology configuration decides the number of UA-model blocks in the simulation. For a descriptive purpose, the classical structure of the SI-E, SC-E, and SR-E require (N-1) equalizer for N series cells. Thus, (N-1) UA-model blocks are implemented and one UA-model block emulates the equalization process of 2 adjacent cells. By recording the parameter of the equalizers, the performance indices of the equalizers are assessed. Hence, the advantage and disadvantages of the equalizers are compared to choose the better candidate.

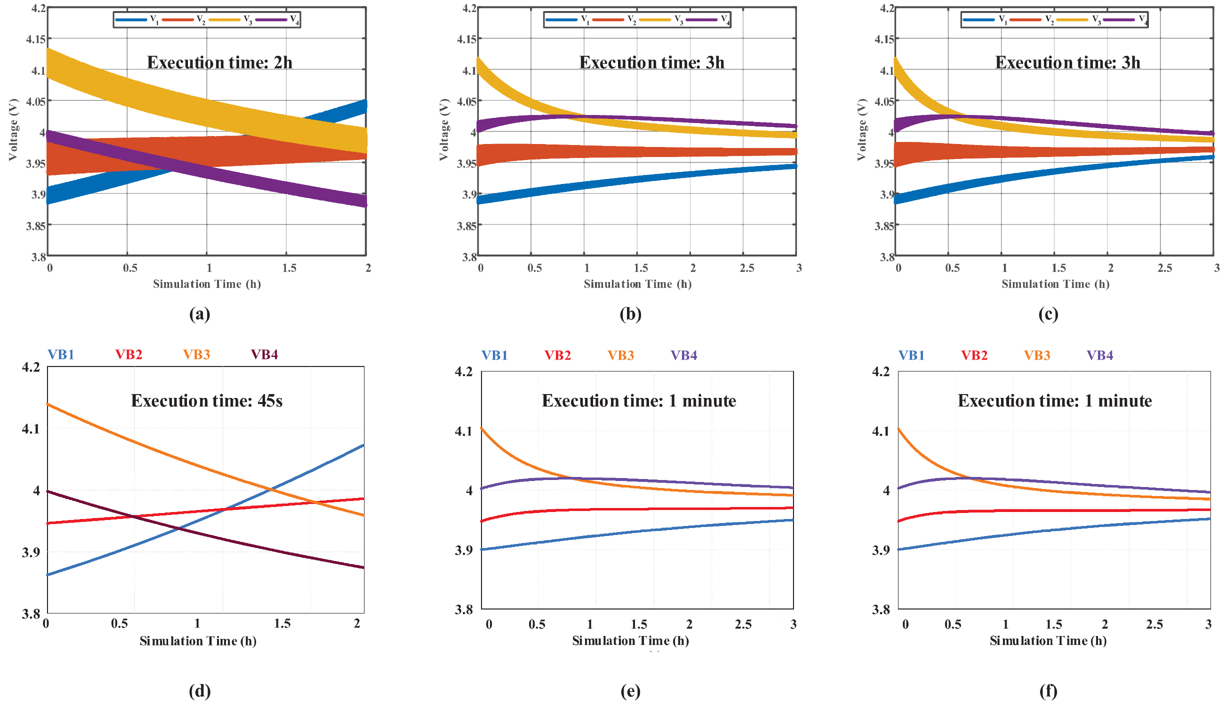
III. PERFORMANCE VERIFICATION

To verify the model accuracy, four series-connected 18650 Li-ion battery cells (3.6V/2.6A) with three switched-passive-network equalizers are simulated by UA-model which are implemented in PSIM. To get the reference results, the equalizers



(a) (b) (c) (d)

Fig. 3: Topology configuration of switched-passive-network and their unified average model (UA-model): (a) SI-E; (b) SC-E; (c) SR-E; and (d) UA-model for all.



(a) (b) (c)

(d) (e) (f)

Fig. 4: Voltage profile of the cells during the equalization process: (a) SI-E in RTSS; (b) SC-E in RTSS; (c) SR-E in RTSS; (d) UA-model of SI-E in PSIM; (e) UA-model of SC-E in PSIM; (f) UA-model of SR-E in PSIM;

are also implemented on a real-time simulation system (RTSS). The setups of the circuit parameters in the simulation of both PSIM and RTSS are made similar for a fair comparison. The circuit parameters for each method are summarized in Table I, where f_{sw} is the switching frequency; L is the balancing inductance; C is the balancing capacitance; R is the circuit resistance including the parasitic resistance of the components and wiring; D is the duty ratio. For all methods, the switches are controlled by one complementary PWM signal-pair for the autonomously energy transfer. Because it is hard to predict the equalization time, the simulations are terminated after 2h for SI-E, and after 3h for SC-E, and SR-E, respectively.

The voltage profiles of the battery cells are shown in Fig. 4, where the results of both RTSS and PSIM are illustrated. By comparing the voltage profile from RTSS and PSIM, it is observed that the UA-model successfully re-enacted the

TABLE I:
Simulation Setups for PSIM and RTSS

	SI-E	SC-E	SR-E
Setting Circuit Parameter	$f_{sw} = 20kHz$ $L = 400\mu H$ $R = 0.15\Omega$ $D = 0.45$	$f_{sw} = 20kHz$ $C = 2200\mu F$ $R = 0.15\Omega$ $D = 0.45$	$f_{sw} = 20kHz$ $C = 200\mu F$ $L = 0.47\mu H$ $R = 15\Omega$ $D = 0.45$
Initial SOC	$SOC_{1,2,3,4} = 70,\ 80,\ 95,\ 85$		

behaviors of the battery cells and the equalizer during the equalization process. For the SI-E, the autonomous control scheme shows a bad performance as Fig. 4(a) and 4(d), where the voltage deviation becomes larger after 1.5h. For the SC-E and SR-E, the equalization process can be autonomously executed, where the voltage deviation of the cells are gradually equalized. The voltage deviation of the cells at the end of the equalization process are the same in both RTSS and PSIM cases. Thus, the UA-model successfully replaces a RTSS for a long-term equalization emulation. On the other hand, the UA-model based simulation only requires a short execution-time. While the RTSS requires an exact amount of execution time equal to the actual operation time, the proposed UA-model only takes about 1-minute for 3h test. Hence, the UA-model can dramatically reduce the simulation time and reduce the computation burden of PC.

Besides, during the equalizer development, assessing the performance of the equalizer under different scenarios is a critical step. For examples, the dependency of the equalization performance on the initial voltage distribution of the cells, the impact of the battery aging on the equalization, or the optimal design of the equalizer circuit. Because the energy mismatching between the cells are arbitrary in the actual application, the voltage distribution tests are the most effectively way to assess the impact of topology configuration on the equalization. For a fair comparison, the energy level of the cells should be the same in every test scenarios for any equalizer. Alas, it is un-confident to ensure that the initial conditions of the cells in every practical tests are the same. With the mentioned advantages, the UA-model is a powerful solution to assess the equalization performance.

For an illustrative purpose, the SI-E, SC-E, and SR-E are compared under three test scenarios as Fig. 5 by utilizing UA-models which is developed in this paper. The battery capacity and circuit parameters of the equalizer are the same but the initial voltage of the cells are distributed as follows:

- Scenario #1: the SOC levels of the cells are descending from cell #1 to #4 as Fig. 5(a).
- Scenario #2: the SOC distribution is a convex type, where the high-SOC cells are at the middle of the string as Fig. 5(b).
- Scenario #3: the SOC distribution is a concave type, where the high-SOC cells are at two end of the string as Fig. 5(c).

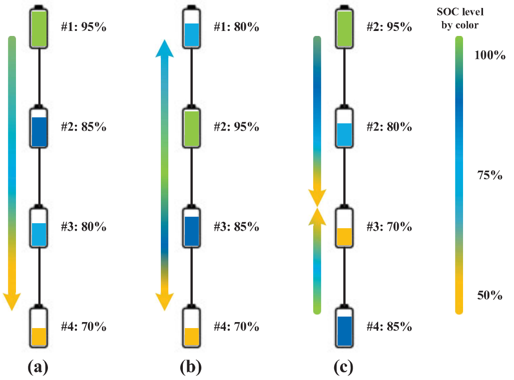


Fig. 5: Initial SOC-distribution of the cells in: (a) Scenario #1, (b) Scenario #2, (c) Scenario #3.

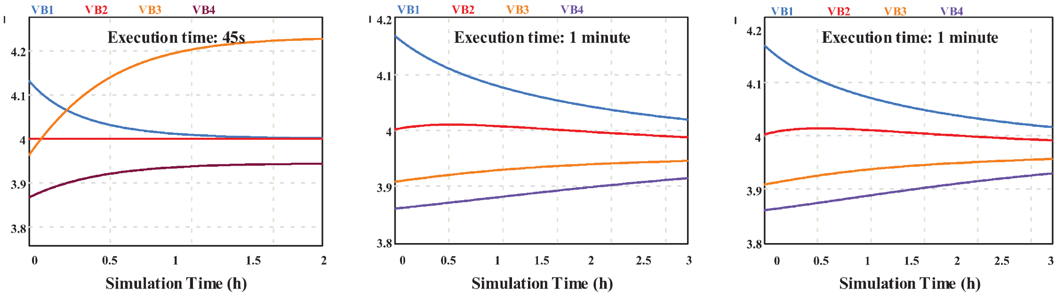
Observed that these three test scenarios are the most worst-cases test scenarios for the battery equalizer. Based on the test results, the following criteria are assessed:

- The equalizers should overcome the initial voltage distribution and show a good performance in every test scenarios.
- The equalization speed should be good and similar in every test scenarios.

The simulation results of the SI-E, SC-E, and SR-E in three test scenarios are illustrated in Fig. 6, Fig. 7, and Fig. 8, respectively. It is observed that the SI-E requires a more complex control method than the autonomous control scheme adopted in SC-E and SR-E. The impact of the initial voltage distribution to the equalization performance is strong, where the voltage deviation become larger than the initial condition after 2h. On the contrary, the autonomous control scheme show a good performance in SC-E and SR-E, where the voltage deviation is equalized gradually just by turning on and off the upper and lower switches alternately. However, the initial voltage deviation impact is still strong due to the limitation of the classical architecture. The final voltage deviation and the equalization speed of SC-E and SR-E are dissimilar in three test scenarios. The SR-E shows a better performance than the SC-E due to its smaller equivalent resistance. Once again, the proposed UA-model is proved to be very useful in the performance assessment of various active equalization schemes.

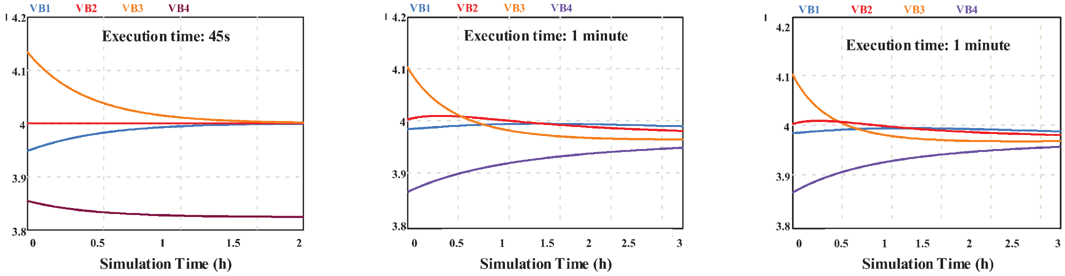
IV. CONCLUSION

A unified average model of switched-passive-network equalizers is proposed. The proposed model can be applied for the most promising configurations such as SI-E, the SC-E, and the SR-E. The UA-model consists of two controlled current sources to re-enact the energy transfer mechanism inside the equalizer. Besides, the resistance of the equalizer can be used to assess the power loss of the equalizer circuit. The comparison between simulation results on PSIM and the voltage profile on real-time simulation system only revealed a minor difference between the two methods. On the other hand, the execution time is significantly reduced.



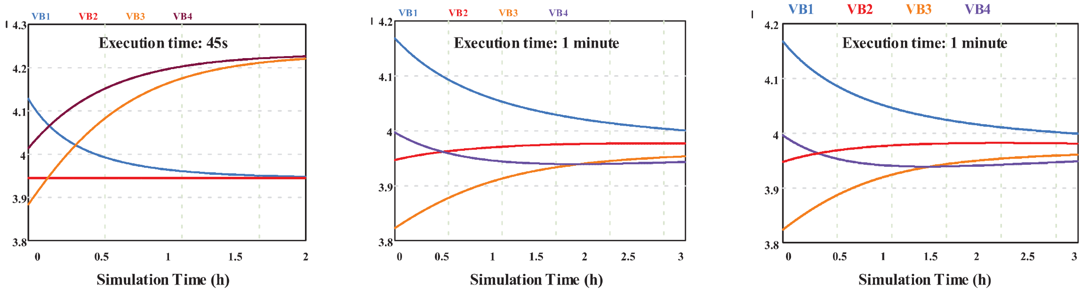
(a) (b) (c)

Fig. 6: Voltage profiles of the cells in scenario #1: (a) SI-E, (b) SC-E, (c) SR-E.



(a) (b) (c)

Fig. 7: Voltage profiles of the cells in scenario #2: (a) SI-E, (b) SC-E, (c) SR-E.



(a) (b) (c)

Fig. 8: Voltage profiles of the cells in scenario #3: (a) SI-E, (b) SC-E, (c) SR-E.

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TECHNICAL SECTION 21

JULY 17TH, 2022

Energy Conversion
Circuit Laboratory

SCAN ME

Agenda

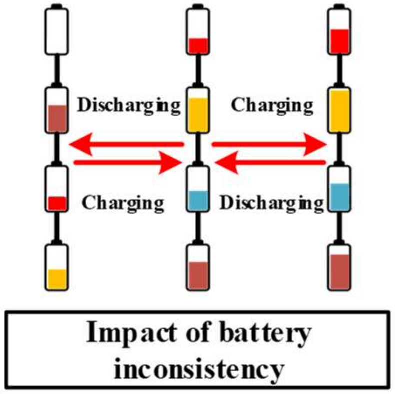
- Research Motivations
- UA-model and Its Applications
- Performance Verification
- Conclusion

Research Motivation – Cell inconsistency

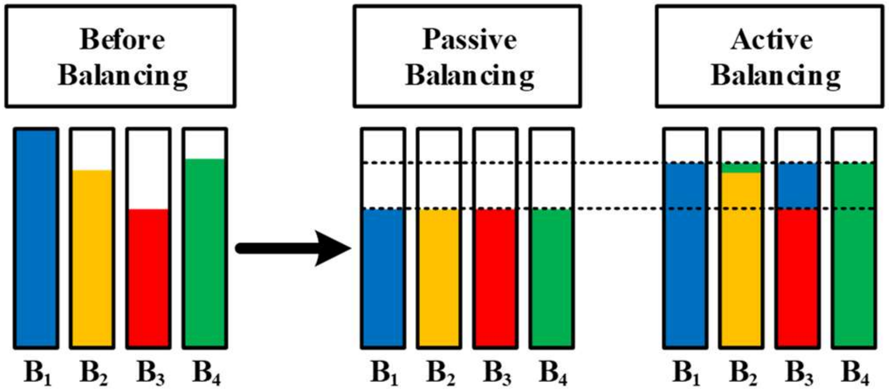
- Cell inconsistency in **series battery connection**
  - The characteristics of battery cells are so different that it may causes:
    - ❑**Reduction of the available capacitance**
    - ❑Possible **over-charging** and **over-discharging** to the battery cells

→**Battery equalizers** are required to solve address **the cell inconsistency issue.**

***By virtue of energy regenerative scheme, active balancing methods** have **a higher efficiency.**



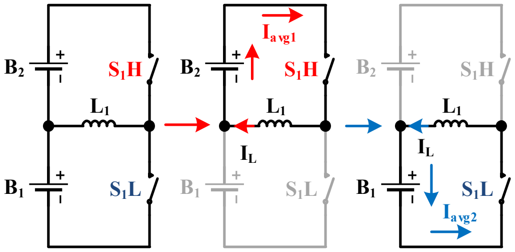
Impact of battery inconsistency



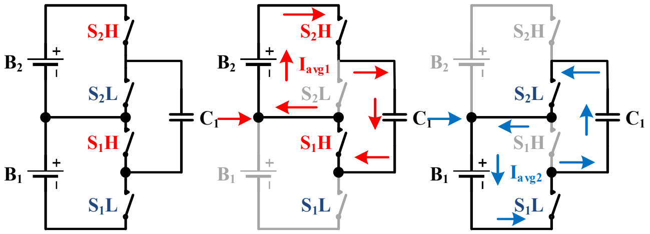
Research Motivation – SPN Equalizer

- **Switched passive-network equalizers (SPN-E)** utilize one inductor (**SI-E**), one capacitor (**SC-E**), or one LC resonance circuit (**SR-E**) as an **energy tank** to **transfer energy from one cell to the others**.
- **Operation principle** of the SPN-E is **similar in terms of concept.**

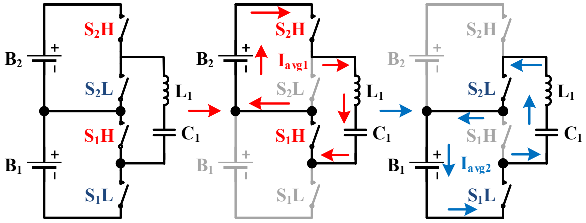
SI-E



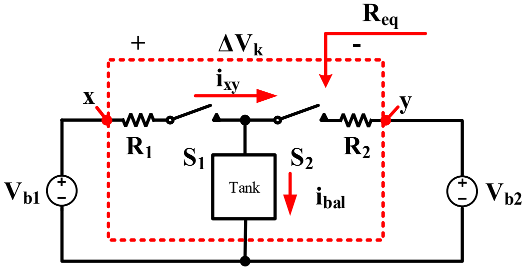
SC-E



SR-E



Model of SPN_E



Research Motivation – Long Term Simulation

- **In simulation, SPN-E requires a very high sampling rate (Ex: 1us).**

➔ Require a **huge memory** and **computation capability.**

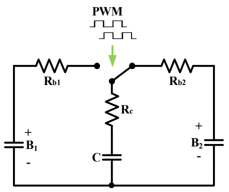
- **Three common solutions** for a **long term simulation**:
  - **To replace** the **battery cell** by **a capacitor**
  - **To reduce** the **capacity of the cell**

➔ **Circuit parameter** is **changed** that the **operation of the equalizers** is **dissimilar** to the **actual application**.

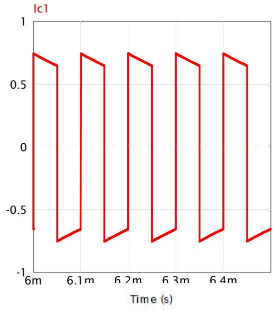
➔ Simulation results become useless! ☹☹☹

  - **To utilize a real-time simulation system (RTSS)**

➔ **Quite expensive** that just a few lab. can afford to use.

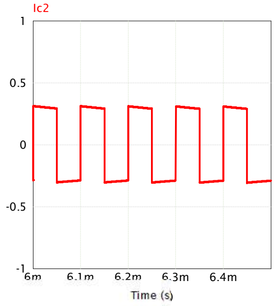


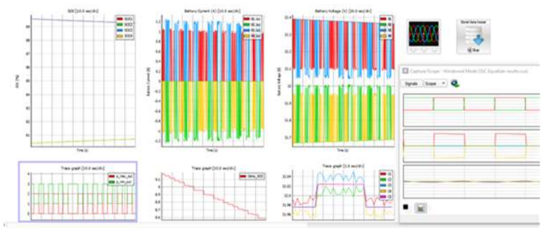
Q = 2.6Ah



Capacitor Current

Q = 0.26Ah



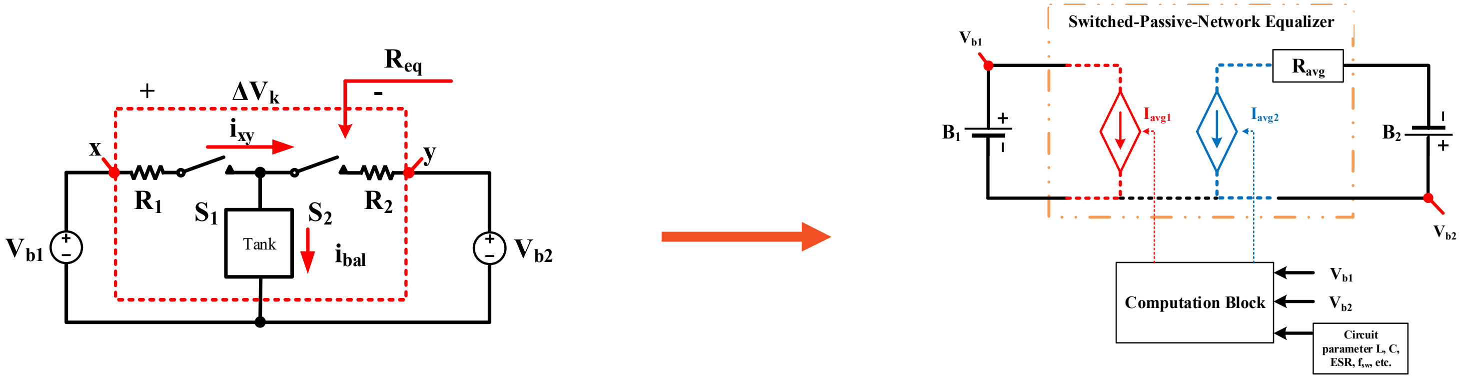


Unified Average Model

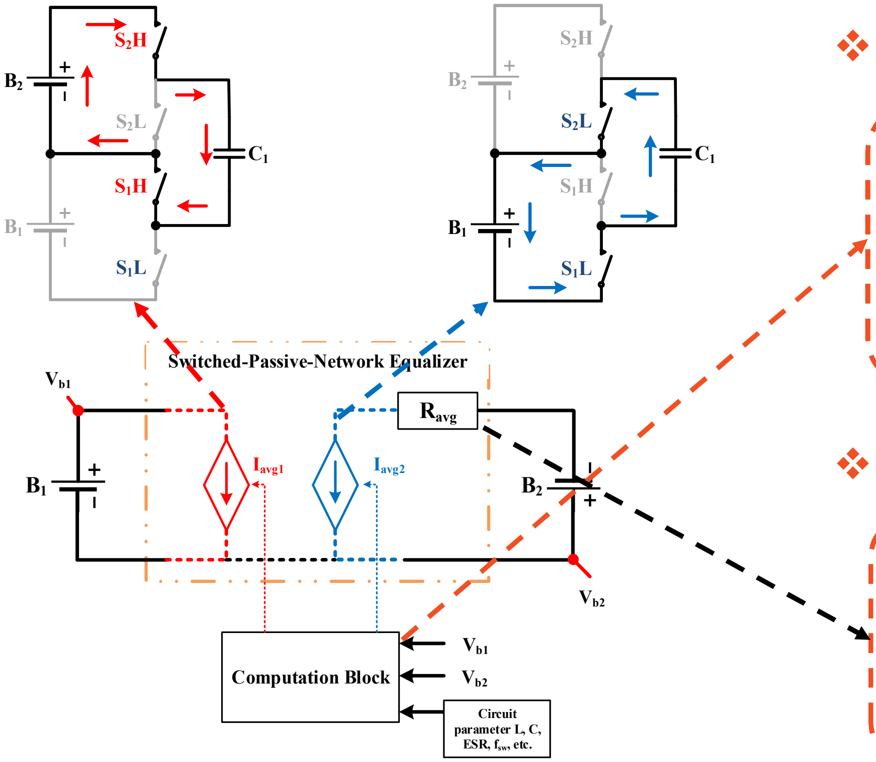
- **Switching elements** in the simulation can **be replaced** by **an average model.**

➔ **Sampling rate** can be **significantly reduced** to **shorten the execution time**.

- **An unified average model (UA-model)** is proposed to **emulate the equalization process.**
- **Two controlled current sources** are used to **reflect the charge transfer process** between the two battery cells.
- **Whole day equalization process** can be simulated just **in 1 minute**.



Unified Average Model of SC-E



- **Average equalization current of the cells:**

$$I_{avg1} = \frac{1}{2}(V_{b1}-V_{b2})Cf_{sw}(1-e^{\frac{-D_1}{f_{sw}R_1C}}), \tag{6}$$

$$I_{avg2} = \frac{1}{2}(V_{b1}-V_{b2})Cf_{sw}(1-e^{\frac{-D_2}{f_{sw}R_2C}})e^{\frac{-1}{2f_{sw}R_2C}}, \tag{7}$$

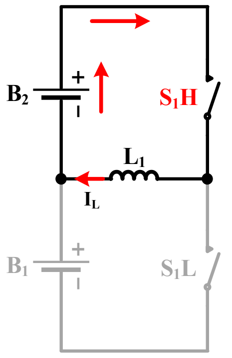
- **Equivalent resistance and power loss:**

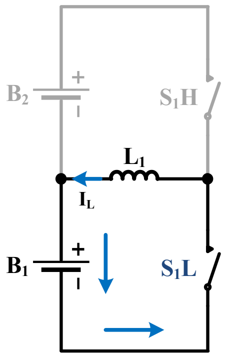
$$P_{loss} = I_c^2 R_{eq}. \tag{9}$$

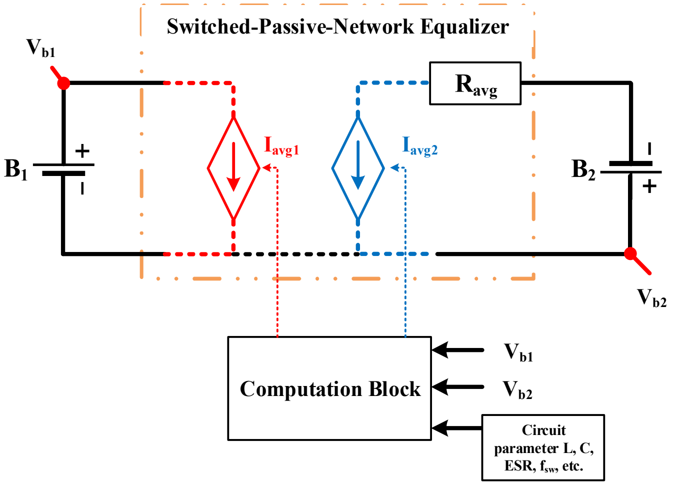
$$R_{eq} = \frac{1}{f_sC}\frac{e^{\frac{D_1}{f_s\tau_k}}e^{\frac{D_2}{f_s\tau_m}}-1}{\left(e^{\frac{D_1}{f_s\tau_k}}-1\right)\left(e^{\frac{D_2}{f_s\tau_m}}-1\right)}, \tag{10}$$

P. -H. La and S. -J. Choi, "Direct Cell-to-Cell Equalizer for Series-Connected Batteries Using Switch-Matrix Single-Capacitor Converter and Optimal Pairing Algorithm," in IEEE Transactions on Power Electronics, doi: 10.1109/TPEL.2022.3147842.

Unified Average Model of SI-E







- **Inductor current:**

$$I_L = \frac{DV_{b1} - (1-D)V_{b2}}{D^2(R_1 + R_L) + (1-D)^2(R_2 + R_L)} \qquad (1)$$

- **Average equalization current of the cells:**

$$I_{avg1} = < i_L > = DI_L \qquad (2)$$

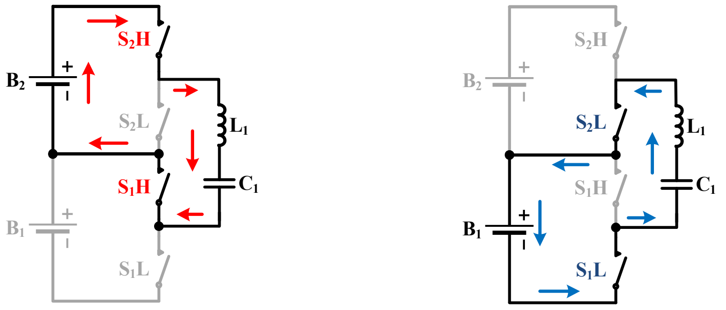
$$I_{avg2} = (1-D)I_L. \qquad (3)$$

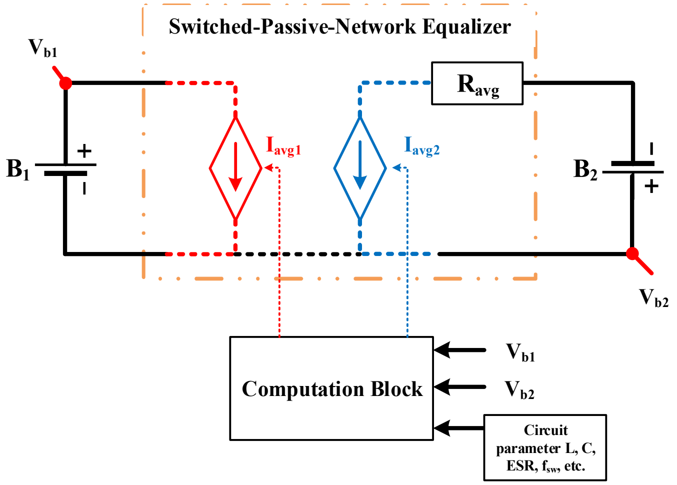
- **Equivalent resistance and power loss:**

$$R_{SI} = \frac{2(V_{b1} - V_{b2})}{I_L}, \qquad (4)$$

$$P_{SI} = R_{SI} I_L^2 \qquad (5)$$

Unified Average Model of SR-E





❖ Average equalization current of the cells:

$$I_{avg1} = \frac{1}{2}(V_{b1} - V_{b2})Cf_{sw}\frac{(1+e^{\frac{-\beta_1\pi}{\omega_{r1}}})}{(1-e^{\frac{-\beta_1\pi}{\omega_{r1}}})}, \qquad (11)$$

$$I_{avg2} = \frac{1}{2}(V_{b1} - V_{b2})Cf_{sw}\frac{(1+e^{\frac{-\beta_2\pi}{\omega_{r2}}})}{(1-e^{\frac{-\beta_2\pi}{\omega_{r2}}})}, \qquad (12)$$

Where

$$\beta_1 = \frac{R_1}{2L}, \qquad (13)$$

$$\beta_2 = \frac{R_2}{2L}, \qquad (14)$$

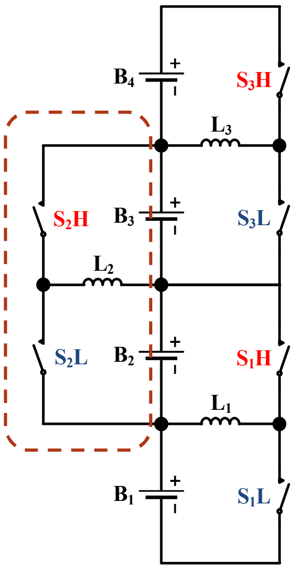
$$\omega_r = \sqrt{\frac{1}{LC} - \beta^2}, \qquad (15)$$

❖ Output equivalent resistance and power loss:

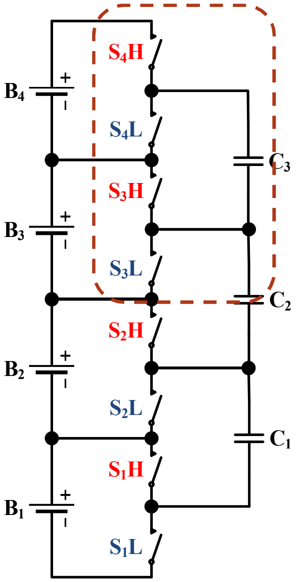
$$R_{SR} = \frac{1}{f_{sw}C}\frac{1+e^{\frac{-\beta\pi}{\omega_r}}}{1-e^{\frac{-\beta\pi}{\omega_r}}}, \qquad (16)$$

$$P_{loss} = R_{SR}I_{avg}^2 \qquad (17)$$

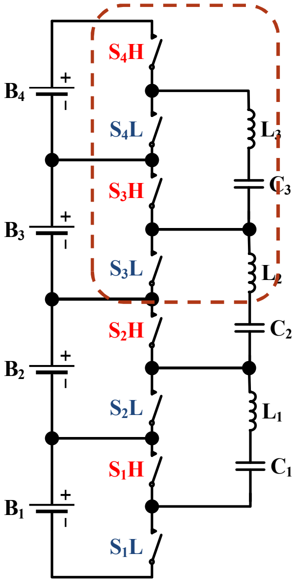
Application of UA-Model to Performance Assessment



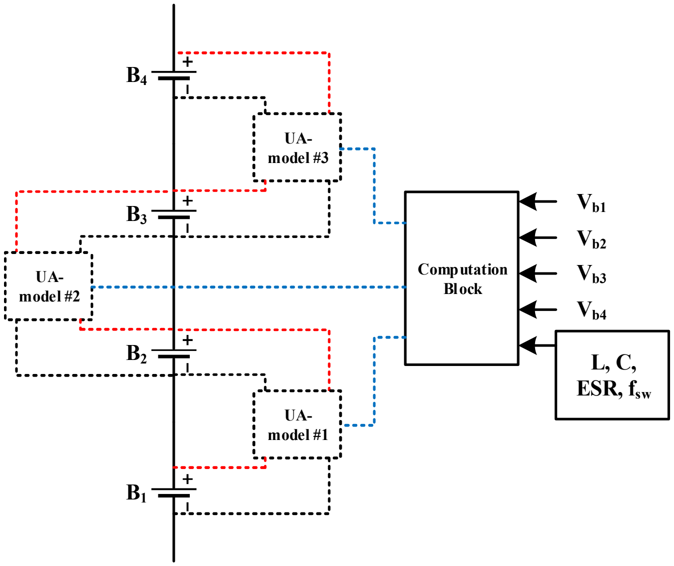
Classical SI-E



Classical SC-E



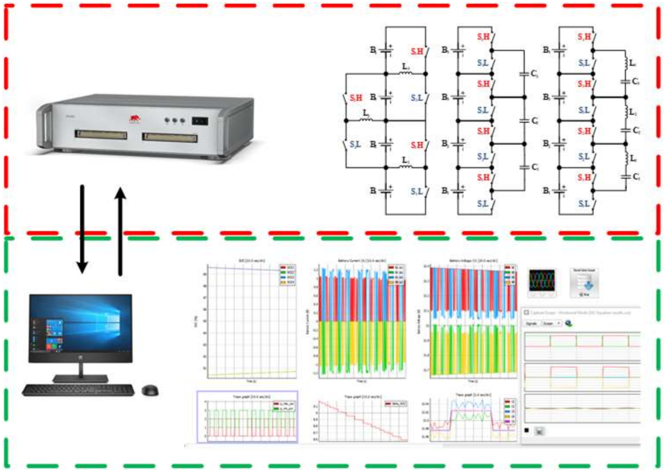
Classical SR-E



Implementation of UA-Model

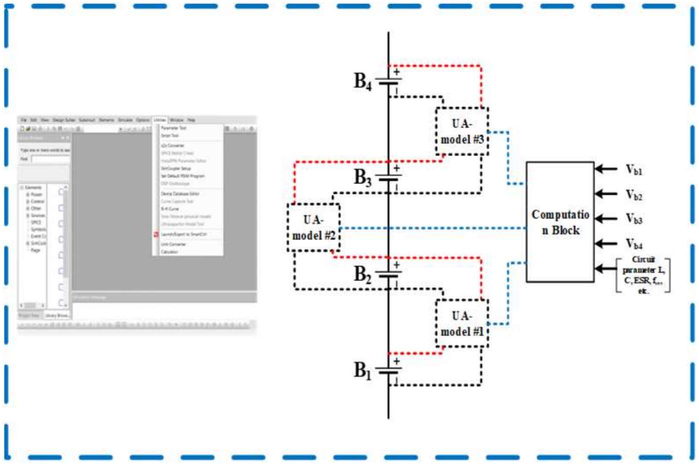
- **One UA-model block** represents **one equalizer circuit for 2 adjacent cells.**
- **Topology configuration** decides **the number of UA-model blocks.**

Performance Verification – RTSS versus UA-model



RTSS (Typhoon HIL 602+)

VS

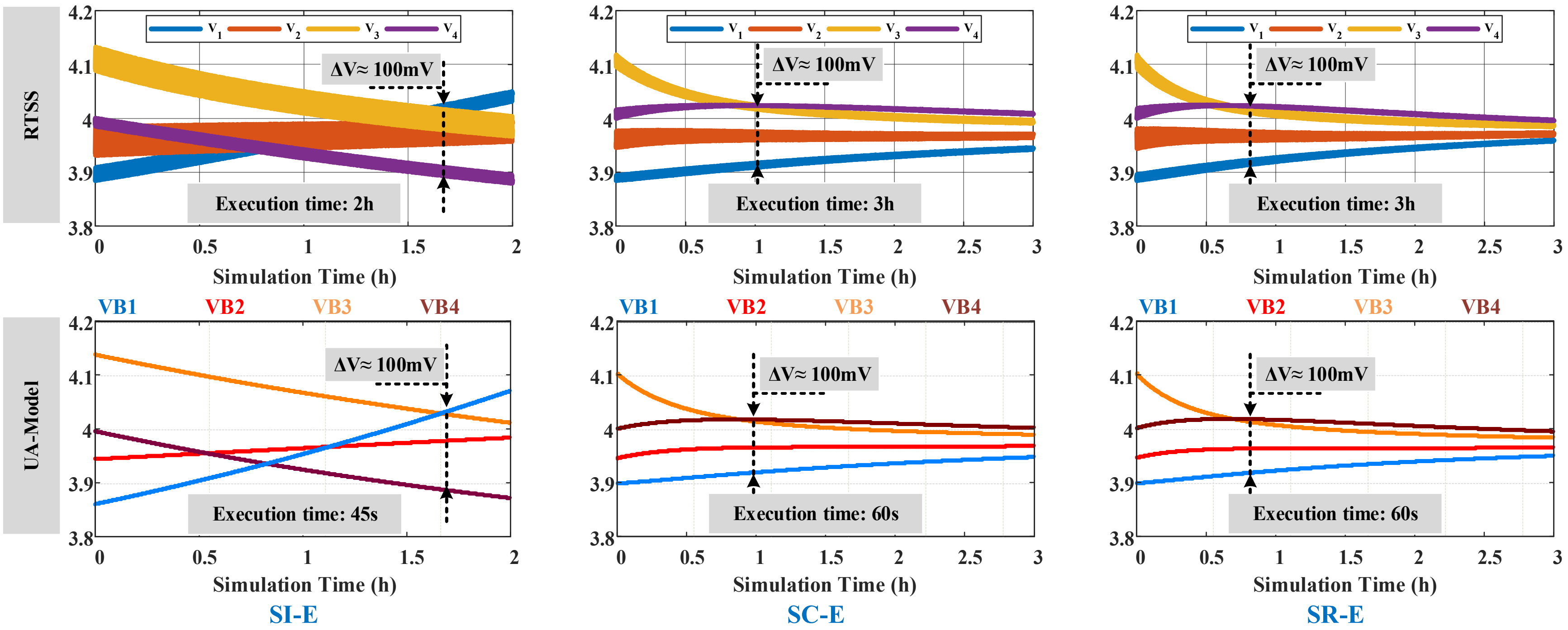


UA-Model on circuit simulation software (PSIM)

- **Switching model** of the equalizer is implemented on **RTSS.**
- **UA-model** is implemented on **PSIM software.**

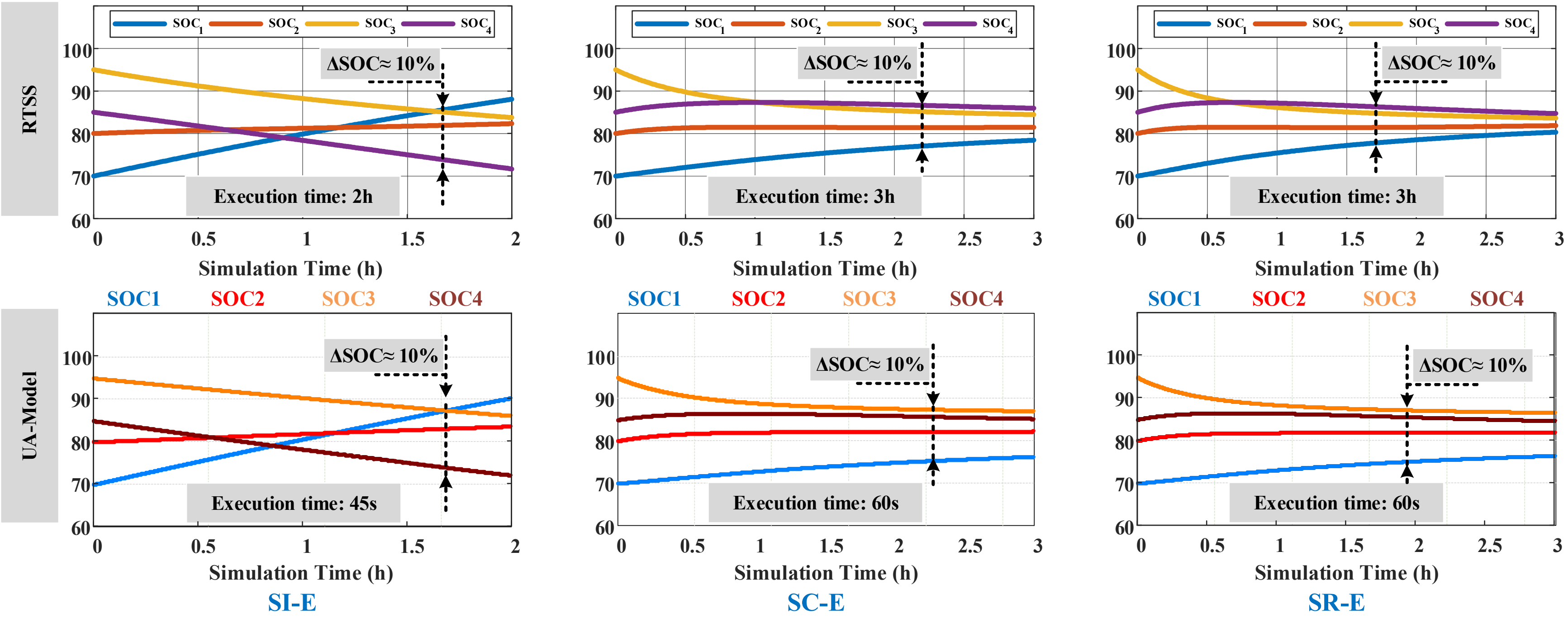
	SI-E	SC-E	SR-E
Setting Circuit Parameter	$f_{sw} = 20kHz$ $L = 400\mu H$ $R = 0.15\Omega$ $D = 0.45$	$f_{sw} = 20kHz$ $C = 2200\mu F$ $R = 0.15\Omega$ $D = 0.45$	$f_{sw} = 20kHz$ $C = 200\mu F$ $L = 0.47\mu H$ $R = 15\Omega$ $D = 0.45$
Initial SOC	$SOC_{1,2,3,4} = 70,\ 80,\ 95,\ 85$		

Performance Verification – RTSS versus UA-model



- Performance of the equalizers on **RTSS and UA-model are similar**.
- **UA-model** just requires about **60s to simulate 3h's equalization process.** **(Cf. RTSS needs 3h.)**

Performance Verification – RTSS versus UA-model



SI-E SC-E SR-E

- Performance of the equalizers on **RTSS and UA-model are similar**.
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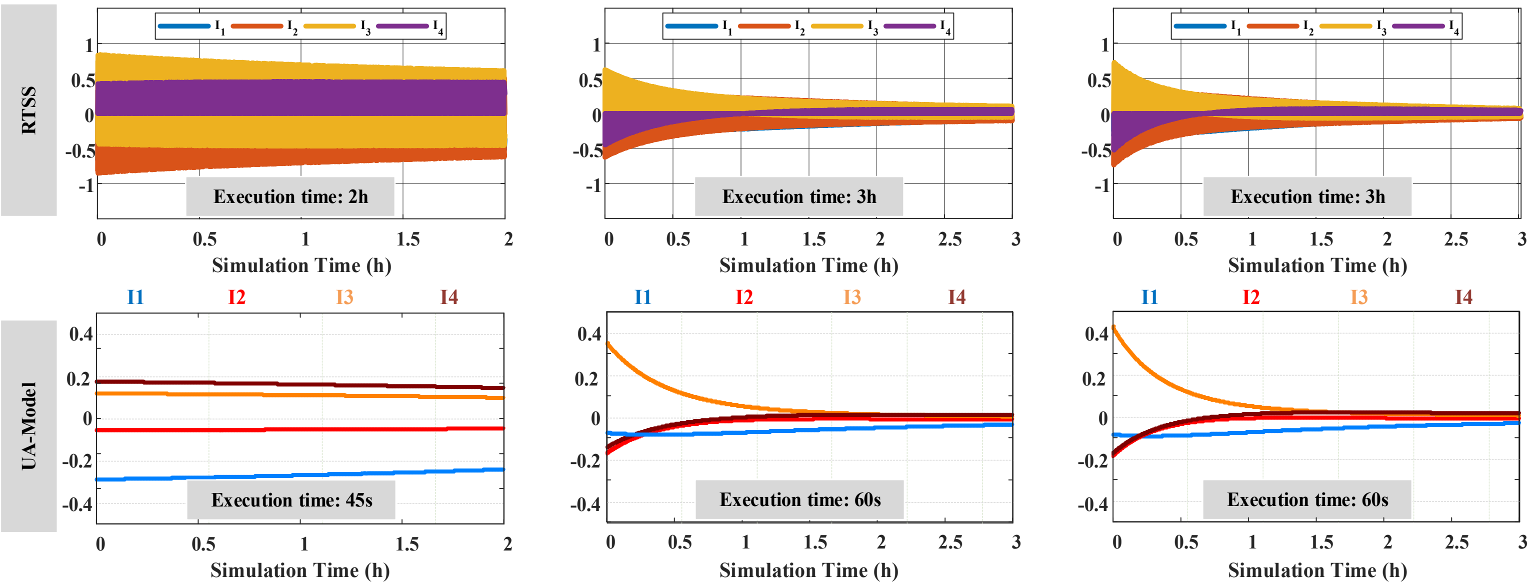
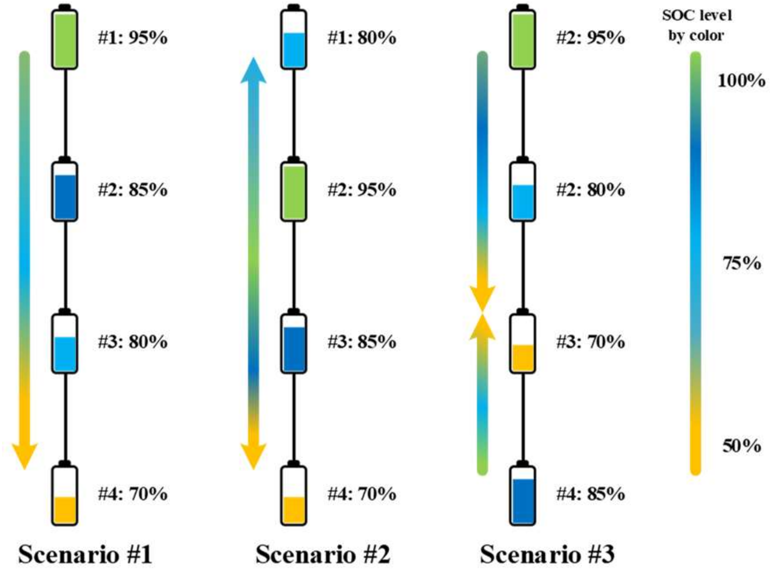
Performance Verification – RTSS versus UA-model



SI-E SC-E SR-E

- Current profile of the cells illustrate the charge exchange between them during the equalization.
- **Amplitude of average equalization current equals to the averaged value of the switching current.**
- **Behaviors of the equalizers in two simulation platforms are the same.**

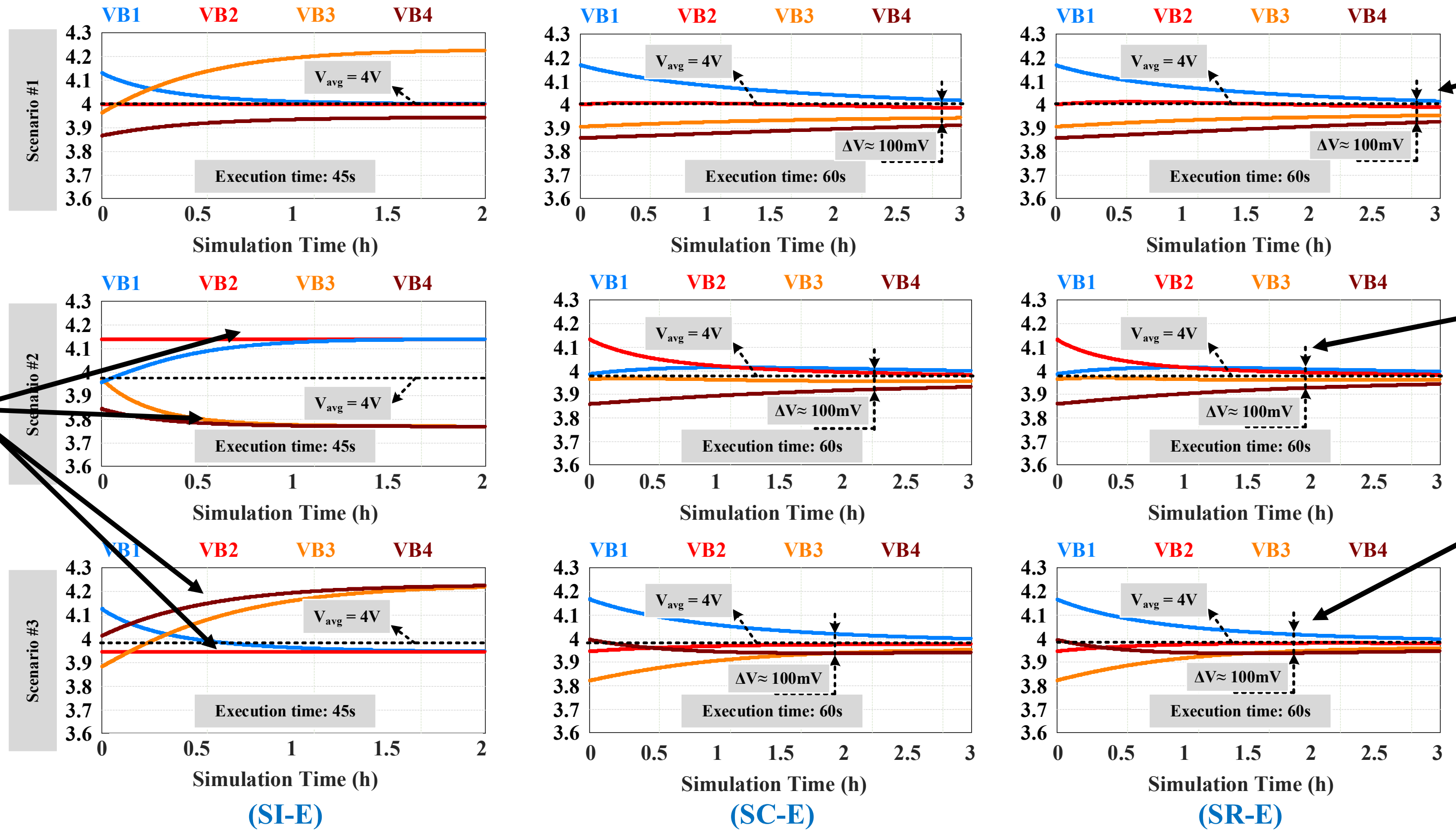
Equalizer Performance Assessment Under Different Initial Condition – Use Case of UA-Model



	SI-E	SC-E	SR-E
Setting Circuit Parameter	$f_{sw} = 20kHz$ $L = 400\mu H$ $R = 0.15\Omega$ $D = 0.45$	$f_{sw} = 20kHz$ $C = 2200\mu F$ $R = 0.15\Omega$ $D = 0.45$	$f_{sw} = 20kHz$ $C = 200\mu F$ $L = 0.47\mu H$ $R = 15\Omega$ $D = 0.45$

- **Cell-inconsistency** in series battery string is **randomly**.
- **Performance of the equalizers** should be **similar** **under various voltage distribution.**
- **Circuit parameters and control scheme are the same in every simulation for a fairly comparison.**

Equalizer Performance Assessment Under Different Initial Condition – Use Case of UA-Model



(SI-E)

(SC-E)

(SR-E)

Equalized point

Equalized point

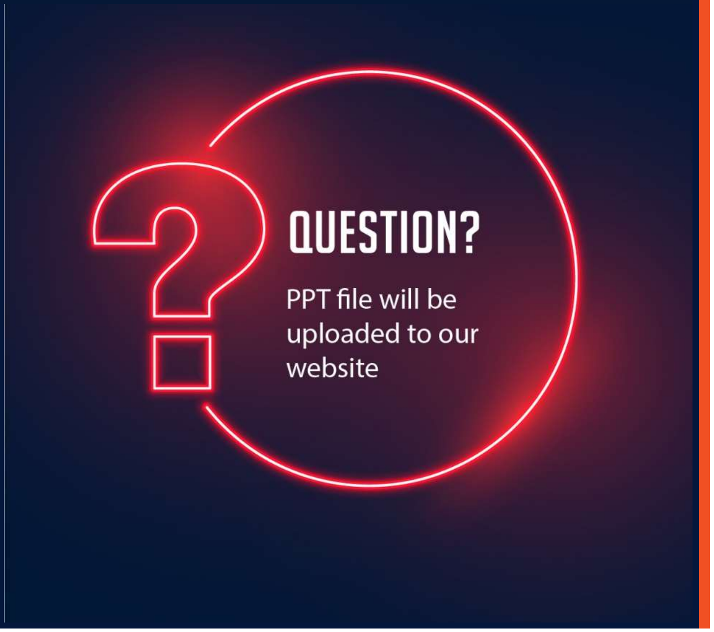
Equalized point

Adjacent cells equalization only

Conclusion

- **A unified average model** of the **switched-passive-network equalizer** is proposed to assess the **equalizer performance** in the **long-term operation.**
- The proposed **UA-model** can be implemented for the **most promising topology configurations such as SI-E, SC-E, and SR-E**.
- The comparison between the **simulation results on PSIM software** and **real-time simulation system** only revealed a **minor difference.**
- The **execution time of the overall simulation** is **significantly reduced**.
- **UA-model** is **a powerful tool for the equalization development** in terms of: **theoretical analysis verification**, **comparative study of various topologies**, **performance assessment under various initial conditions**, etc.

Thank You For Your Attention!



PPT file will be uploaded to our website

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