Study Of Active Voltage Balancing Circuits For Higher Voltage Supercapacitor Modules

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Abstract- *Series connected Supercapacitors (SC) having voltage imbalance causes ageing and deterioration in energy storage capability of SC cells, reduces its efficiency and cycle life. Individual SC cells are capable of withstanding only 1 to 3 V. In higher voltage SC modules for various applications, Voltage balancing is necessary to have better cycle life and efficiency. This paper presents various voltage balancing circuits used for voltage balancing, advantages of active balancing circuits over passive balancing circuits. Design of Buck boost converter circuit is discussed in detail; MATLAB simulation results from literature are discussed.*

Keywords: Supercapacitor, Active/passive Voltage balancing, Buck boost converter, MATLAB.

I. INTRODUCTION

Single SC can only withstand very low voltage, 1 to 3 volt maximum. For high voltage applications SC cells to be connected in series and parallel based on application. Balancing circuit is necessary to maintain constant voltage across individual cell to its rated voltage. SC manufacturing offers tolerance on capacitance, this leads to voltage unbalance at the time of charging and discharging. Unbalanced voltage within the module reduces its efficiency and overloading of low capacitance cell. This overloading leads to ageing of SC cell. Ageing results into fatal failure of SC module. Literature review is carried out to study the various voltage balancing circuits. Voltage balancing is nothing but dissipating the extra energy in the form of heat or exchanging the energy between mismatched SC cells.

Voltage balancing circuits are broadly classified as passive voltage balancing and active voltage balancing circuits. This classification is based on the components used within the balancing circuit. Passive balancing circuits remove extra charge from SC cell with help of passive elements i.e. resistor. This ensures balancing of voltage between the SC cells connected within module with respect to module voltage or reference set. Resistor may be fixed resistor and switched resistor based on the system requirement. Active voltage balancing methods extract charge form higher energy cell and supply it to lower energy cell. Various active balancing circuits are used based on the energy storage element used i.e. capacitor or inductive device and converter topologies used for switching.

Passive voltage balancing methods are loss making for the system. Active voltage balancing methods are efficient. In order to achieve higher system voltage with better efficiency and performance of SC modules, various active voltage balancing methods are proposed.

II. VOLTAGE BALANCING CIRCUITS FOR SC MODULE

Detail classification voltage balancing methods is shown in fig 2. Voltage balancing circuits are classified as passive voltage balancing and active voltage balancing. Passive balancing can be further classified as fixed resistor balancing and switched resistor balancing circuits. Active voltage balancing circuits are classified according to active element used such as inductor/transformer based, capacitor based and converter based active balancing circuits. [1-5].

A. Passive Voltage Balancing Circuit for SC module:

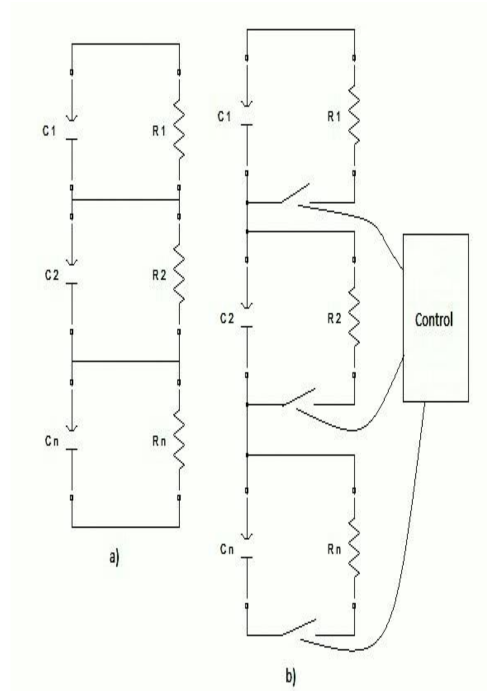

Fig.1: Passive Balancing Circuits [1] [3]

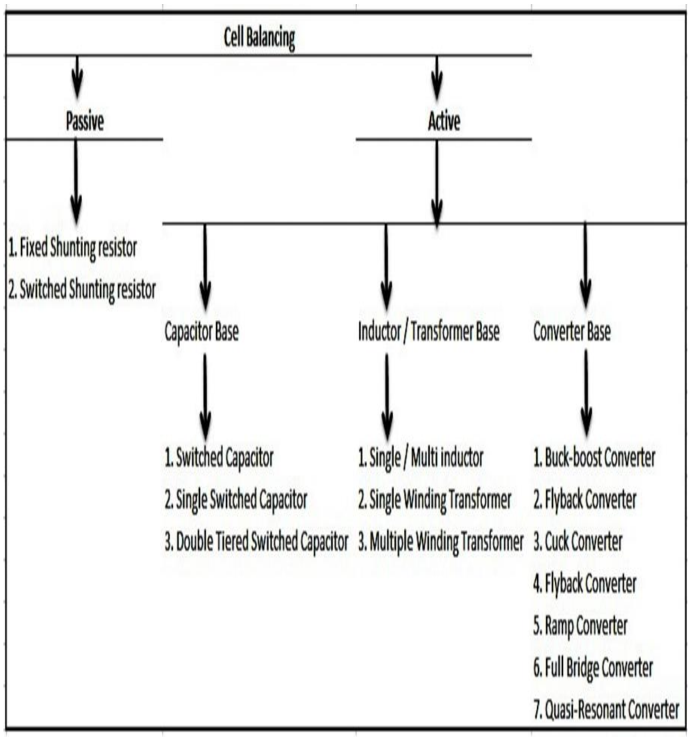

Fig.2: Classification of Voltage Balancing Circuits [3].

Fig.1 shows the passive balancing circuits, passive balancing is the simple method for voltage balancing. Equal voltage distribution is ensured across each SC cell by connecting identical resistor across each SC cell. SC will get discharged through parallel resistor when charging circuit is removed, so it is a disadvantage. [1] To increase the efficiency switched resistor balancing circuit is used. Sensing and control circuit will sense the voltage unbalance and give signal to particular switch to operate. So resistor will not be connected continuously. As resistor will dissipate the extra energy in the form of heat, effective cooling system is required for passive balancing circuits. For low power applications passive balancing circuits can be used.

B. Active Voltage Balancing Circuits for SC module:

Based on active element used active voltage balancing circuits are classified as shown in fig.2.

Capacitor or inductor is used as external storage devices. Energy exchange can be done easily using switching logic. Capacitor or inductor switching based balancing circuits are simple to control; no intelligent control system is required as compared to converter based balancing circuits. In this paper flyback converter and buck boost converter is discussed in detail.

1. Flyback converter based voltage balancing:

Fig. 3 shows flyback converter based balancing circuit After detection of unbalance in voltage in series connected SC module switch Q is turned on fig.3a) entire stack energy is transferred to flyback transformer and when switch Q is turned OFF, energy is transferred mostly to lower energy SC cell fig.3b). [2] [3]

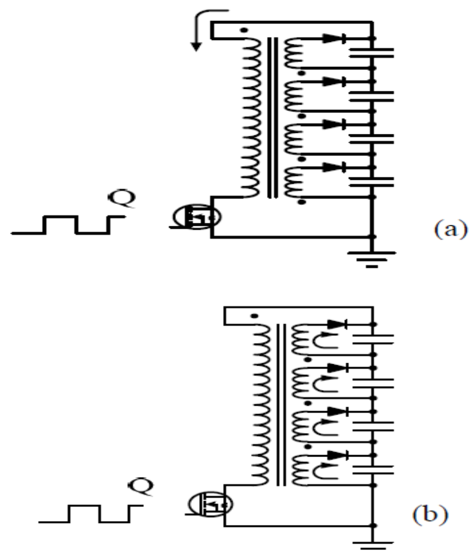

Fig.3 Flyback converter based balancing circuit [2].

a) Q turned ON b) Q turned OFF [2].

Duty cycle d is 0.5 for the circuit to provide optimum stress on circuit elements. After voltage balancing is complete flyback converter can be disabled. Multi-winding transformer used for energy exchange between SC cells. It charges and discharges based on converter signal [2][3].

Literature review shows that this method is inefficient as energy flow takes place in every SC cell on detection of voltage unbalance. This is the limitation for flyback converter using multi-winding transformer. Ideally it should directly transfer the energy to lowest energy SC cell to increase efficiency.

Operating modes of flyback voltage balancing are listed below:

I: Constant switching frequency
II: Constant primary winding peak current
III: Constant Power.

2. Buck-boost converter based voltage balancing circuit for SC modules:

Extra energy in SC cell in not dissipated in this circuit. It is exchanged between SC cells with higher voltage to SC cell with lower voltage.

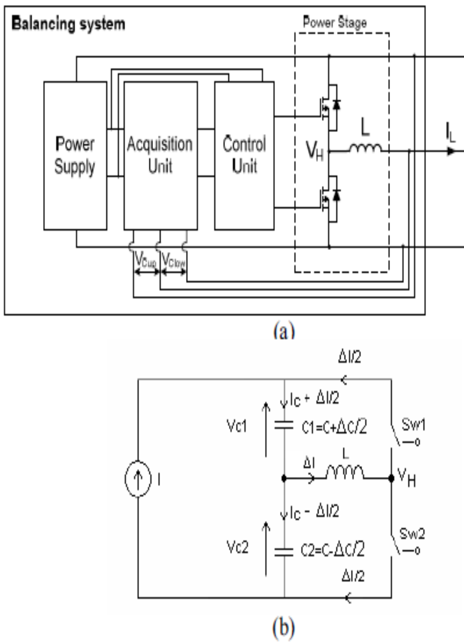

Fig.4: SC voltage balancing using Buck-boost converter a) Block diagram b) Circuit analysis [4].

DC/DC converter i.e. buck-boost converter is shown in fig.4. Buck is step down operation. Bust is step up operation. Buck-boost converter is used to maintain constant power output. Here it is used to transfer energy between SC cells. To achieve the goal it has two operating periods. First period it extracts energy from higher voltage SC cell. In second period it supplies this energy to lower voltage SC cell. Acquisition unit detects voltage balance and gives command to control unit. Switching order is decided by control unit to switch ON/OFF respective SC cell. Controlled switching ensures reduction in voltage unbalance [4].

III. CIRCUIT DESIGN

Current to be shared plays important role in balancing circuit design, the exchange current ΔI. Fig.4b) shows buck-boost converter and average current through each SC cell. Where ΔI is inductor average current and ΔI/2 is switch average current. Lower capacitance SC cell will have lower charging current and vice versa to have constant SC cell voltage. The goal is to charge both the cells at maximum voltage at the same time.

This is expressed in below equation 1

$$\left.(v_{C2}-v_{C1})\right|_{t_c}=0$$

$$\int_0^{t_c}\left(\frac{I-\Delta I}{C-\Delta C/2}-\frac{I+\Delta I}{C+\Delta C/2}\right)\cdot dt+\underbrace{v_{c20}-v_{c10}}_{\Delta v_i}=0 \qquad (1)$$

Above equation can be simplified by neglecting second order terms. As equation 2:

$$I\cdot\int_0^{t_c}\left(\frac{\Delta C}{C}-\frac{\Delta I}{I}\right)\cdot dt+C\cdot\Delta v_i=0 \qquad (2)$$

Exchange current ΔI is time dependant. It is limited by circuit components.

The product of charging current and charging time can be given as equation 3.

$$I\cdot t_c=C\cdot(V_{Max}-V_i)=C\cdot\Delta V_{Cc} \qquad (3)$$

ΔVcc represents voltage increase in one device due to charging process, when balancing circuit is working.

$$\frac{\Delta C}{C}+\frac{\Delta v_i}{\Delta V_{Cc}}=\frac{\Delta I_{\max}}{I} \qquad (4)$$

Equation 4 shows maximum exchangeable current because of mismatch in voltage and mismatch in capacitance.

High capacitance SC cell will have high leakage current.

1. Selection of switches and inductor:

Inductor is to be charged and discharged completely in each cycle. Inductor gives a triangular waveform. Maximum current through the inductor and switch is twice the exchangeable current between SC cells.

Ilmax = Isw max = 2ΔImax (5)

Based on the SC ratings inductor rating is to be decided. Equation 6 gives the relation to find out inductor ratings:

$$L=\frac{V_{Max}}{I_{L\max}}\cdot\Delta t_{ON}\approx\frac{V_{Max}}{4\cdot\Delta I_{\max}\cdot f} \qquad (6)$$

IV. EXPERIMENTAL RESULTS

Voltage balancing circuit was designed considering maximum charging current of 10A and 20% of ΔC/C. ΔImax should be greater than 2A. The maximum inductance current is fixed at 6A when the voltage in each SC reaches its maximum value. The operation voltage range of the storage system (two SCs) is between 2.7V and 5.4V. The balancing circuit was designed .The control unit is a PIC16F684 microcontroller. The circuit was tested. The stack charging current was 10A, and the voltage in each SC was measured. Fig. 5 shows the exchanged current waveform and the voltage VH in the switches' shared terminal. The cycle begins when voltage VH goes to zero, meaning the lower switch is active first. Then, the upper switch turns on, and voltage VH reaches the sum of the SC voltages (VC1 +VC2). At the end of the inductor discharging process the switch turns off before the inductor current reaches zero, and the inverse diode of the switch finishes the discharge. This is seen as an increase in VH before the end of the cycle due to the diode voltage drop.

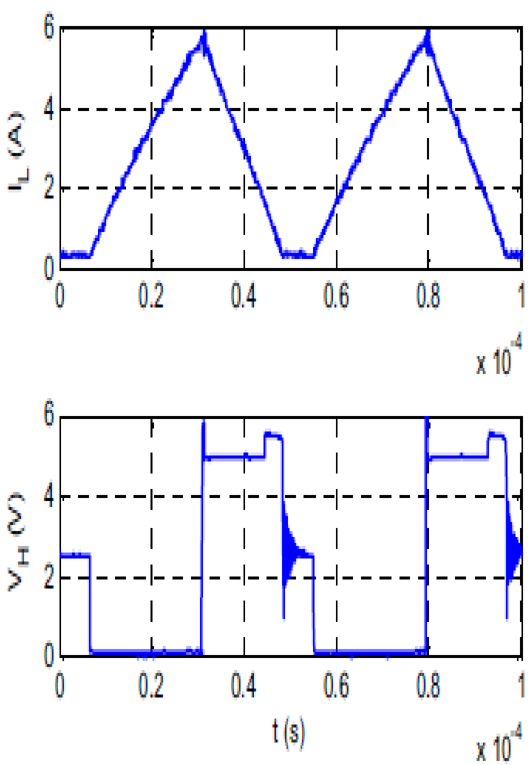

Fig.5: Current through inductor and shared point voltage [4]

Fig. 6 shows a charging process with the balancing circuit in Fig. 2.a using the 100F/2.5V SC. The two devices are initially charged at different values, and then the balancing circuit turns on at 1.5V when the unbalance threshold is reached, and it ends when the SCs are balanced.

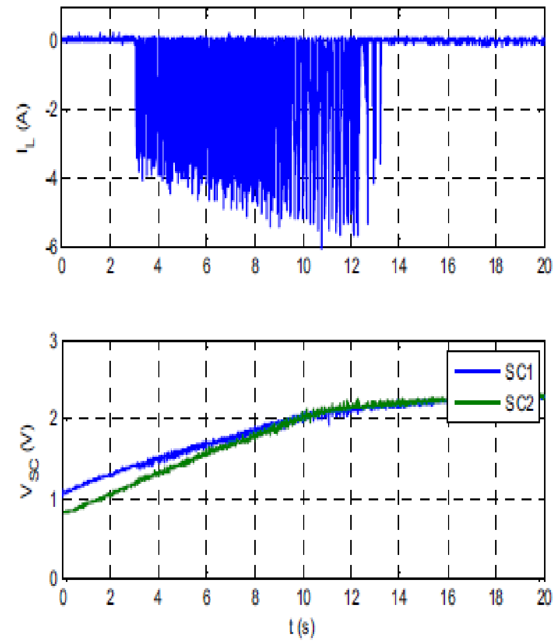

Fig.6: Charging of SC: Inductor current and SC voltage [4].

Fig. 7 shows 45 SC cells connected in series using buck- boost converter.

Fig.7: 45 SC stack with buck-boost converter [4].

V. CONCLUSION

Detailed study carried out to understand the difference between passive and active balancing circuits. Where power loss is major concern active voltage balancing methods are to be used instead of passive balancing circuits. Efficiency of SC module can be increased by using active voltage balancing methods. Buck boost converter is efficient than flyback converter for voltage balancing of SC module.

REFERENCES

[1] I. D. Oltean, A. M. Matoi and E. Helerea, "A supercapacitor stack - design and characteristics," in Proc.IEEE Optimization of Electrical and Electronic Equipment (OPTIM), 2010, page 214-219.

[2] Ponggorn Kulsangcharoen, Christian Klumpner, Mohamed Rashed, Greg Asher Department of Electrical and Electronic Engineering, Faculty of Engineering, University of Nottingham "Evaluation of a Flyback Regenerative Voltage Equalisation Circuit for Series-Connected Supercapacitor Stacks." University Park, Nottingham, NG7 2RD, UK.

[3] Mohamed Daowd, Noshin Omar, Peter Van Den Bossche, Joeri Van Mierlo, "A Review of Passive and Active Battery Balancing based on MATLAB/Simulink". International Review of Electrical Engineering (I.R.E.E.), Vol. xx, n. x, 2011.

[4] Federico Ibanez, J. Vadillo, J.M. Echeverria, L. Fontan CEIT, "Design Methodology of a balancing network for supercapacitors" IEEE 2013.

[5] Yanqing Qu, lianguo Zhu, liefeng Hu, "Overview of Supercapacitor Cell Voltage Balancing Methods for an Electric Vehicle" NSW 2007, Australia.