An Active Forward Fly-back Balancing Circuit for Series Connected Supercapacitors

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Abstract—This paper presents an active voltage balancing approach using a forward fly-back power converter. In the proposed balancing scheme, cell with the higher voltage is selected to extract the extra energy and then a proportion of this extracted energy is distributed to other supercapacitors via the proposed circuit. A system structure consisting of five supercapacitors is built up to verify operation of the proposed scheme.

Index Terms: Supercapacitor, voltage balancing, forward fly-back converter

1. Introduction

Supercapacitors are receiving a lot of attention as energy storage device because of high power density and short charge/discharge time. However, due to contemporary technology limitations, supercapacitors have low operating voltage. Accordingly, a series connection of supercapacitors is needed to reach the appropriate voltage level for high power applications. When connected in series, unfortunately, supercapacitors with different internal parameters could suffer from the voltage unbalance, which decreases the life and expectancy of the supercapacitors. In order to overcome this problem, a voltage balancing circuitry is required [1][2][3].

This paper presents an active voltage balancing circuit using forward fly-back power converter. The aim of this paper is to ensure the voltage equalization across the supercapacitors by transferring the extra energy from cell with the higher voltage to the cell with lower voltage.

2. Proposed Balancing Scheme

2.1 Configuration and Operating Principle

The proposed voltage balancing scheme is shown in Fig.1. It consists of a forward fly-back converter with a pack of "*i*" supercapacitors connected in series and MOSFET switches and diodes. Each supercapacitor is connected in parallel with the primary winding of the forward fly-back transformer. The MOSFET switches and diodes provide the path for power flow of each supercapacitor and are controlled by a digital controller.

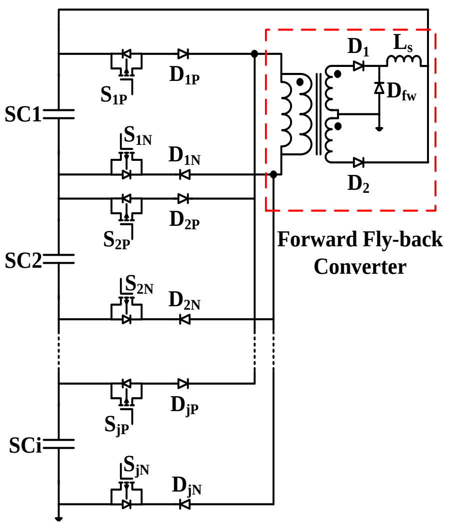

Fig.1 Circuit diagram for proposed balancing scheme

The forward fly-back converter in the proposed balancing scheme works in discontinuous conduction mode. If the voltages of two or more supercapacitors are different, switches of higher voltage cell are switched ON or OFF until the voltages reach the predetermined level. In this process, the balancing circuit operates in different circuit configurations and they are referred as modes of circuit operations. The complete operating principle of the balancing circuit is explained with the help of equivalent circuit diagrams for these different operating modes. For better understanding of operating principle of the proposed circuit, the voltage across the supercapacitor "SCi" is assumed to be higher than other supercapacitors. Fig.2 shows the operating principle of the proposed scheme in different modes.

- **Mode 1[SiP/SiN are ON]:** When the switches across SCi are ON, the voltage of SCi appears across the primary winding of the transformer and according to turn ratio of the transformer a proportion of primary voltage appears across the output inductor. In this mode the forward fly-back converter works as forward converter as shown in Fig.2 (a) and the feedback current to charge the remaining supercapacitors with lower voltage is determined by (1). The power flow path is shown by bold lines.

$$i_{fb} = \frac{V_{Ls}}{L_s} \cdot T_{on} \tag{1}$$

where, T_{on} stands for ON duration

- **Mode 2[SiP/SiN are OFF]:** When the switches across SCi are turned OFF, the power flow path and directions of currents are changed as in Fig.2 (b). In this mode the forward fly-back converter work as fly-back converter and the feedback current is determined as the sum of the output inductor current and tertiary current. These currents are given by following equations

$$i_{fb} = i_{Ls} + i_t \tag{2}$$

where, $$i_{Ls} = \frac{-V_{pack}}{L_s} \cdot T_{reset} \tag{3}$$

$$i_t = i_m \cdot \frac{N_p}{N_t} \tag{4}$$

and, T_{reset} stands for time for dissipation of energy from inductor and magnetizing circuit of transformer, i_m for magnetizing current and i_t for tertiary winding current

- **Mode 3[SiP/SiN are OFF]:** When all the energy stored in output inductor and magnetizing inductance is dissipated, then the feedback current becomes zero. In this mode, all the currents remain zero until the next turn-on signal is generated.

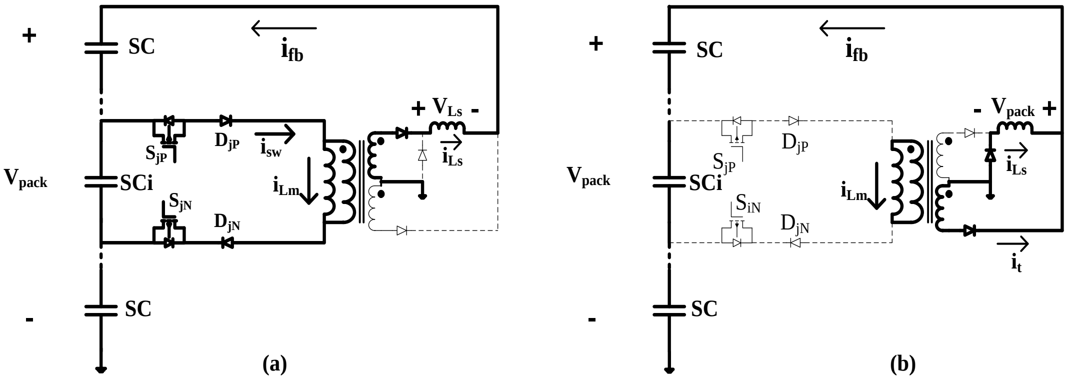

Fig.2 Equivalent circuit when SCi has higher voltage (a) mode-1 of circuit operation (b) mode-2 of circuit operation

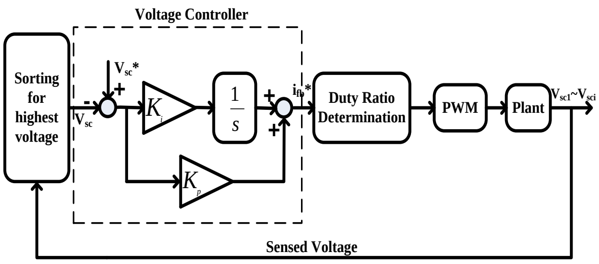

Fig.3 Control block diagram for proposed scheme

2.2 Control Strategy

In the proposed voltage balancing scheme average feedback current is used to generate the switching signal. The block diagram for the digital controller is shown in Fig.3. It demonstrates that the highest voltage cell is sorted out at first and the voltage of the cell is controlled through PI controller to produce the feedback reference current. From the average current analysis derived from the 3 mode operation, the duty ratio to generate the feedback current reference is calculated as (5).

$$D1^2 = \frac{i_{fb*}}{\left(\frac{V_{sc}-V_{pack}}{V_{sc}}\cdot\left[\frac{1}{2\cdot L_s}\cdot\left\{\left(\frac{N_s}{N_p}\right)^2\frac{V_{sc}^2}{V_{pack}}-\left(\frac{N_s}{N_p}\right)\cdot V_{sc}\right\}+\frac{1}{2\cdot L_m}\cdot\frac{V_{sc}^2}{V_{pack}}\right]T_s\right)} \tag{5}$$

To ensure the discontinuous conduction mode, the duty ratio must be limited. The maximum duty ratio is determined by (6) and the final duty ratio for voltage balancing is the value which satisfies both conditions given by (5) and (6).

$$D_{\max} \le \frac{V_{pack}}{V_{sc}\cdot\frac{N_t}{N_p}+V_{pack}} \tag{6}$$

3. Experimental Results

A 5 supercapacitor stack has been fabricated to verify the proposed voltage balancing scheme. Circuit parameters for the experiment are given in table 1.

Table 1 Circuit parameters for experiment.

Device	Explanation
Supercapacitor(SC1~SC5)	100 [F], 2.8 [V]
Switching Frequency	10 kHz
Output Inductor	90 uH
Transformer	Ns/Np =12 Nt/Np=6 Lm: 35.5 uH

The experimental result for the voltage balancing is shown in Fig. 4. As supercapacitors "SC4" and "SC5" have higher voltage in start, therefore they are controlled alternatively. The voltage reference is the average of the voltage across all the supercapacitors i.e. 2.42 [V] and 120 seconds are taken for all the supercapacitors to trace the reference voltage.

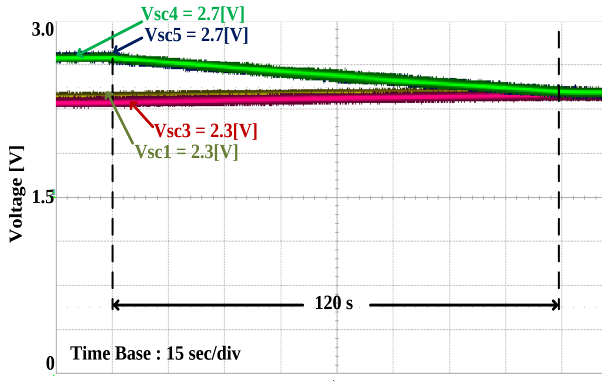

Fig. 4 Experimental result for voltage balancing

4. Conclusion

This paper presents a new voltage balancing scheme using forward fly-back power converter, which ensures an optimal storage of energy with no overvoltage across any supercapacitor connected in series. Thanks to proposed voltage balancing circuit, it is possible to transfer the energy in both ON and OFF modes and the balancing of the voltage between supercapacitors is fast. Experimental results in Fig. 4 shows that for balancing the voltage of five supercapacitors, each of 100[F] capacitance 120 seconds are required.

Reference

[1] John R. Miller. John M. Miller, "Fundamental and Application Engineering of Electrochemical Capacitors" (ECCE), 2009, September

[2] Gai Xiao Dong, Yang Shi Yan, Yang Wei, Huang Jun, "Analysis on Equalization Topology and System Architecture for Series-Connected Ultra-Capacitors", (VPPC), September 3-5, 2008, China

[3] P. Barrade, "Comparative Study of Solutions for the Active Equalization of the Voltages. 7th International Conference on Modeling and Simulation of Electric Machines" 2002(8): 18-21R

[4] Jongwon Shin, Chang-Yoon Chun, Jonghoon Kim, Bo-Hyung Cho, "Selective Fly-back Balancing Circuit with Improved Balancing Speed for Series Connected Lithium-ion Batteries" CoST-Rec 2010