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A Series Regeneration Converter Technique for Voltage Balancing of Energy Storage Devices

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Abstract

A single series resonant converter has been designed to balance the voltage level of a storage battery for electric vehicles. The proposed design has been simulated and verified by using two 100F supercapacitors instate of the conventional rechargeable battery. A voltage monitoring circuit detects the voltage condition of the individual capacitor and sends the voltage status to the control circuit for action. A technique has been developed to control a set of switches to transfer the current between the capacitor to balance the voltage level. The MATLAB simulated result shows the balancing circuit decreases the voltage difference between the two supercapacitors from 200 mV to 0V in 140 seconds, which is less than the existing methods. This fast voltage balancing technique can be used in the battery management system or electric vehicles for long lasting the battery life.

***Keywords**: Voltage balancing; electric vehicles; supercapacitor; battery; series resonant converter*

1. Introduction

With the world's continual economic increase, there have been huge developments of the electric vehicle in the transportation sector where a suitable substitute for Diesel or Gas is required as a convenient energy storage system. To a significant extent, fortunately, the goal of reducing greenhouse gas emissions may be aligned with the pursuit of other energy-related objectives, such as developing indigenous renewable resources and reducing local forms of pollution. In the near term, however, there will be tensions. Sustainable energy policies are more likely to succeed if they also contribute toward other societal and economic development objectives. Governments should look across policies to maximize positive interactions and avoid creating cost-cutting incentives.

The efficient exploitation, storage, and regulation of energy are important steps to reduce the dependence on expensive gas and diesel. Energy storage devices (ESD), which consists of batteries and supercapacitors, is nowadays very common product in the market. This ESD is increasingly used in portable electrical apparatuses, power system consumer applications and industries, military applications, telephone industry, energy storage system for photovoltaic system, space vehicles, electrical wheelchair and especially in electric vehicles system [1]. Each individual energy storage device has marginally dissimilar capacity due to aging, manufacturing tolerances and environmental situations. After a number of charging/discharging cycles, the energy storage devices or modules show a tendency to go out of balance in the form of unsatisfactory voltages along the series. Due to the imbalanced tendency, some energy storage devices or modules charge/discharge at a sharp rate and other energy storage devices or modules charge/discharge at a slower speed.

The energy storage devices or modules, like cells or batteries, are tempting due to their minor gauges and flexibility to assembly [2]. But supercapacitor has surpassed them because of its exclusive features namely, virtually infinite number of charging/discharging cycles, very high capacitance and inclusive operational temperature range. Supercapacitors can easily fulfill highly active loads because they have much specific power ratings than most extant batteries [3]. For electric vehicle application, supercapacitors can be used as a provisional ESD in combination with fuel cells or battery packs. A supercapacitor is also used as the particular energy source in electric vehicle [2], [4]. For a long distance application, supercapacitors have minor exact energy rating bans as well as potentially decreasing the battery thermal pressure

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and extended battery lifecycle by working in combination with the batteries to engage the braking energy and resource the energy through the vehicle acceleration [5].

Supercapacitor voltage characteristics depend on several issues namely, capacitive tolerance, leakage currents and self-discharge rates [6], [7]. For the aforementioned reasons, capacitive tolerance performs [8] the main role in voltage deviation if supercapacitors are connected in series. Though the supercapacitors are manufactured by the same company, their capacitances are not equal because of their altered chemical characteristics being dependent on the temperatures. For series coupled supercapacitors, current pass through supercapacitors' string are equal for all but each single supercapacitor voltage can be an imbalance [9]. During charging period, supercapacitors with maximum capacitance will be at minor voltages and not extend their full capability and those with minor capacitance will be at maximum voltages, and tentatively can be spoiled due to overvoltage. Therefore, to regulate them, it is essential to control the specific voltage of every single supercapacitor that is connected in series. Based on the arrangement of switching function, researchers have used different voltage equalization techniques [5], [10]-[12] which are, passive voltage equalization and active voltage equalization. A passive voltage equalization technique is also called an exhaust voltage equalization technique because an exhaust component coupled in parallel connection is used to avoid or draw excessive energy from a cell. In a resistive shunt equalization method [13], [14], the resistors associated with a shunt component through every cell will be of the similar value. Consequently, a strong cell disperses more power through the resistor than a weak cell, and the cells become equalized with time.

An active voltage equalization technique is also known as non-dissipative voltage equalization as it operates the active or non-dissipative components for the transfer of energy from one cell to another. In a switched-capacitor technique [12-16], a capacitor is commonly switched among the nearby cells. If there is a variance in voltage between the two nearby cells, then the voltage transfers from the stronger cell to the weaker cell with the assistance of a joint capacitor between two cells. The weaknesses of this technique are that though the cells in a series are balanced with their nearby cells; but, they don't do it with respect to the reference voltage, and that the equalizing time is too long [9], [17], [18].

In this paper, cell to cell a single series resonant converter balancing circuit is proposed. Though this converter is generally used for the voltage balancing of ESD, it is used for the supercapacitor in the proposed design. Switching frequency of this resonant converter is set similar to the resonant frequency because of charging or discharging time the resonant will just run half a period of the resonant frequency. The circuit impedance is reduced so that the converter can affect the zero-voltage gap between two ESD. This resonant converter works like an active multi-winding transformer circuit which can transfer energy among supercapacitors. The proposed circuit decreases the converter cost and can be manufactured in a smaller pack.

The rest contents of this paper have been organized as follows: In section 2, single series LC resonant tank voltage balancing scheme has been described. Section 3 contains the working principle and the equivalent circuit. Waveforms of resonant converter and voltage balancing, obtained from simulation, have been analyzed in section 4. In section 5, conclusions have been highlighted.

2. Proposed Voltage Balancing Technique

The proposed converter has been connected with a single series resonant tank circuit, presenting in Figure 1. This circuit consists of series connected ESD in which ESD_1 & ESD_n have two MOSFET switches and ESD_2 to ESD_{n-1} have four MOSFET switches that are associated with the resonant converter via busbar. Anti-series MOSFET switches are used to avoid body diode conduction when low voltage MOSFETs can't prevent the negative voltage due to the MOSFET fundamental body diode. All switches with every ESD are operating by the same signal.

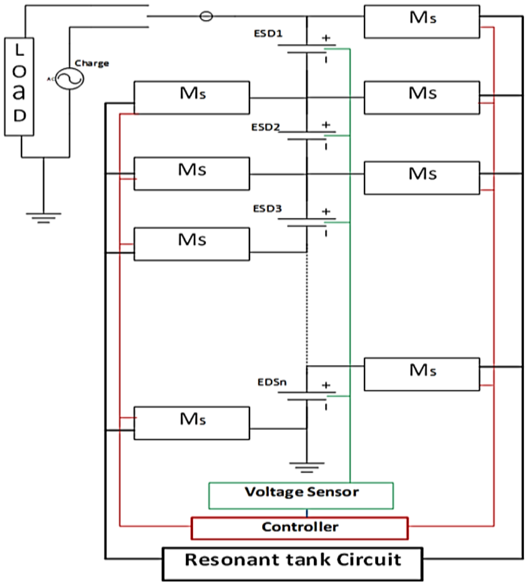
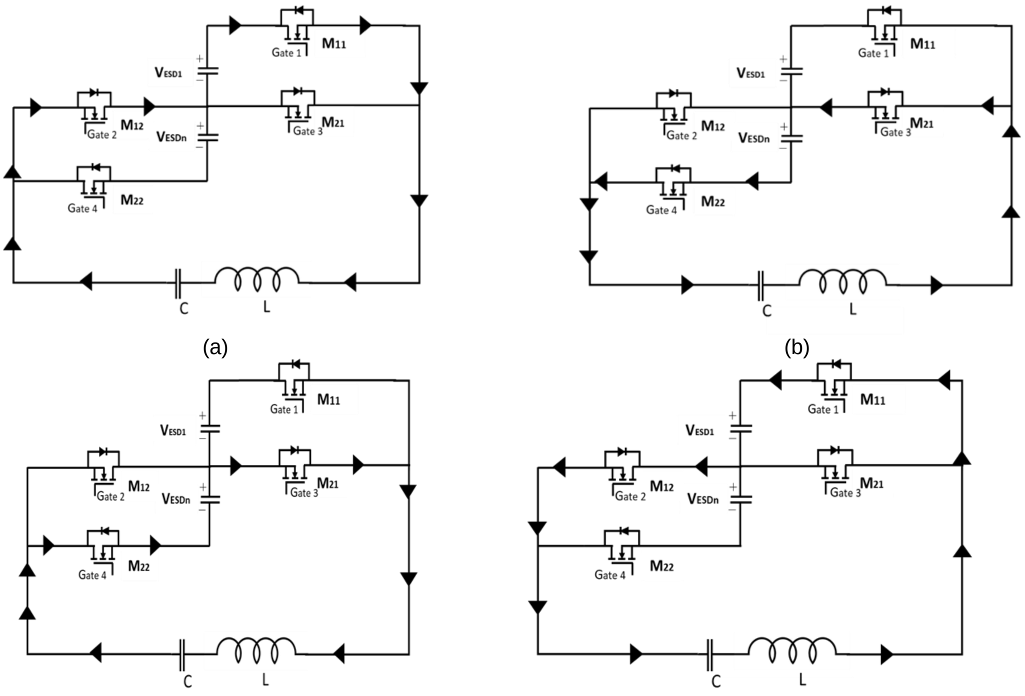


Figure 1. Effects of selecting different switching under dynamic condition

3. Working Principle

The operating principle of the proposed voltage balancing circuit is that it can balance between the two energy storage (ES) cells when their voltage difference is highest. In the resulting study, it is assumed that voltage, the voltage of ESD_1 cell is higher than the voltage of ESD_n cell. Every single cell operates in two operation modes, and each operation mode has two types of operation states for charging as well as discharging. Figure 2 has shown current routes for the operation of balance converter.



(a) (b)

(c) (d)

Figure 2. Current transportation path of the proposed circuit. (a) Energy store in LC from ESD_1, (b) LC release the energy and ESD_n store this energy, (c) Energy store in LC from ESD_n, (d) LC release the energy and ESD_1 store this energy

3.1. Working Mode I: ESD_1 > ESD_n

Charge state: In this stage, M_{11} and M_{12} are turned ON, and M_{21} and M_{22} are turned OFF. ESD_1, M_{11}, LC, and M_{12} form a bus circle and the current direction of the circle is clockwise, as shown in Figure 2(a). LC is charged by ESD_1 at this time.

Discharge state: In discharging condition, M_{11} and M_{12} switches are turned OFF, and consequently, M_{21}, M_{22} are turned ON. ESD_n, M_{21}, LC and M_{22} form a bus circle. The resonant tank releases all reserve energy to ESD_n, the resonant inductor current direction is anticlockwise, as shown in Figure 2(b). ESD_n is charged by LC at this time.

3.2. Working Mode II: ESD_n > ESD_1

Charge state: M_{21} and M_{22} are turned ON, M_{11} and M_{12} are turned OFF. ESD_n, M_{21}, LC and M_{22} form a bus circle and the current direction of the circle is clockwise, as shown in Figure 2(c). LC is charged by ESD_n at this time.

Discharge state: M_{21} and M_{22} are turned OFF, and M_{11} and M_{12} are turned ON. ESD_1, M_{11}, LC and M_{12} form a bus circle. The resonant tank releases all reserve energy to ESD_1, the resonant inductor current direction is anticlockwise, as shown in Figure 2(d). ESD_1 is charged by LC at this time.

3.3. Circuit Analysis

Using switches to transfer energy through a single resonant tank is used in the two-ES cell voltage balancing system as shown in Figure 2. The switches are controlled by a pair of complementary signals. MOSFET switches M_{11} and M_{12} are turned ON simultaneously in half of a switching cycle and MOSFET switches M_{21} and M_{22} are turned ON in another half cycle. The two-state circuits are shown in Figure 2. The following analysis is based on the proposition of ESD_1 > ESD_n.

When MOSFET switches M_{11} and M_{12} are turned ON and M_{21} and M_{22} are turned OFF, the resonant tank is connected via Bus in parallel with ESD_1 through M_{11} and M_{12} as shown in Figure 2(a). ESD_1 and LC form a resonant loop. Both of the voltage across the capacitor C and current i_r begin to increase as shown in the state Equations (1) to (3).

$$i_r = \frac{1}{L}\int_{t_0}^{t} V dt + i_{t_0} \tag{1}$$

$$L_r \frac{di}{dt} + V_{c_r} = V_{sc1} \tag{2}$$

At the resonant time,

$$V_{c_r} = V_c + \Delta V_{sc1}(\cos \omega t + \theta) \tag{3}$$

Here, V_{c_r} refer to voltage of resonant capacitor.

When MOSFET switches M_{21} and M_{22} are turned ON and M_{11} and M_{12} are turned OFF, the resonant tank is connected in parallel via Bus with ESD_n through M_{21} and M_{22} as shown in Figure 2(b). Switched capacitor C is activated to discharge by ESD_2. The resonant current starts to increase in opposite direction. LC, and ESD_n form a resonant loop as follows in Equations (1), (4) to (5).

$$L_r \frac{di}{dt} + V_{c_r} = V_{sc2} \tag{4}$$

At the resonant time

$$V_{c_r} = V_c - \Delta V_{sc1}(\cos \omega t + \theta) \tag{5}$$

In operational state, allowing for the standard voltage balance of the resonant capacitor V_c completed switching cycle shows in Equation (6).

$$i_L DT - i_L(1-D)T = 0 \tag{6}$$

Here, *D* is the duty cycle and *T* is the switching time.

4. Simulation Result and Discussion

An active charge balancing topology is developed using the MATLAB SIMULINK-2016 software. Two-supercapacitor voltage balancing converter technique was used for the topology. The capacitance of the two supercapacitors was 100F and voltages were initially set to 2.70V and 2.50V. All MOSFET switches were operated by pulse generator signals with 50% 0f each duty cycle and the switching frequency is same as resonant frequency. The inductor of the resonant tank was selected to 87μH and capacitor of the resonant tank was selected to 220 μF and initial voltage is 0 V. Simulation circuit shown in Figure 3.

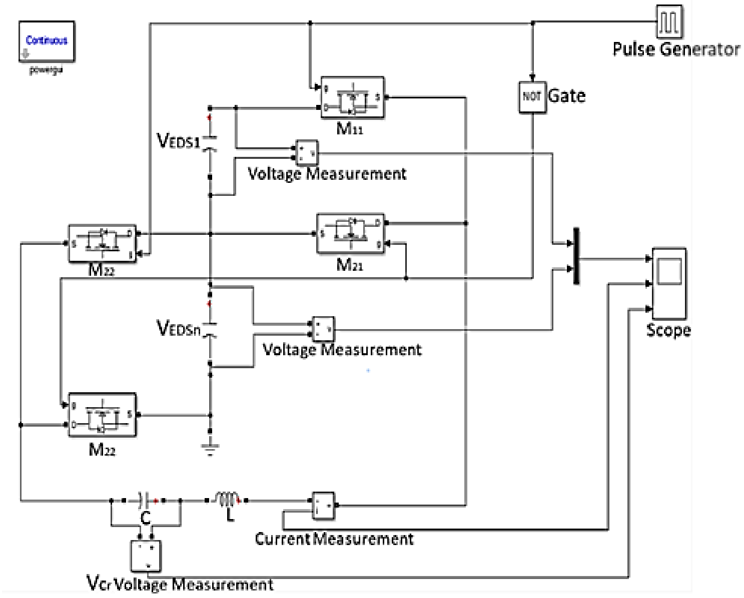


Figure 3. Simulation circuit using MATLAB SIMULINK-2016

Figure 4 shows that the pulse signal in gate 1, gate 2 and Gate 3, gate 4, resonant current and resonant capacitor voltage. The switching frequency is 1.15 kHz and that is equal to the resonant frequency. There is no switching voltage drop and circuit loss and charging/discharging state amplitude have same in resonant tank oscillation. In Figure 5 also shows the pulse signal in gate 1, gate 2 and gate 3, gate 4, resonant current and resonant capacitor voltage. The switching frequency is 575.2 Hz and that is half of resonant frequency. From the Figure 5 it can be seen that there is no switching voltage drop and circuit loss and charging state amplitude and discharging state amplitude have not same in resonant tank oscillation and current through the circuit is interrupted. For this reason, after 140 seconds voltage difference between two supercapacitors are 180mV that shown in Figure 6.

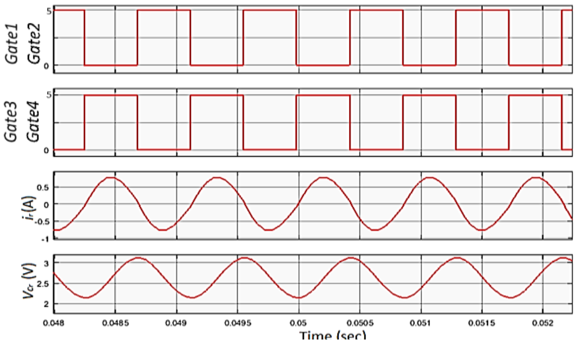


Figure 4. Simulation waveforms of the two supercapacitor scheme with an internal resistor ($f_r = f_s$)

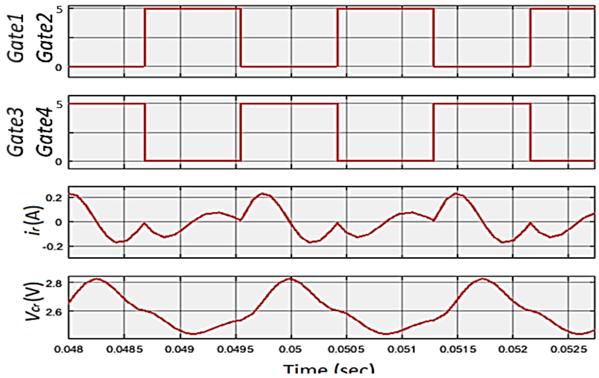


Figure 5. Simulation waveforms of the two supercapacitor scheme with an internal resistor (f_r = $2f_S$)

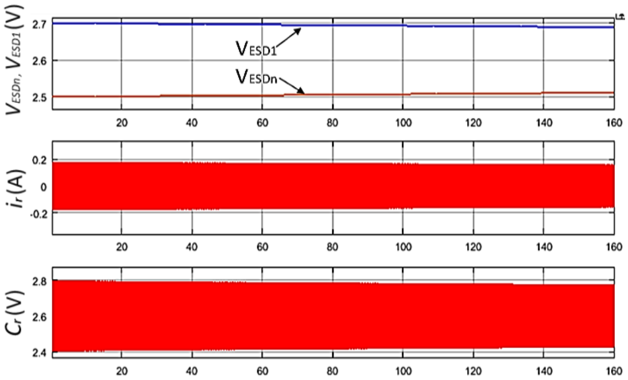


Figure 6. Simulation waveforms of the two supercapacitor voltage balancing scheme (fr = 2fs)

Figure 7 shows two supercapacitor voltage balancing result. In operation time, when the voltage gap between two supercapacitor decreases, resonant current as well as the amplitude of the resonant capacitor oscillation also decrease simultaneously. After 140 seconds, voltages between two supercapacitors are equal and the resonance stops.

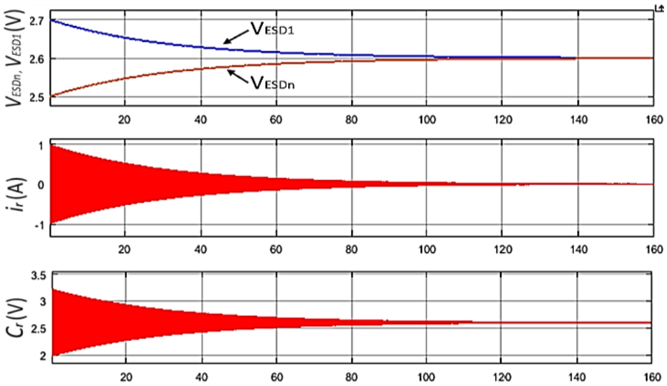


Figure 7. Simulation waveforms of the two supercapacitor voltage balancing scheme

4. Conclusion

In this paper, a novel bus connected any cell to cell voltage balancing technique is proposed and a single series resonant converter is used for balancing. In ESD, including Li-ion batteries and supercapacitors are joined in series to run into higher bus voltage required for EV. Based on the study and analysis, this topology has some advantages that can be summarized as follows:

a) Balancing efficiency of any connected cell to any connected cell is increased.
b) Takes less balancing time and has a small circuit size.
c) Easy to control and easy module implementation.
d) As single LC resonant tank is used via a bus connection, the cost of the circuit is smaller.

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