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Design and Analysis of Voltage Equalizer with Series-Parallel Switched-Capacitor for Battery/Supercapacitor Strings

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ABSTRACT: Series-parallel switched-capacitor power converter is reconfigured as a new voltage equalization circuitry for series-connected batteries or super capacitors. The model of the new voltage equalizer is derived and successfully used to analyze the equalization speed and energy loss. It is a very useful tool to analyze and design switched-capacitor-based equalization systems to meet different balancing speed requirements. Large numbers of battery or super capacitor cells are usually connected in series to meet high operating voltage requirements. All series-connected cells are therefore charged and discharge together. Due to non-uniform properties of individual cell, repeated charging and discharging will cause small imbalance in the form of unequal voltages existed among cells. To overcome this problem, the voltage balancing device, also known as a voltage equalizer, is indispensable equipment in battery management systems. Other type of active cell balancing methods is implemented by employing switched-capacitor (SC) as the energy transfer component. It has the advantages of small size and cost-effective as well as easy control. The analysis and modeling methods can be extended to other switched-capacitor-based voltage balancing systems. A prototype is built and the experimental results are also provided to confirm the theoretical analysis and modeling method.

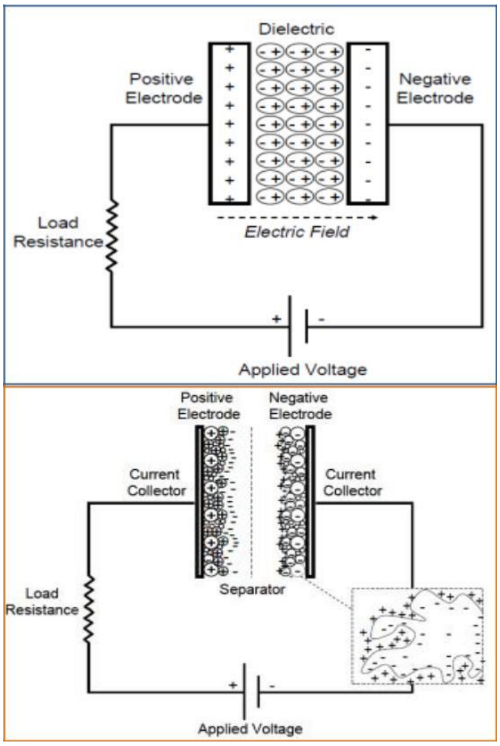
I. INTRODUCTION

In response to the changing global landscape, energy has become a primary focus of the major world powers and scientific community. There has been great interest in developing and refining more efficient energy storage devices. One such device, the super capacitor, has matured significantly over the last decade and emerged with the potential to facilitate major advances in energy storage. Super Capacitors (SC's) are energy storages having similarities with batteries and conventional capacitors. Unlike batteries, SC's store electrical energy, not chemical energy. Unlike capacitors SC's contain moving ions. Super capacitors (SCs), also known as electric double-layer capacitors or ultra-capacitors, are energy storage devices that store electrical energy without chemical reactions. Super capacitors (SC's) using now and in future possibilities are Regenerative braking, releasing the power in acceleration, Starting power in start-stop systems, Regulate voltage to the energy grid, Capture power when lowering loads and assisting when loads are lifted, Back-up power in any application where quick discharge/charge is required. Super capacitor manufacturers are **Europe** Skeleton technologies, WIMA, Yunasko, Batscap, All small players, etc., **US** Maxwell, Ioxus, etc., **Korea** Nesscap, Samwha LS Mtron, etc., **Japan** Panasonic, Murata, NEC, Nichicon, JSR Micro, etc.

II. SUPERCAPACITOR & APPLICATIONS:

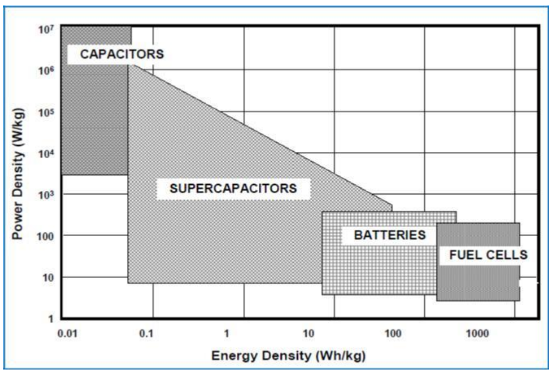
a) Working of Supercapacitor

Conventional capacitors consist of two conducting electrodes separated by an insulating dielectric material. When a voltage is applied to a capacitor, opposite charges accumulate on the surfaces of each electrode. The charges are kept separate by the dielectric, thus producing an electric field that allows the capacitor to store energy. Super capacitors are governed by the same basic principles as conventional capacitors. However, they incorporate electrodes with much higher surface areas A and much thinner dielectrics that decrease the distance D between the electrodes. Thus from above equations, this leads to an increase in both capacitance and energy.



b) Applications of Super Capacitor:

Super capacitors also are able to achieve comparable power densities. Additionally, Super capacitors have several advantages over electrochemical batteries and fuel cells, including higher power density, shorter charging times, and longer cycle life and shelf life. Super Capacitor can be used like a secondary battery when applied to DC circuit. The best suited applications of Super Capacitor are back-up device for the power shut-down of micro computers and RAM's. The performance improvement for a super capacitor is shown in a graph termed a "Ragone plot." It presents the power densities of various energy storage devices, measured along the y- axis, versus their energy densities, measured along the x-axis.It is seen that super capacitors occupy a region between conventional capacitors and batteries.



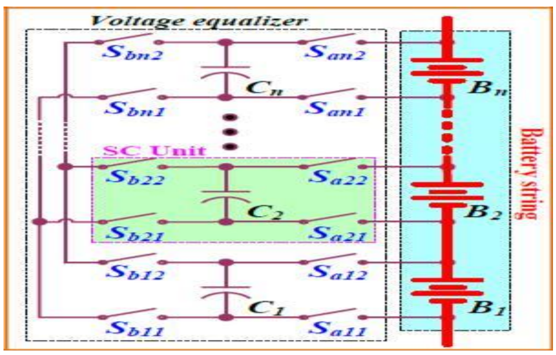
III. SWITCHED CAPACITOR (SC) VOLTAGE EQUALIZATION:

a) Introduction

Switched Capacitor (SC) scheme shuttling charge to adjacent cells was shown to increase the energy efficiency along a series string of connected battery cells. The switched capacitor method uses *n*-1 capacitors for a string of *n* batteries. The switched capacitor method, where one switched capacitor is implemented in every two adjacent cells and the equalizing path is controlled by the complementary switches *Si*1 and *Si*2 (*i*=1, 2,...,*n*).The charge is transferred from one cell to an adjacent one through an individual cell equalizer. Where the input signal is continuously available and applied to the circuit and the output signal is continuously observed. Called "continuous-time" circuits, such amplifiers find wide application in audio, video, and high speed analog systems. In many situations, however, we may sense the input only at periodic instants of time, ignoring its value at other times. The circuit then processes each "sample," producing a valid output at the end of each period. Such circuits are called "discrete-time" or "sampled-data" systems. a common class of discrete-time systems called "switched-capacitor (SC) circuits." Our objective is to provide the foundation for more advanced topics such as filters, comparators, ADCs, and DACs. Most of our study deals with switched-capacitor amplifiers but the concepts can be applied to other discrete-time circuits as well.

b) SC Voltage Equalization System

Series-connected batteries or electric double-layer capacitors (EDLCs) are widely used in handheld and portable consumer products, electric vehicles, as well as renewable energy applications such as photovoltaic and wind power generation systems.



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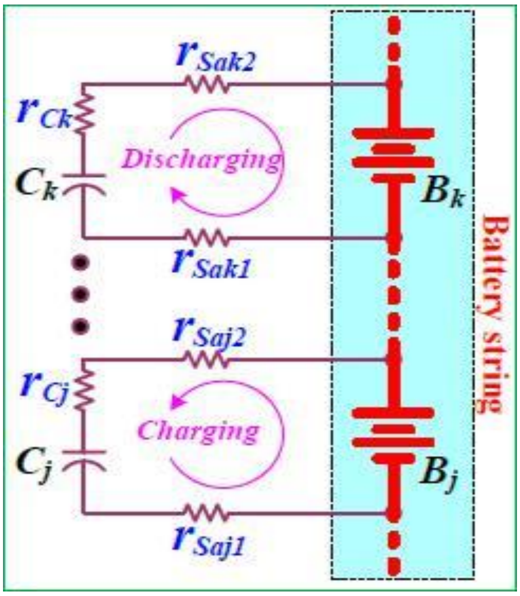
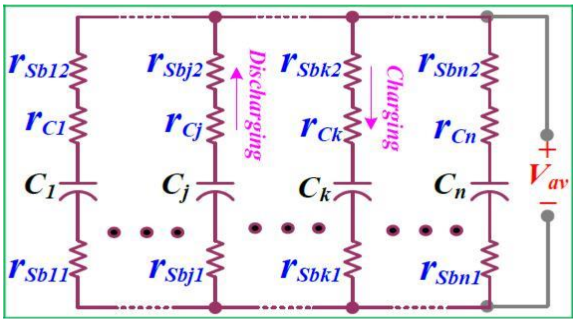
As a unit, the series string is charged and discharges together. Because of non-uniform individual cell properties, united operation causes the small imbalance in the form of unequal voltages among series cells during charging and discharging periods. Overcharge and deep discharge both will cause the battery cell to be deteriorated forever or even worse. The poor performance of single cell will limit the normal operation of the whole series string The voltage balancing device, also known as voltage equalizer, is therefore indispensable equipment in battery management systems (BMS)

c) Circuit Description & Operation Principle:

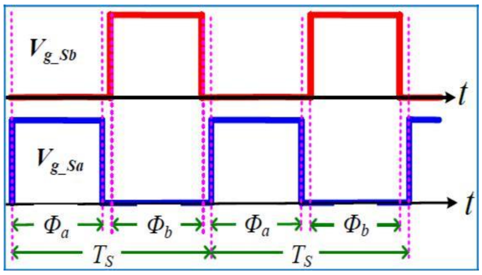
Switched capacitor (SC) voltage equalizers are developed by using SC converters to directly transfer charge from the higher voltage battery / ELDC cells to the lower ones.



The main advantages of this technique are that the bulky magnetic components are no longer needed and just a pair of complementary pulse signals with fixed duty ratio 0.5 is required to control all switches. It means SC voltage equalizer can be design with smaller size and lower cost. The switched capacitor (SC) cell balancing, is shown in Fig. As illustrated it requires *n-1*capacitors and *2n* switches to balance *n* cells. Its control strategy is simple because it has only two states. In addition, it does not need intelligent control and it can work in both recharging and discharging operation.

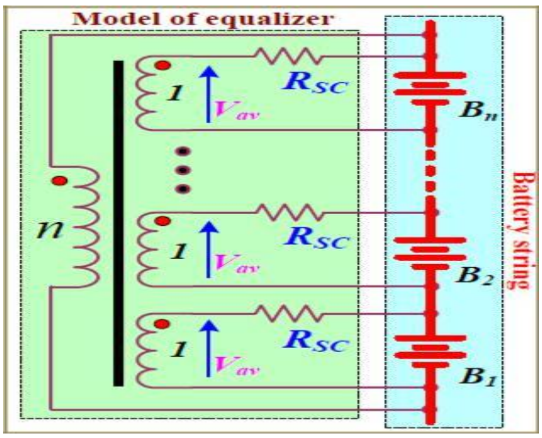


The equalization start by applying two complimentary signal of the PWM with duty cycle of 50% (actually the duty cycle is set to 45% to avoid shoot-through, case where the adjacent MOSFETs is on and shortened the cell) the signal. Each signal to group of MOSFETs and the charge will shuttle from one cell to another based on the voltage difference between them.

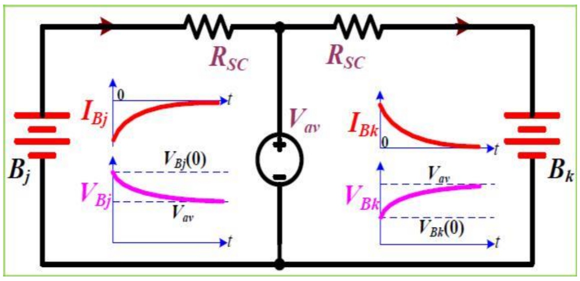


d) Advantages of SC Balancing System

The main advantages of this technique are that the bulky magnetic components are no longer needed and just a pair of complementary pulse signals with fixed duty ratio 0.5 is required to control all switches. It means SC voltage equalizer can be design with smaller size and lower cost. It does not need intelligent control and it can work in both recharging and discharging operation.



Series-connected batteries or electric double-layer capacitors (EDLCs) are widely used in handheld and portable consumer products, electric vehicles, as well as renewable energy applications such as photovoltaic and wind power generation systems.It shows the energy can be transferred from the higher voltage cells to the lower ones directly, rather than just be transferred between adjacent cells like the equalization circuit.



The voltage equalization process could be regarded as each separated battery cell discharges to or be charged by the constant voltage source *Vav* .It depicts the common voltage *Vav* in the model is constant for the whole equalization process even though all cell voltages are varied. In the power transfer process, there is no charge lost or produced and the total amount of charge is therefore always constant.

IV. ANALYSIS OF SC VOLTAGE EQUALIZER

a) Balancing Speed

There is a linear relationship between the cell voltage and the amount of charge storied in the cell. With the operation of the series-parallel SC voltage equalizer, charge transfers from the higher voltage cells to the corresponding switched capacitors during the phase *Φa* firstly. And then, these charge flows to other switched capacitors during the phase *Φb*. For the next phase *Φa*, the same amount of charge is released to the lower battery cells. In the power transfer process, there is no charge lost or produced and the total amount of charge is therefore always constant. It means the balancing time is mainly decided by the capacity of battery cell and the equivalent resistance of the SC equalizer.

b) Loss of Energy Conversion

The energy conversion loss is determined by the initial cell voltage distribution and the ended state instead of the balancing speed.

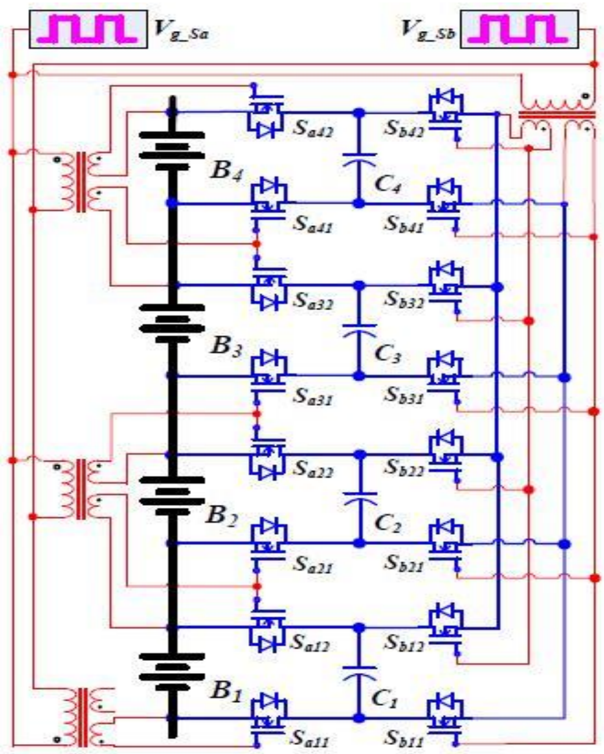
c) Design Steps

To meet different requirements of the balancing speed, circuit parameters including the value of capacitors and switching frequency can be determined according the model of SC balancing circuits.

V. SIMULATION MODEL AND PERFORMANCE EVALUATION

a) Simulink Model OF Proposed System

The circuit diagram of a four-cell series-parallel SC equalizer prototype built in laboratory. Multiple pulse transformers are employed to implement the gate drivers and all switches are implemented by N-channel MOSFET (IRLU8743PBF, 30V/3.1mΩ). For the switched capacitor *C*, two types of NICHICON NS-series electrolytic capacitor (100μF/21mΩ, 220uF/10mΩ) are used for the test. The pair of complementary control signals Vg_{Sa} and Vg_{Sb} is varied between 10 kHz and 30 kHz.With the four-cell SC voltage equalizer prototype, the cell balancing processes for two-, three- and four-cell supercapacitor strings are measured under different parameter conditions (*C*=220μF or 100μF; *f*=10kHz or 30kHz) that the equalization durations for two-, three- and four-cell are basically the same under the same experimental parameters.



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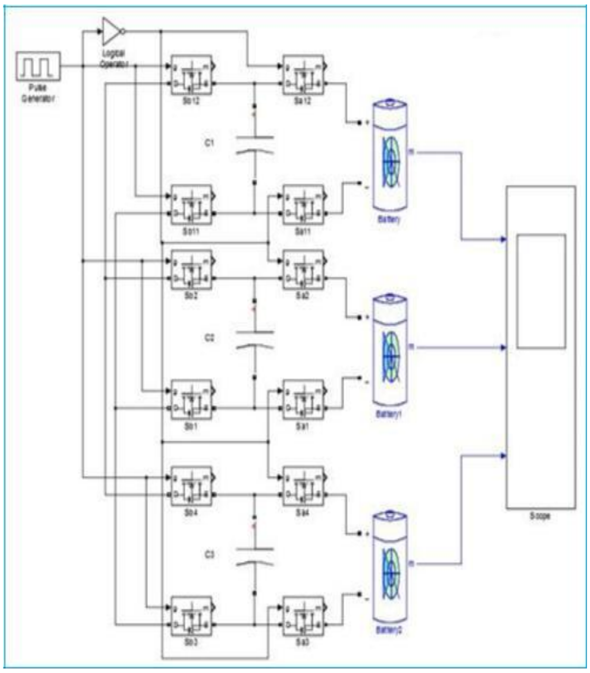
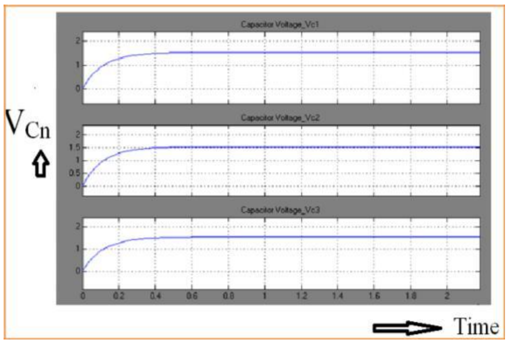
It means the balancing time is independent of the cell number & this conclusion is consistent with the model. The energy loss calculated according to the initial and final voltages is also added in each sub-figure. It can be found from each row that the energy loss is almost independent of the balancing time.

In order to make a systematic evaluation of the proposed scheme, it is assumed that the battery pack consists of *n* cells connected in series. Equalization speed is one of the major design parameters for a battery balancing scheme, because the serious imbalance in cell voltages is usually generated during the fast charge or discharge of battery, which reduces enormously the available capacity of the battery pack.In order to make a systematic evaluation of the proposed scheme, it is assumed that the battery pack consists of *n* cells connected in series. Equalization speed is one of the major design parameters for a battery balancing scheme, because the serious imbalance in cell voltages is usually generated during the fast charge or discharge of battery, which reduces enormously the available capacity of the battery pack.

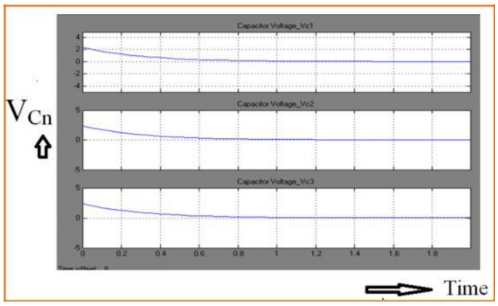


In general, the equalization speed is determined by the maximum equalization current and the average switching cycle. The maximum equalization current decides the transferred power among the cells in one switching cycle, and the average switching cycle to complete the charge transportation from the source cell to the target one decides the equalization speed and efficiency. The energy can be transferred directly from the source cell at any position to the target one at any position in the stack. Theoretically, it only takes one switching cycle to complete the charge transportation, which makes the cell balancing faster and more effective. In conclusion, the proposed equalizer offers a better equalization speed. Capacitor voltage in charging mode of operation is shown in Fig.5.4

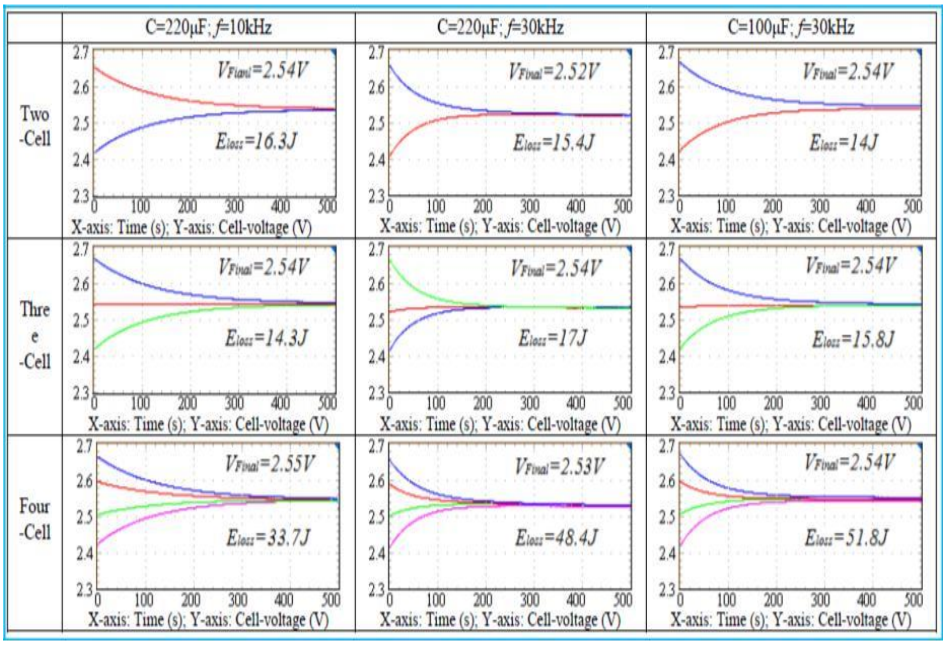
b) Discussion of Simulation Results



a) Capacitor voltage in charging mode of operation



b) Capacitor voltage in Discharging mode of operation



Output equalized voltage for series – parallel switched capacitor voltage equalizer

VI. CONCLUSION

The circuit configuration and operation principle of the series–parallel SC voltage equalizer are analyzed in this paper. Based on the detail state analysis, its model depicted as an ideal dc multi-winding transformer with multiple equivalent resistors is derived. The key of the model is the value of the equivalent resistor that related to the switching frequency and capacitance. Based on the model, the voltage equalization speed can be determined. It is very useful in practice to decide the switching frequency and select appropriate SCs to meet the different balancing speed requirements. The energy conversion loss is also discussed based on the derived model. Furthermore, four-cell equalizer prototype is built in laboratory to verify the theoretical analysis. A common equalizer, direct cell-to-cell methods (DCTCMs) is introduce to overcome the disadvantages of the adjacent cell-to-cell methods (ACTCMs). By using a common equalizer such as a capacitor, this method achieves the direct cell-to-cell charge transportation between any two cells in the battery stack. The DCTCMs consist of three methods: the flying capacitor, the flying inductor and the multiphase interleaved converter.

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