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Series Connected Super Capacitor and Li-Ion Capacitor Cells: Active Voltage Equalization

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Abstract: *Energy storage package usually consists of multiple cells. The associated cell equalization is important for cell package design. An innovative and efficient switched-capacitor balancing circuit is proposed in this paper to achieve cell voltage balancing for a package of hybrid energy sources. The key feature is that the balancing is not just restricted to equal cell voltage but is extended to different cell combinations that will be beneficial for non-sorted cell packages, for different types of Li-ion cells, and for other applications, such as second-life retired batteries. The topology and operation process of each switching state for this voltage equalizer are analyzed in detail. The mathematical derivation, software simulation, and laboratory experiment are conducted to verify the feasibility of this model. This proposed voltage equalizer is especially useful with the increasing establishment of hybrid systems, which take advantages of different types of energy sources or energy storage devices.*

Keywords: Voltage Balancing, Hybrid Energy Sources, Super Capacitors.

I. INTRODUCTION

Eco-friendly products become a major player of the global power and renewable energy industry. Batteries and super-capacitors (SC) are widely used in electric vehicles, distributed generation systems, energy storage systems and so on [1]–[3]. As the power of a single cell of battery or SC cannot provide sufficient driving force to loads, a series string of battery or SC units are required to fulfill the voltage and power requirements for high power applications [4].

However, different batteries and SCs in the same series have different characteristics such as capacitance, equivalent series resistance (ESR), equivalent series inductance (ESL) and self-discharging rate, which may lead to voltage imbalance between each cell in a system [4], [5]. In practice, although sorting is used before packaging in order to ease this phenomenon, the imbalance effect becomes more serious when the energy storage devices get aged. This imbalance phenomenon is now a well-known problem in series-parallel connection [1], [4], [6]. Due to unavoidable mismatch of each cell, the capability of the energy storage system cannot be fully used. In a charging cycle, the charging current stops when most or a portion of cells are fully charged while in the discharging cycle, the energy devices stop when most or a portion of cells are discharged to a lower limit [7], [8]. Voltage of cells shall be made equal to the required value to solve these unbalancing problems. The balancing is important especially when a group of electric vehicles (EV) batteries are in series connection to make up the high voltage for driving motor. Balancing for energy storage to the power distribution and renewable energy storage are in high demand and suitable technology of balancing is urgently needed for a number of applications. A variety of cell voltage equalizers have been presented which can be classified into three main types, including cell selection, passive methods and active methods [9]. Integrating cells with similar performance in one package is the simplest way, but the accuracy and efficiency during sorting are proved to be low. Passive method is the most widely used technology. Resistors in parallel with the cells are switched on when they have higher state-of-charge (SoC) than others or when the cells approach the peak withstanding voltage. As the energy dissipates into the resistor, additional heating loss is generated. For energy-saving purpose, the charging and discharging currents of each cell can be actively con- trolled to keep the same SoC among all cell units such that the higher energy can be transferred into the cells with lower energy using power converter circuit, instead of wasting as the heat loss. This active method is proved to be more efficient so that many advanced equalizers have been designed based on it using switched-capacitors, inductors, transformers or converters [1]–[4], [10]–[21]. Voltage balancing based on the switched-capacitor has simple structure and easy control [14]–[16]. References [17] and [18] are used switched-

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capacitors; the series–parallel switched-capacitor voltage equalizer are presented in [19]; converters applied in [20] to form the equalizer; induction motor in [21] could get the balancing function, but these papers mostly emphasize the balancing of single cells and series-parallel connections are applied for converters and inverters [23], [24]. Future EVs or distributed generation systems with hybrid energy systems are promising which take advantage of both battery and SC. As battery has high energy density while SC has high power density, they are combined to provide better performance of acceleration, emergency response [25] and energy storage [26]. Besides, integrating retired batteries from aged EVs into grid energy storage will greatly promote environmental protection and the re-use concept. However the compatibility issue between different cell brands imposes restraints on the development of energy storage system because cells have different back- ground in age, brand and chemicals. The technique proposed in this paper is intended to achieve the voltage balancing of a package of energy sources with a newly developed switched-capacitor circuit, regardless of the source types. Balancing techniques for different voltage ratios should be developed to improve the existing balancing methods and prepare for future vast applications of various balancing requirements. The circuit proposed could balance the voltage ratio not only 1:1 but also any preset ratio. Due to the increasing popularity of hybrid energy systems, the balancing system proposed in this paper is practical and useful for further development.

II. SWITCHED-CAPACITOR VOLTAGE BALANCING CIRCUIT

(i) Circuitry Description and Operation Principle- As indicated in Fig.1, the circuitry of the series-parallel switched-capacitor balancing circuit system consists of a package of hybrid energy sources and SC. Parameter n is defined in (1) where VP is the voltage of the source package and VSC is the voltage of SC. Three transistors and two capacitors form a balancing unit. The operation process of the proposed balancing system is divided into clock phase φ_a and clock phase φ_b with different switch positions as shown in Fig.2.

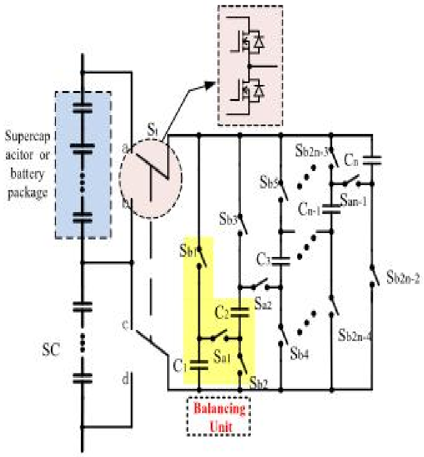

Figure 1. Voltage balancing circuit of package series-parallel switched-capacitor

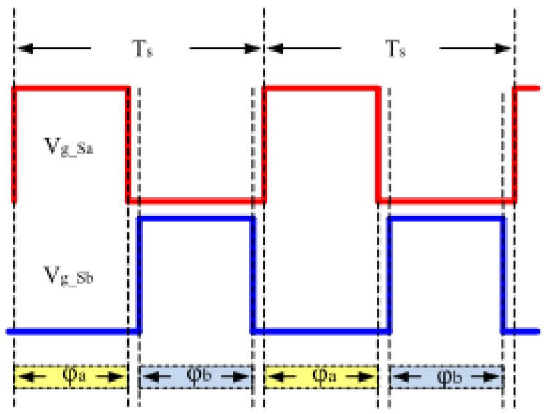

Figure 2. Control signal of the switches

$$n = \frac{V_P}{V_{SC}}$$

Fig.3 (a) illustrates the circuit in φ_a. When each pole of the main switch S_t is turned to connect a-c position, the source package is in series connection to the switched-capacitors.

When S_t is turned to connect b-d position in φ_b, the SC is in parallel connection to the switched-capacitors as shown in the Fig.3 (b).

(ii) State Analysis in Clock Phase φ_a- All the switches S_t, S_a and S_b in Fig. 1 can be implemented by N-channel MOSFET and controlled by the signals shown in Fig. 2. Fig. 3(a) shows the connection of the switch S_t . During the clock phase φ_a, St is in a-c position and capacitors C_1, C_2 to C_n are in series connection to the source package. If the voltage of source package is higher than that of switched-capacitors C_1, C2 to C_n, the switched-capacitors will be charged from the package.

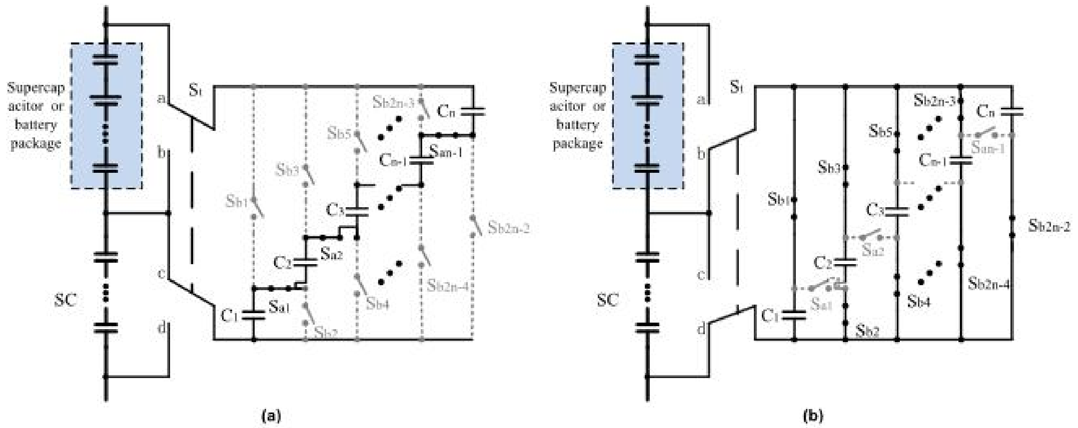

Figure 3. Working principle of the proposed balancing system. (a) Series to the source package; (b) Parallel to the SC

(iii) State Analysis in Clock Phase Φ_b- In the duration of φ_b, S_t is changed to b-d position and all the switched-capacitors are in parallel. When the voltage of the SC is higher than the voltage of the switched-capacitors connected in parallel, charge will transfer from the SC to switched-capacitors. Otherwise, SC will be charged by the switched-capacitors. $v_{Ci}(t)$ and $i_{Ci}(t)$ are the instantaneous voltage and current of the switched capacitors.

III. PASSIVE CELL BALANCING TECHNIQUES

Passive cell balancing utilizes a bleeding resistor in parallel to each cell and routes excess charge in the cell to a resistor which dissipates heat. Active cell balancing schemes overcomes this inefficient method and instead uses a DC-DC converter or a switched capacitor network to route charge to lower voltage cells. Typically, a passive cell balancing topology will have resistors connected in parallel with the cell through a power switch as shown in Fig.4. This technique is simple, easy to be implemented and inexpensive. However, it is not recommended as the energy from the higher voltage cell is lost in the balancing resistor in the form of heat which drastically reduces efficiency of the system. This technique additionally demands voltage monitoring for each cell to turn on and off the power switch. Adopting dissipative method also demands a good balance between heat dissipation and effectiveness of balancing, as excessive heat dissipation will complicate thermal management. Non-uniform temperature among cells in a string will only worsen voltage imbalance.

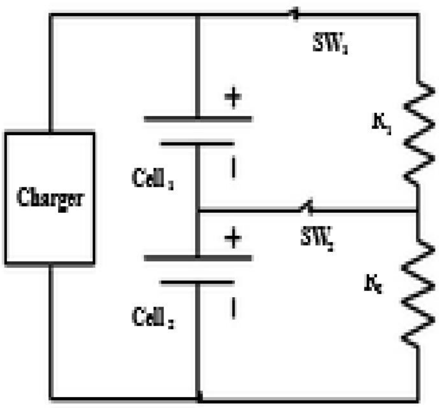

Fig. 4 Passive cell balancing using shunt resistances

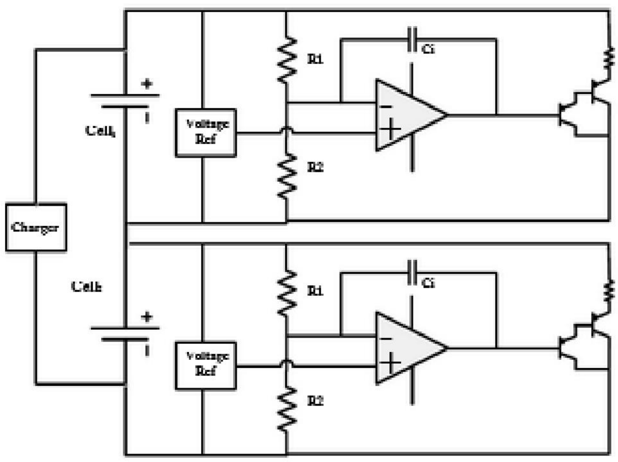

Fig. 5 Passive cell balancing using transistors and op-amps

A dissipative cell balancing technique utilizing transistors and op-amps as shown in Fig. 5 has also been previously attempted. In a string, when a cell reaches the maximum voltage level by constant current charging (this value is set by the voltage reference and divider) the current is routed around the cell while the cell is still being subjected to constant voltage charging; until every cell in the string reaches the maximum voltage. This technique is comparatively more efficient than using dissipative resistances in continuous mode as the current is only diverted to the transistors at the end of constant current charging. It does not need voltage monitoring and hence it is also cheaper.

IV. APPLICATIONS OF HIGH CAPACITANCE DEVICES

High capacitance cells may be used wherever high power delivery or electrical storage is required. This section outlines a small number of typical applications.

(i) Transport-The dynamic response requirements in many transport applications are ideal for super capacitor usage. Large internal combustion engines are currently started using the vehicle battery. The vehicle's battery is often oversized to accommodate this high power load. It also takes longer to recharge a battery due to higher internal resistance. Cold climates can also have a negative effect on battery performance. Therefore to provide power to the starter motor super capacitors are considered an excellent alternative to large lead acid batteries. Super capacitor technology is an excellent candidate for hybrid drive trains (either using internal combustion engine or fuel cell power plants) in electric cars as they can provide the high dynamic response required for good acceleration and regenerative braking.

(ii) Renewable Generation-Many renewable sources of energy are characterized by their transient nature; such as wind and solar generation. The variations in source energy and load demand cause shortfalls and surpluses in energy. Therefore, intermediate energy storage, capable of fast transients to match the energy source, is required and is an ideal application for super capacitors. Super capacitors can be used, either stand-alone or in hybrid with other energy storage systems, to control the power quality of PV array generation plants or wind generation and are usually connected via DC/DC converter to the DC link to stabilize generator output. There are also applications for direct integration with the grid-side converter.

(iii) Micro-Grid-Micro-grids are proposed in a number of different forms however many contain the requirement for some form of energy storage. Micro-grids with distributed generation can utilize energy storage for power quality during load transients.

(iv) Distribution- Good low voltage ride through capability is an important quality for distribution applications as well as distributed generation. Super capacitors have been proposed as energy storage media to provide the injected current to withstand fast grid voltage drop-out. Voltage sag compensation for sensitive loads using super capacitor energy storage systems canbe used to reduce outages caused by periodic dips in grid voltage.

V. CONCLUSION

In this paper, series-parallel circuit configuration and operation principles of the innovative switched capacitor voltage equalizer are demonstrated to effectively promote the use of hybrid source package composed of different cells. The equivalent circuit of the balancing model is described to show the process of voltage balancing. The key of the model is the use of an equivalent resistor which corresponds to the switching frequency and capacitance. The switching frequency and capacitance can be further adjusted to obtain the desired operation performance. An equalizer prototype for a package of energy sources with double voltage ratio is built in practical experiment to substantiate the validity of theoretical analysis. This innovative voltage equalizer is proved to be efficient and practical for industrial application. With the coming high demand in energy storage for mobility and renewable energy, the proposed technology provides a future development tool for non-equal cell integration. The components used in balancing is low-cost and of high efficiency.

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