

# Forward Fly-back Voltage Balancing Circuit for Series Connected Super Capacitors Using Digital Control

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**Abstract**— Supercapacitor is an electrical energy storage device which offers remarkably high energy density when compared to conventional capacitors and high power density when compared to batteries. While using the supercapacitors for energy storage, the main disadvantage is their limited voltage due to contemporary technology restrictions. Therefore, for higher voltage operation supercapacitors are connected in series to achieve the appropriate voltage level. Because of the difference in the magnitude of capacitance of cells, local over-voltage appears on one or more supercapacitor cells. This over-voltage decreases the lifetime and energy storage efficiency of the associated cell, which can be improved considerably by balancing the voltages across each supercapacitor. 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. The feasibility of the proposed balancing scheme has been verified by computer simulation and experimental results.

**Keywords**-component: Supercapacitor, voltage balancing, forward fly-back converter

## I. INTRODUCTION

Electrical energy has made significant effects on the development of civilization. So far, infinite sources including wind, hydraulic and solar sources as well as finite sources such as coals, oil and etc have been used to make electrical energy. As important as the sources are, efficient energy storage is vital in these modern days. Devices with low cost, light weight and high efficiency have always been of great interest. Batteries were an early countermeasure to this concern. They have high energy density and low self discharge rate. However, due to their low power density and relatively high cost, their applications are limited. Alternatively, conventional capacitors were introduced but they also have limitations of low energy density. Over the last decades, supercapacitors have been a reliable and efficient energy storage device. Figure 1[1] shows characteristics of energy storage devices and indicates that the supercapacitors are 10 times as low as batteries in terms of energy density but

have 20 times bigger power density. Furthermore, when compared to conventional capacitors, supercapacitors have higher energy density and lower power density. In other words, supercapacitors have filled up gaps between batteries and conventional capacitors as energy storage devices. Additional characteristics of three energy storage devices are presented in Table 1[2][3][4].

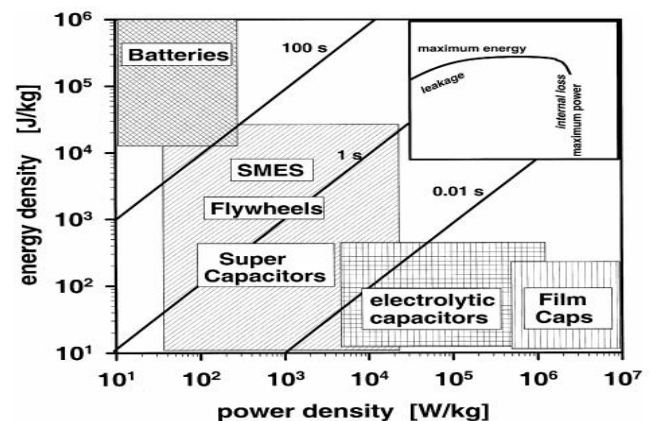


Figure 1 Ragone plot showing energy density vs. power density for various energy-storing devices

Due to the characteristics discussed above, supercapacitors find possibilities in various applications. However, because of the current technology limits, the applicable voltage of supercapacitors is very low, which usually ranges from 2.3 V to 2.8 V. Hence it is required to connect a number of supercapacitors in series for higher power applications to obtain appropriate voltage level. In the mean time, when combined in series, if voltages of each cell are not in equilibrium owing to different capacitances of the cells or other reasons, local over-voltage may appear across the cells. This could decrease the lifetime and energy storage efficiency of the associated cells. Consequently, voltage balancing circuits should be implemented in series connection of supercapacitors. In this paper, a forward fly-back converter circuit for voltage balancing with digital control algorithm is suggested.

TABLE I. COMPARISON OF DIFFERENCES PROPERTIES OF ENERGY STORAGE DEVICES

	Supercapacitor	Conventional Capacitors	Batteries
Charge/Discharge Time	Milliseconds to Seconds	Picoseconds ( $10^{-12}$ ) to Milliseconds	1 to 10 hrs
Charge Rate	Very High, same as discharge rate	Very High, same as discharge rate (greater than Super Cap)	Limited by reaction rate
Power Density	10 to 1000 kW/kg	0.25 to 10,000 kW/kg	0.005 to 0.4 kW/kg
Energy Density	1 to 5 Wh/kg	0.01 to 0.05 Wh/kg	Up to 150 Wh/kg
Operating Temperature	-40 to +85 °C	-20 to +100 °C	-20 to +65 °C
Operating Voltage	2.3V - 2.8 V/cell	6 to 800 V	1.25 to 4.2 V / cell
Capacitance	100 mF to > 2F	10 pF to 2.2 mF	N/A
Life	>1,000,000 cycles	>100,000 cycles	150 to 1500 cycles
Pulse Load	Up to 100 A	Up to 1000 A	Up to 5 A
Cycle Efficiency	<75% to >95%	>95%	<50% to >90%

## II. PROPOSED BALANCING SCHEME

Figure 2 demonstrates a forward fly-back converter with a pack of  $i$  supercapacitors connected in series and a set of  $j$  MOSFET switches and diodes.

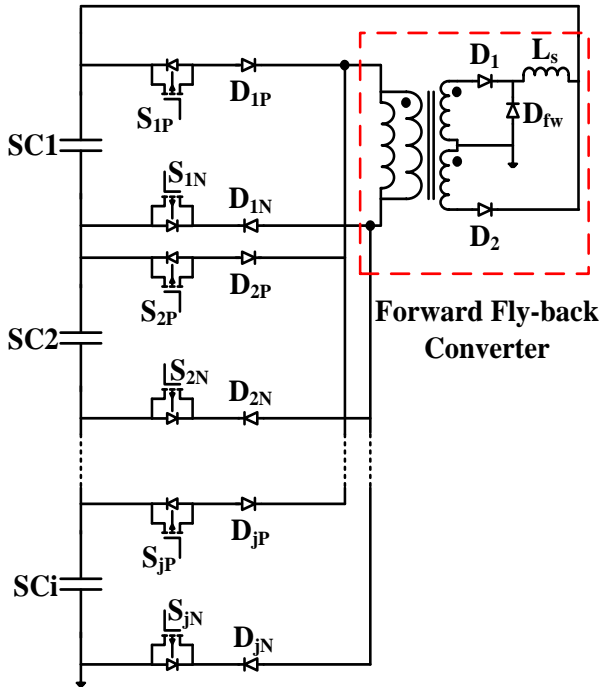


Figure 2 Circuit diagram for proposed balancing scheme

Each supercapacitor is connected in parallel with the primary winding of the transformer. The MOSFET switches and diodes provide the path for power of each supercapacitor and these MOSFET switches are controlled by a digital controller. When the voltage across  $i$ th cell is higher than the other cells, a control signal is generated from the controller to turn on the switches across the cell with the highest voltage. The PWM signal is generated such that the switch “SiP” is always ON until the voltage across the respective cell remains

higher while the switch “SiN” acts as the main switch of the forward fly-back converter during the whole balancing operation.

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. Figure 3 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 Figure 3 (a). The power flow path is shown by bold lines. Numerical expressions for ON time are given as below. First of all, voltages are determined as (1).

$$V_p = V_{sc1}$$

$$V_s = V_p \cdot \frac{N_s}{N_p} \quad (1)$$

$$V_t = V_p \cdot \frac{N_t}{N_p}$$

Then the voltage across inductor “Ls” is,

$$V_{Ls} = V_s - V_{pack} \quad (2)$$

Where,

$V_p$  : Voltage across primary winding

$V_s$  : Voltage across secondary winding

$V_t$  : Voltage across tertiary winding

$$V_{pack} = V_{SC1} + V_{SC2} + \dots + V_{SCi}$$

The feedback current to charge the remaining supercapacitors with lower voltage is determined by (3).

$$i_{fb} = \frac{V_{Ls}}{L_s} \cdot T_{on} \quad (3)$$

Where,  $T_{on}$  stands for ON duration

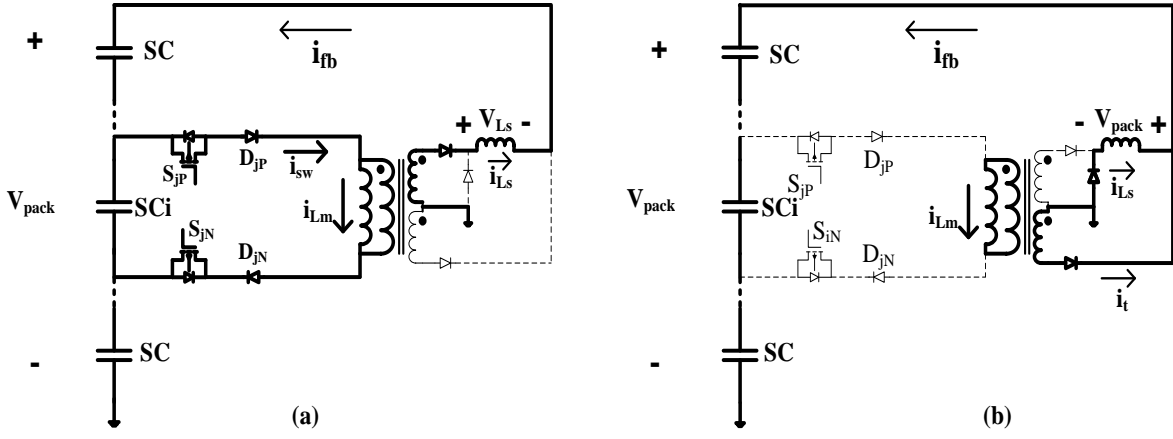


Figure 3 Equivalent circuit when SCi has higher voltage (a) mode-1 of circuit operation (b) mode-2 of circuit operation

- 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 Figure 3 (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,

$$i_{fb} = i_{Ls} + i_t \quad (4)$$

$$\text{Where, } i_{Ls} = \frac{-V_{pack}}{L_s} \cdot T_{reset} \quad (5)$$

$$i_t = i_m \cdot \frac{N_p}{N_t} \quad (6)$$

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.

### III. 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 Figure 4. 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 of operations, the duty ratio to generate the feedback current reference is calculated as (7).

$$DI^2 = \frac{i_{fb}^*}{\left( \frac{V_{sc} - V_{pack}}{V_{sc}} \cdot \left[ \frac{1}{2 \cdot L_s} \cdot \left\{ \left( \frac{N_s}{N_p} \right)^2 \frac{V_{sc}^2}{V_{pack}} - \left( \frac{N_s}{N_p} \right) \cdot V_{sc} \right\} + \frac{1}{2 \cdot L_m} \cdot \frac{V_{sc}^2}{V_{pack}} \right] T_s \right)} \quad (7)$$

To ensure the discontinuous conduction mode, the duty ratio must be limited. The maximum duty ratio is determined by (8) and the final duty ratio for voltage balancing is the value which satisfies both conditions given by (7) and (8).

$$D_{max} \leq \frac{V_{pack}}{V_{sc} \cdot \frac{N_t}{N_p} + V_{pack}} \quad (8)$$

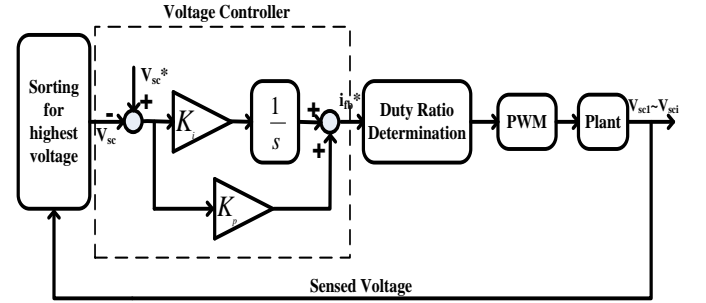


Figure 4 Control block diagram for proposed scheme

### IV. COMPUTER SIMULATION

For computer simulation, only the diode voltage drops in series with the switches are considered while other components such as switches, supercapacitors and transformers are assumed to be ideal. All the circuit parameters used for simulation are given in Table II. The maximum duty is limited to 0.47 according to (8) and switching frequency is set to 10 kHz.

TABLE II. PARAMETERS OF PROPOSED SCHEME FOR COMPUTER SIMULATION

Device	Explanation
Supercapacitors Vsc1 ~ Vsc5	Capacitance: 20 F Vsc1=Vsc3=2.3 [V], Vsc2=2.1[V], Vsc4=Vsc5=2.7[V]
Output Inductor	90 uH
Transformer	Ns/Np =12, Nt/Np=6 Magnetizing Inductance: 36 uH

As the conditions are presented in Table II, the voltages across both SC4 and SC5 are same and higher than the other

supercapacitors. Hence, according to the proposed control scheme, supercapacitor ‘SC4’ is selected at first to control the voltage through the forward fly-back converter. When its voltage becomes lower than the voltage of supercapacitor ‘SC5’, then SC5 is selected to transfer the extra charge and this process continues till the voltages across each supercapacitor are balanced.

Figure 5 shows the switch current for supercapacitors ‘SC4’ and ‘SC5’. It shows that the ‘SC4’ and ‘SC5’ are conducting alternatively to balance the voltage. The peak value of the capacitor current seems to be high but it is in agreement with the analysis in chapter 2 with the circuit parameters given above. Figure 6 shows the corresponding voltages in primary, secondary and tertiary windings with diode voltage drops.

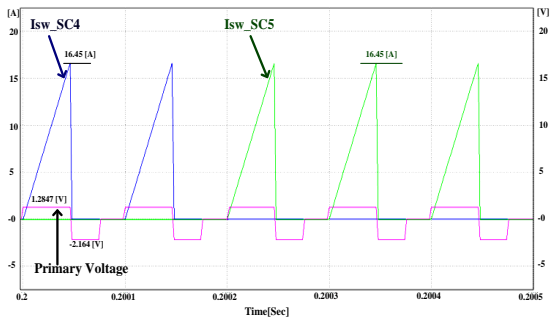


Figure 5 Primary voltage and switch current due to supercapacitor 4 and 5

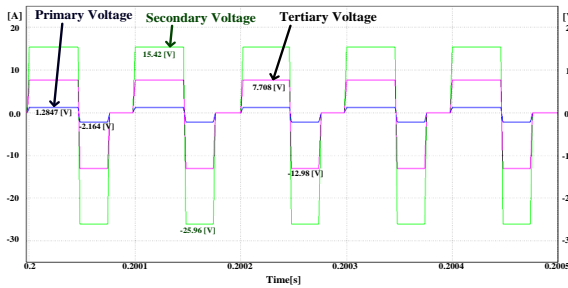


Figure 6 Voltage across primary, secondary and tertiary winding of transformer

Figure 7 shows feedback current of the circuit. During ON time, this current is same as the output inductor current, while in OFF time it consists of the summation of the inductor and tertiary current.

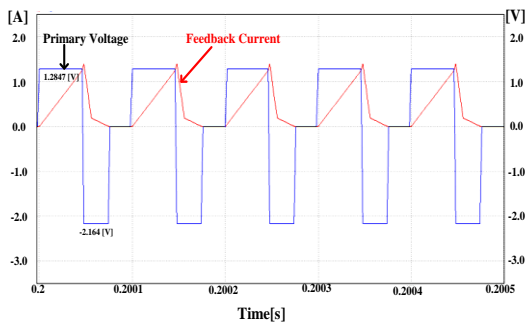


Figure 7 Feedback current to the pack of supercapacitors

Figure 8 shows the final simulation results for the balancing of the voltage. Since it takes a lot of time to finish the balancing, only some part of the process is presented but the basic idea of the proposed scheme is clear from result.

All the balancing result will be shown from experiments in chapter 5.

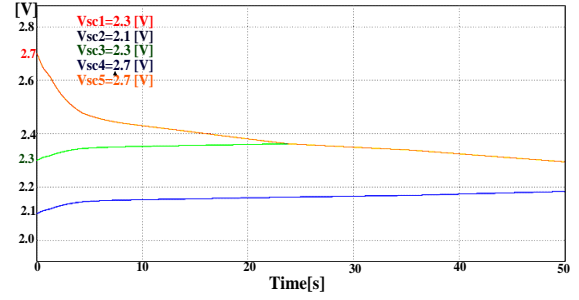


Figure 8 Process of voltage balancing

## V. EXPERIMENTAL RESULTS

For verification of the theoretical and computer simulation analysis, an experiment is setup for 5 supercapacitors. For practical realization, as all the losses in the circuit components should be considered, so the turn ratio of the transformer is set higher than the theoretical analysis case. All the designed values for the transformer and output inductor are given in Table III.

TABLE III. PARAMETERS OF SELECTED PARAMETERS FOR EXPERIMENTAL SETUP

Device	Explanation
Supercapacitors SC1 ~ SC5	Capacitance: 100 F Rated Voltage: 2.8 V
Output Inductor	90 $\mu$ H
Transformer	PC40EI33/29/13-Z Ns/Np =12, Nt/Np=6 Magnetizing Inductance: 36 $\mu$ H

An experimental setup shown in Figure 9 has been designed to verify the proposed scheme. All the parameters of the components in the experiment are same as the simulation, shown in Table III.

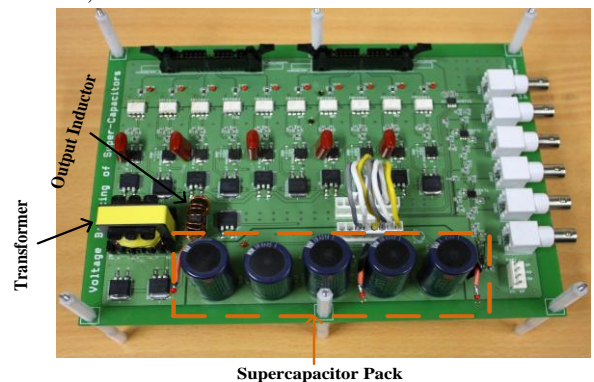


Figure 9 Experimental setup for proposed scheme

For these experiments, maximum duty is limited to 0.5 and the sampling frequency is set to 10 kHz. The initial

voltages of all of the five supercapacitors are given in Table IV.

TABLE IV. INITIAL VOLTAGES ACROSS EACH SUPERCAPACITOR TO VERIFY FEEDBACK CURRENT

Supercapacitor	SC1	SC2	SC3	SC4	SC5
Voltage	0.8 V	0.8 V	0.8 V	0.8 V	2.4 V

Figure 10 shows the experimental result of gating signal, primary voltage, secondary voltages and switch current. As the voltage across SC5 is higher than the other supercapacitors, so the switches across SC5 are controlled to transfer the charges from SC5. When the switches are ON, switch current will flow through the switches S5P/S5N due to which voltages appear across windings of the transformer and output inductor. The switch current is the sum of inductor current and the magnetizing current.

Figure 11 shows the feedback current when both forward and fly-back sides of the forward fly-back converter are working. When the switches across the capacitor with higher voltage are ON, after considering all the diode voltage drops, the scaled (according to primary to secondary turn ratio) voltage applied to the secondary is higher than the pack voltage, so the diode D1 is

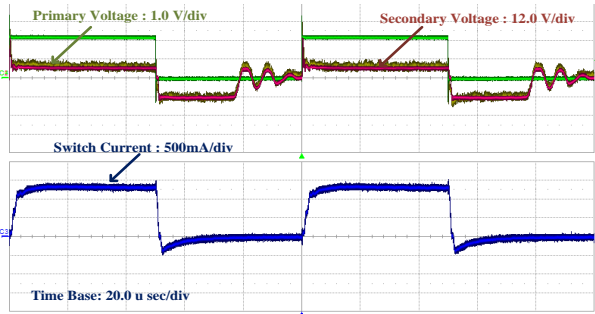


Figure 10 Switch current when both forward and fly-back sides are working

forward biased and current will flow through the forward side of the converter. When switches are turned off, the current will flow through the feedback path due to the energy stored in output inductor and tertiary winding. So at start, both forward and fly-back sides of the converter are working.

As the balancing process continues the voltage across SC5 will gradually decrease. At the time when secondary voltage will become lower than the pack voltage, then the current in the forward side of the converter will be cutoff and no current will flow through the forward side of the converter. But the current through fly-back side of the converter continue to flow till the end of voltage balancing across each supercapacitor. Table V shows the voltage across each supercapacitor when forward current is cutoff and only fly-back current is flowing. Figure 12 represents the experimental result when only fly-back current is flowing through the circuit.

TABLE V. VOLTAGES ACROSS EACH SUPERCAPACITOR WHEN ONLY FLY-BACK WORKS

Supercapacitor	SC1	SC2	SC3	SC4	SC5
Voltage	0.95 V	0.95 V	0.95 V	0.95 V	1.8 V

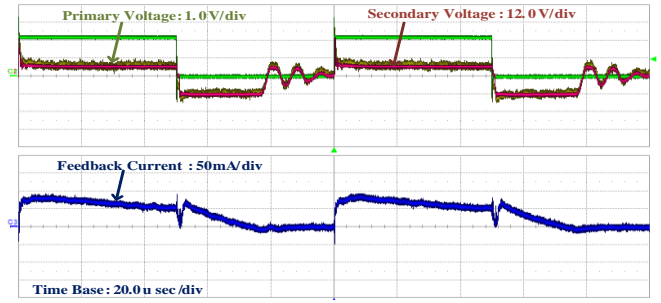


Figure 11 Feedback current when both forward and fly-back sides are working

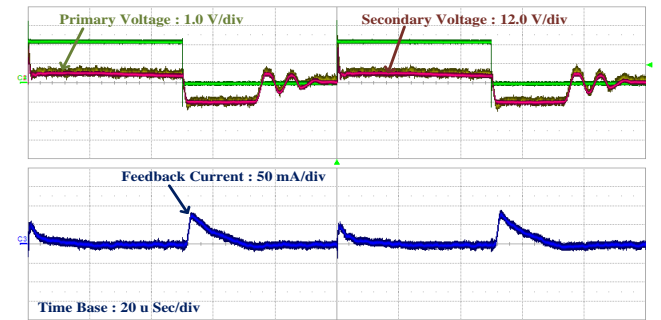


Figure 12 Feedback current when only fly-back sides is working.

Figure 13 depict the experimental results for voltage balancing. The initial voltages before balancing are shown at the starting point in Figure 13. 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.

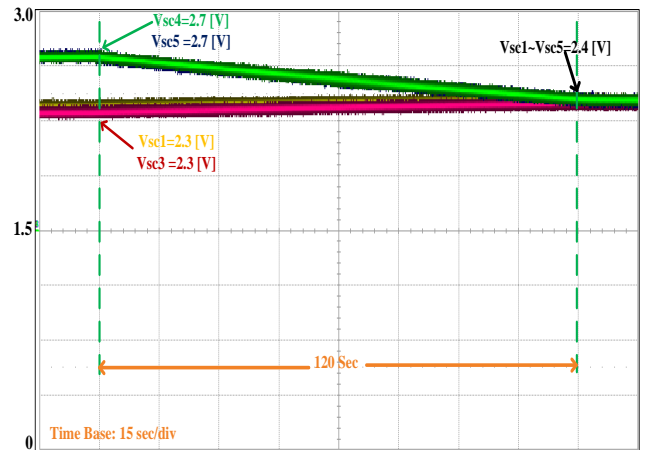


Figure 13 Experimental results of voltage balancing by the proposed scheme

## Conclusion

Supercapacitors are reliable and efficient energy storage devices, also they provide high energy and power density. For this reason and because of the low operating voltages of Supercapacitors, it is required to study about the way in which this new energy storage device can be used for high voltage applications in an optimal way. For high voltage application of Supercapacitors, a series connection is needed which results in a problem of overvoltage across one or more supercapacitors. For better performance and efficiency of supercapacitors this overvoltage must be avoided.

In this paper 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 Figure 13 shows that for balancing the voltage of five supercapacitors, each of 100[F] capacitance 120 seconds are required.

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