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Research of Supercapacitor Voltage Equalization Strategy on Rubber-Tyred Gantry Crane Energy Saving System

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Abstract: A model for supercapacitor voltage equalization strategy is analyzed, and on this basis a supercapacitor voltage equalization method for Rubber Tyred Gantry Crane (RTG) energy saving system is proposed, namely active voltage equalization method based on Buck-Boost converter. The equalizing speed of the proposed method is fast. Firstly, the working principle and process of the voltage equalization circuit is analyzed in detail. In addition, design of active voltage equalization circuit parameters and control strategy are given. Finally, simulation analysis of the series connection of supercapacitors module is performed. Results show that this method for equalizing voltage can avoid over-voltage of each cell and possess practicable and high value for supercapacitor RTG energy saving system.

Keywords: supercapacitor, energy saving, rubber tyred gantry crane (RTG), voltage sharing, sesign of active equalization circuit

1. Introduction

Supercapacitor is a novel energy storage device based on the principle of the double layer-electrolyte capacity, which has many merits such as long lifetime, high efficiency, fast dynamic response, etc. So it is a power storage technology that has a bright future in power storage development. The power driver system in energy -saving RTG is composed of the diesel generator set, power balance system (made by supercapacitors), controller and the rising electromotor. Supercapacitors are used for storing energy from which electromotor generates and brakes energy when the load is fallen down, the supercapacitors release the energy which has been stored when the load is raising. Thus the original energy which is consumed by the braking resistance is recycled totally, then the purpose of energy saving and environment protection is realized.

Due to the lower voltage of a single supercapacitor, generally speaking, the series and parallel connection of supercapacitors form the energy storage module to meet the energy storage capacity and higher voltage requirements. However, the operational voltage of supercapacitors is different, and a local over-voltage can appear over one or several supercapacitors, which would affect the lifetime and reliability of the system. Therefore, it is essential and critical to research and realize supercarpacitors voltage equalization technology for improving the supercapacitors power storage technology.

The present supercapacitors voltage equalization technology mainly includes zener diode type, switch resistor type, switch capacitor type, inductor type, forward converter type and flyback converter type voltage equalization circuits, etc. The switching resistor type and voltage-regulator diode type voltage equalization circuits consume amount of energy because of utilizing energy-consuming devices, so the system has lower efficiency and poorer reliability [1]. The switching capacitor type and inductor type voltage equalization circuits have ineffective energy flowing, especially when the two adjacent supercapacitors voltage difference is very closer or when much more supercapacitors are in series connection, balancing speed will be slower [2]. Forward converter type and flyback converter type voltage equalization circuit have a higher efficiency, but they are not attractive, because they also have many demerits such as complicated magnetic circuit, big volume, difficult extended winding and large voltage equalization error, etc [3]. In view of the existing problems of the above voltage equalization methods, the paper proposes an active voltage equalization method based on the principle of Buck-Boost converter, this method can transfer energy from the high-voltage supercapacitors to the low-voltage ones through the converter rapidly, and it has the character of the low energy loss and the high equalizing speed in the process of charging and discharging.

2. Analysis of Voltage Equalization Model

The supercapacitor charging equalizing model is shown in Figure 1. On the basis of the paper [4], the model is further analyzed in detail. Assuming the value of two optional supercapacitors are C_1 and C_2, d_1 and d_2 are capacity deviation values of the supercapacitors C_1 and C_2 respectively, we define the values of C_1 and C_2 as below:

$$C_1 = C(1+d_1)\,,\quad C_2 = C(1+d_2) \tag{1}$$

where C is the reference value for capacitors.

If two supercapacitors are connected in series, both of the initial voltage values are zero, a constant current I charges supercapacitors, the voltage difference during the same time t is defined as following:

$$\Delta U = \left|U_{C1} - U_{C2}\right| = \frac{\Delta C}{C_1 C_2} It \tag{2}$$

where ΔC is the capacity difference between C_1 and C_2.

If two supercapacitors are connected in series, both of the initial voltage values are zero, when different constant currents I_{c1} and I_{c2} charge supercapacitors, the voltage difference during the same time t can be expressed as in (3):

$$\Delta U = \left(\frac{I_{c1}}{C_1} - \frac{I_{c2}}{C_2}\right)t \tag{3}$$

Substituting (1) into (3) when the voltage difference is zero, the relation between charging current and the supercapacitor capacity deviation can be obtained as follows:

$$\frac{I_{c1}}{I_{c2}} = \frac{C_2}{C_1} = \frac{1+d_1}{1+d_2} \tag{4}$$

If two supercapacitors are connected in series, both of the initial voltage values are zero, the supercapacitors voltage rise from zero to the upper voltage U_u when

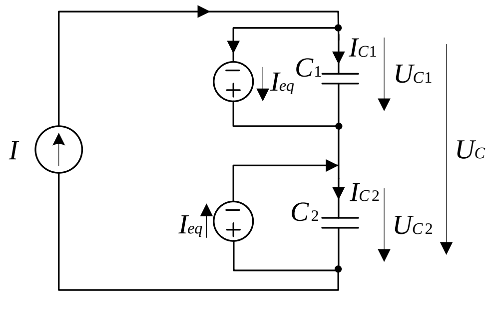

Figure 1. The supercapacitor charging equalizing model

constant current charges supercapacitors, the two cells voltages can be, respectively, calculated as:

$$U_{c1} = \frac{1+d_1+d_2}{2+d_1+d_2}U_c\,,\quad U_{c2} = \frac{1}{2+d_1+d_2}U_c \tag{5}$$

where U_{c1} and U_{c2} are the voltages across the supercapacitors C_1 and C_2 at the end of charging and U_c is the total voltage. Obviously, the two supercapacitors capabilities are same when $d_1 = d_2 = 0$, thus, the capacitors voltages can be described as: $U_{c1} = U_{c2} = U_c/2 = U_u$.

As Figure 1 is shown, assuming a current of equalizing current supply $I_{eq} = k_j I$ (both the two current supplies are reverse direction) is parallel connected with each capacitor side, k_j is equalizing coefficient. Then, the charging current across C_1 and C_2 can be, respectively, described as:

$$I_{C1} = I(1-K_j)\,,\ I_{C2} = I(1+K_j) \tag{6}$$

Substituting (6) into (4), the ration between constant current source I and the charging current I_{eq} can be expressed as follows:

$$k_j = \frac{d_2 - d_1}{2+d_1+d_2} \tag{7}$$

Then, the two supercapacitors charging current can be, respectively, calculated as:

$$I_{c1} = \frac{2+2d_1}{2+d_1+d_2}I\,,\quad I_{c2} = \frac{2+2d_2}{2+d_1+d_2}I \tag{8}$$

Usually the supercapacitor capacity deviation d is not zero, but it is a random value, which variable range is $-10\% \sim +20\%$. The relation between the equalizing current I_{eq} and the charging current I can be calculated from d and (7) when the supercapacitors are in voltage equalization state.

$$I_{eq} \geq 0.143I \tag{9}$$

From (3), it can be concluded that if the supercapacitors initial voltage is not zero, the voltage difference ΔU will decrease gradually, and k_j value continues to increase, the voltage difference across the supercapacitors reduces more quickly.

3. Active Voltage Equalization Circuit

In view of the energy of the high-voltage supercapacitors is directly transferred to the low-voltage supercapacitors, this paper proposes an effective voltage equalization method-Active Circuit of Voltages Balance for the Series Supercapacitors. This method compares with the methods of “INDUCTION”, and it is characterized by the low energy loss and the high equalizing speed in the process of charging and discharging.

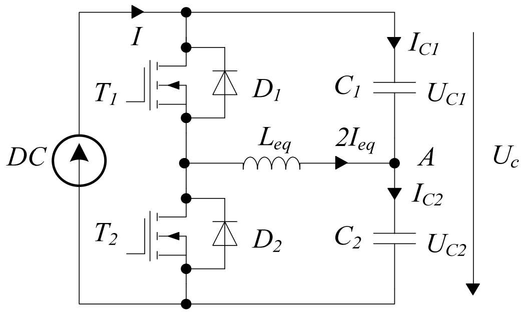

Figure 2. Active circuit of voltages equalization for two series supercapacitors

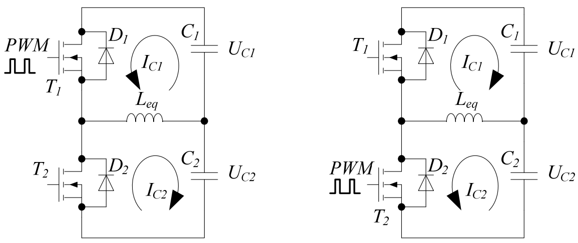

Figure 3. The principle circuit of active voltages balance

3.1 The Basic Operational Principle

As shown in Figure 6, switches T_1, T_2 are MOSFET; diodes D_1, D_2 are continued flow diodes; L_{eq} is the energy storage inductor; C_1, C_2 are two adjacent series cells, respectively. A Buck-Boost converter can be connected with two adjacent cells of supercapacitors.

The basic operational principle is shown in Figure 7. As is shown in Figure 3(a) below, when $U_{c1} > U_{c2}$, a PWM drive signal is given to the switches, and switch T_2 is turned off and T_1 is turned on. While T_1 is on, supercapacitor C_1, switch T_1 and inductor L_{eq} forms a loop circuit, whose current is I_{c1}. The part of energy of supercapacitor C_1 transfers to inductor L_{eq}. While T_1 is off, supercapacitor C_2, inductor L_{eq} and the diode D_2 forms a loop circuit, whose current is I_{c2}. The energy of inductor L_{eq} transfers to supercapacitor C_2. Similarly, as is shown in Figure 3(b) below, when $U_{c1} < U_{c2}$, switch T_1 is turned off and T_2 is turned on. The energy transfers from C_2 to C_1 until the voltages of the two supercapacitors are same.

3.2 Analysis of Operation Process of Voltage Equalization

According to the above principle of voltage equalization, and in order to analyze the operation process of the circuit, assume that the following items are satisfied:

1) It is assumed that the voltage of diode, the internal resistance of inductor, the on-resistance of the switch and the resistance of the circuit are all ignored, and super-capacitors are assumed to be ideal capacitors;

2) The circuit works in discontinuous conduction mode (DCM);

3) The capacity of the supercapacitor C_m is less than that of C_{m+1}, that it is to say, the supercapacitor C_m voltage is higher than C_{m+1}, where m is positive integer;

4) Because of the large capacity of supercapacitors and high swtiching frequency, the supercapacitor can be seen as a voltage supply during a switching period.

Equivalent circuit of active voltage equalization system of two supercapacitors is shown in Figure 4. Referring to the above equivalent circuit, the operating process of the voltage equalization can be analyzed in detail as follows:

3.2.1 Operation Mode 1 ($0 \le t \le D_1 T$)

At $t = 0$, the switch T_m is turned on, the diode D_m is turned off. According to the above assumption, the Figure 4 can be equivalent to Figure 5. During this operation mode, the supercapacitor C_m charges inductor

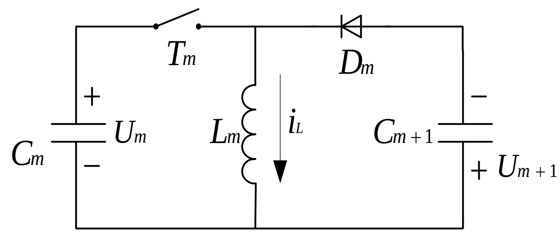

Figure 4. The equivalent circuit of active voltage equalization system

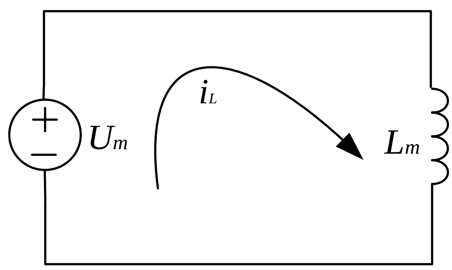

Figure 5. Equivalent circuit at mode 1

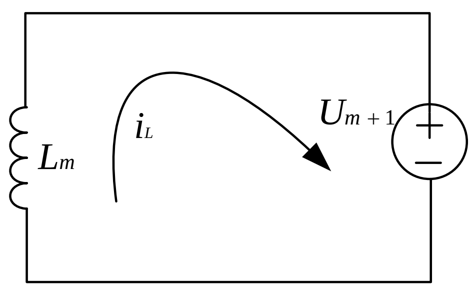

Figure 6. Equivalent circuit at mode 2

L_m, and energy is stored in inductor L_m, the inductor current keeps rising linearly. Thus,

$$L\frac{i_L}{D_1 \times T} = U_m \quad (10)$$

3.2.2 Operation Mode 2 ($D_1T \le t \le (D_1 + D_2)T$)

At $t = D_1T$, the switch T_m is turned off, the diode D_m is turned on. The Figure 4 can be equivalent to Figure 6. During this operation mode, the inductor L_m discharges supercapacitor C_m, energy is transferred to supercapacitor C_m, the inductor current keeps falling linearly from peak value to zero. Thus,

$$L\frac{i_L}{D_2 \times T} = U_{m+1} \quad (11)$$

3.2.3 Operation Mode 3 ($(D_1 + D_2)T \le t \le T$)

In this operation mode, the switch T_m and the diode D_m are all turned off.

4. Design and Simulation of Active Voltage Equalization Circuit

4.1 Design of the Active Voltage Equalization Circuit Parameters and Control Strategy

4.1.1 Operation Range of Duty Ratio

The following conclusion can be obtained from the (10) and (11).

$$U_m \cdot D_1 = U_{m+1} \cdot D_2 \quad (12)$$

When the voltage equalization system works at steady state, the difference between U_m and U_{m+1} is very little. Thus, we can think $U_m = U_{m+1} = U$, in addition, because the circuit works in discontinuous conduction mode(DCM).

Then, $D_1 + D_2 < 1$, $D_1 = D_2$. thus,

$$D_1 = D_2 = D < 50\% \quad (13)$$

From the above inequation, we can obtain $D < 50\%$.

4.1.2 Inductor Selection

In a switching period, the working curve of inductor(L) current is shown in the Figure 7. The average current releases from Supercapacitor to the inductor L is:

$$I_{avg} = \frac{D \times I_L}{2} \quad (14)$$

where I_L is the peak current of inductor, and it can be expressed as below:

$$I_L = \frac{DT \times U}{L} \quad (15)$$

Substituting (14) into (15), thus, the average current can be calculated as follows:

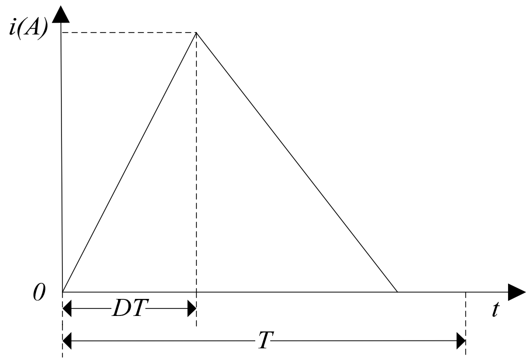

Figure 7. Working curve of inductor current

$$I_{avg} = \frac{D^2 \times T \times U}{2 \times L} \quad (16)$$

From what has been analyzed, it is considered that the average current of the inductor is also the equalizing current of active voltage equalization circuit. According to the principle of voltage equalization of supercapacitors, if the high-voltage supercapacitors release the average current I_{avg} more than the equalizing current I_{eq}, the voltage equalization can be realized. In order to increase the voltage equalizing speed, select the coefficient $k_j \ge 0.2$, then $I_{avg} \ge 0.2 \times I$, and substituting this in Equation into (16), the inductor L can be obtained as follows:

$$L \le \frac{D^2 \times T \times U}{0.4 \times I} \quad (17)$$

In the circuit design, once the energy storage inductor L is selected, there are two ways to adjust the switching period:

1) Selecting the fixed switching period T, the equalizing current will be restrained by the limited cell voltage U in the process of charging and discharging, which makes it as a function of the voltage U;

2) The switching period T changes with the voltage U, which makes balancing current become a fixed value.

4.1.3 Voltage Equalization Control Strategy

Measuring two supercapacitors voltage U_m and U_{m+1}, the voltage difference can be calculated by the Equation $\Delta U_m = U_m - U_{m+1}$, and comparing the difference with the reference voltage U_{ref}, if $\Delta U_m \ge U_{ref}$, then the voltage Equalization circuit begins to work; if $\Delta U_m \le U_{ref}$, then the voltage equalization circuit stops working. In fact, if make all the supercapacitors reach the voltage equalization, every adjacent two supercapacitors will be parallel connected with a Buck-Boost converter, the voltage equalization controller generates different diving signals by analyzing all the measured supercapacitors

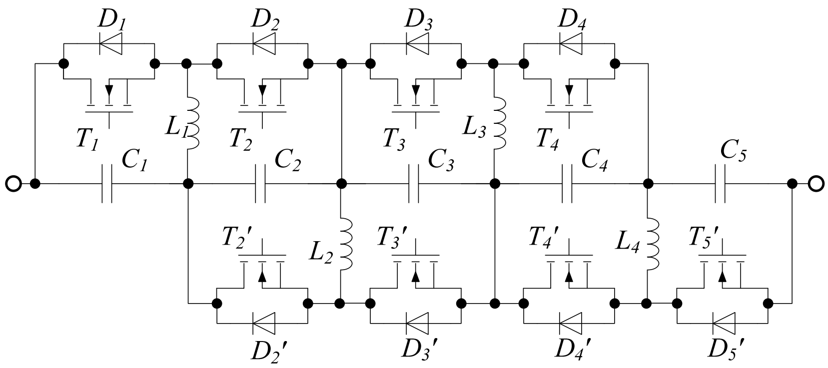

Figure 8. Active circuit of voltages balance for five superca-pacitors series

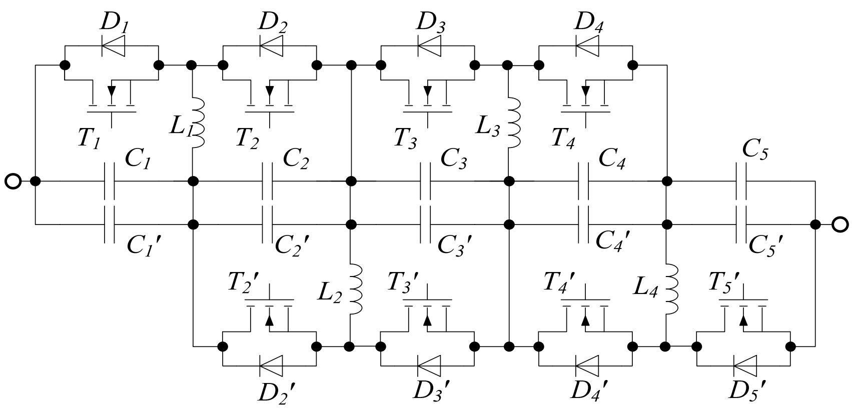

Figure 9. Active circuit of voltages balance for ten supercapacitors

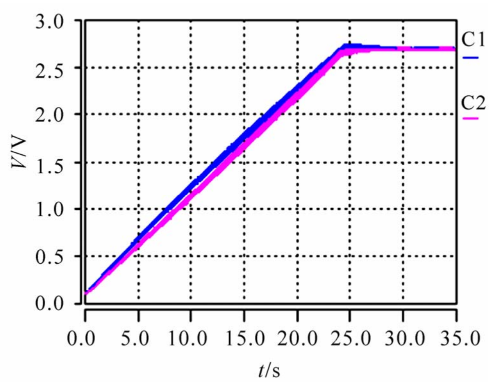

Figure 10. Simulation results of voltages balance for super-capacitors

voltage to drive MOSFET, in this way, equalization among all supercapacitors will be achieved at last.

4.2 The Extension Circuit of Voltage Equalization

Extending the above circuit, we can make it suitable for more series supercapacitor cells to meet the requirement of the RTG energy saving system. As is shown in Figure 8, we can see every two adjacent supercapacitors constitute a group which is controlled to balance voltage by a Buck-Boost converter. For example, the converter, which is composed of T_1, D_1, T_2 and D_2, balances the voltages between C_1 and C_2, and another one is composed of T_2, D_2, T_3' and D_3', balances the voltages between C_2 and C_3.The principle of equalization among C_3, C_4 and C_5 is the same as the above [5].

Considering the demand of hundreds of supercapacitor cells in RTG energy saving system, the series structure, as shown in Figure 8, makes the control components increase markedly and the control circuit become complicated. So the series and parallel structure in Figure 9, can be adopted in practical application.

4.3 Saber Simulation Analysis

In order to verify the character of the active voltage balance circuit in the energy recycling RTG system, we research the circuit composed of two supercapacitor cells in series module by the simulation study of Saber. Assume that the capacitance of one supercapacitor is

800F and the other one is 1000F, the constant charging current is 100A, the rate voltage of the supercapacitor is 2.7 V, the energy storage inductor is 1.36uH and the switching frequency is 10 kHz.

Figure 10 describes the process of charging two supercapacitors. It can be seen, at the end of the process, that the voltages of two supercapacitors become the same, no over-voltage. The result of Saber simulation indicates that active voltage balance circuit amends the inconsistency of the supercapacitor voltage greatly.

5. Conclusions

The active voltage equalization circuit based on the reversible Buck-Boost converter has been discussed in this paper. Theoretical analysis and simulation result show that the active control circuit can better solve the problem of the partial over-voltage over the supercapacitor groups. This method can be applied in the situation of higher charging or discharging current. Therefore, it has a high value to be used in the RTG energy saving system.

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