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Voltage Balancing of Supercapacitors String using Rectifier Diodes: Analytical and Simulation Approach

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Abstract— Supercapacitors (SCs) also called ultracapacitor or electric double-layer capacitors are considered as alternative to energy storage systems in many applications including wind turbines and electric vehicles where frequent charge/discharge and fast dynamic response is required. Due to high power density, fast energy storage characteristics and high efficiency SC is a prime focus in wireless charging for electric vehicles and electric tram systems. Due to technology limitations SCs poses low rated voltage which is insufficient for high voltage applications, although SCs are required to connect in series to achieve desire voltage range but due to internal parameters such as capacitance, equivalent series resistance (ESR) and self-discharge rate SCs draw unbalanced voltages during charge-discharge cycle. In this paper modelling approach for voltage balancing of SCs string using rectifier diodes is proposed, where two sets of SCs string are compared and discussed to verify results. Circuit design and simulation methods are used for this purpose.

Index Terms— Analytical approach, Simulation approach; Rectifier diodes; Voltage balancing; Supercapacitors string; charge/discharge.

1. INTRODUCTION

Supercapacitors (SCs) with high-power density, long life and short charging time is a good energy storage option for many electric applications[1] including short-term high power applications [2-4]. SCs have very high capacitance which is in hundreds or even thousands of Farads [2].

Electric vehicles (EVs) have low carbon emission and environment friendly nature, where batteries with high energy density power these vehicles over long period of time but due to limited life cycle and limited charge and discharge rate SCs are required to store energy as a result of regenerative braking and release energy when load increases thus all energy consumed by braking resistance is recycled and energy saving and environment protection is ensured [5].

SC has low voltage because of technology limits, thus to resolve low voltage problems SCs are used in series and parallel connection which resolves energy storage capacity and high voltage issues but due to the internal parameters (Capacitance, ESR and self-discharging rate), operating voltage, temperature, electrical, mechanical or environmental changes voltage imbalance on each cell can occur during charge-discharge cycles, it also affect the lifetime of SCs.

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To resolve these issues voltage balancing circuits are used which balance the voltage sharing of SCs and improve performance and reliability also extend the lifetime of SCs [3], [5].

Because of instable voltages in series connected cells overvoltage can occur in individual cells, to avoid overvoltage, voltage balancing circuits are required which also strengthen the SC's lifetime [5]. Passive and active balancing techniques are discussed by researchers in many papers where in passive balancing a passive resistor is used to lower the cell charge from fully charged cells, until cell charge matches to the lower cell in the pack. There are two modes of resistor operation either fixed mode or switched mode [3-8]. In active balancing methods charge is removed from higher energy cells and delivers it to lower energy cells [5].

2. SC EQUIVALENT MODELS

Equivalent models are used to observe the terminal behavior of SC. The main purpose of using equivalent model is to study the different characteristics of SC using mathematical techniques and simulation tools. Three commonly used approaches to model SC strings in published literature are discussed in this paper, which are Classical RC equivalent model, Three branch model and Transmission line model [8-12].

A. Classical RC equivalent model

The Classical RC equivalent model is the simplest model of SC which is used to reflect the ideal behavior of SC and describe the performance in slow discharge applications. Classical RC equivalent model comprises of an equivalent series resistance, equivalent parallel resistance and capacitance as shown in figure 1 [8-10], [13-15].

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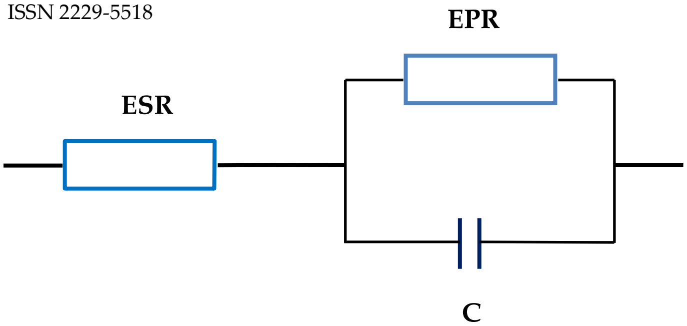

Figure 1: Classical RC equivalent model [9]

B. Three branch model

Three branch model is an extension of classical RC equivalent model as RC equivalent model is not 100% as it only gives good approximation of real device in slow discharge applications that's why there are some inaccuracies between classical RC model and experimental results. In the three branch model number of RC branches are used, these RC branches are chosen according to the duration of response. Three branch model has much larger time duration as compare to the classical RC equivalent model which is 30 minutes [9-11]. Equivalent circuit for three branch model is shown in figure 2.

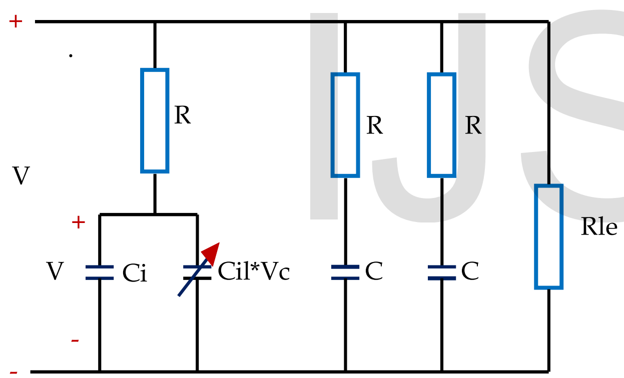

Figure 2: Equivalent circuit of Three branch model [9]

C. Transmission Line model

Transmission line model is used when above mentioned models are unable to exhibits the characteristics of SC. As transmission line model is useful where SC shows non-ideal behavior which is because of the porous material used to form the electrodes. As transmission line model uses five stages which is good for accuracy and it is used for frequencies up to 10 KHz as it is accurate for high frequencies [9]. Equivalent circuit for transmission line model is shown in figure 3.

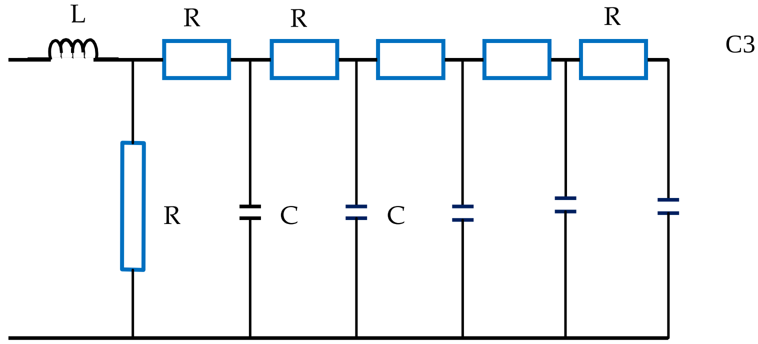

Figure 3: Equivalent circuit of Transmission Line model [9]

Based on classical equivalent model rectifier diode balancing circuit is designed and with the help of

Simulation, results are verified for charge and discharge response of 6 SCs.

3. RECTIFIER DIODE EQUALIZATION/BALANCINGMETHOD

Diodes are used in its forward conduction mode so that each diode has a voltage drop of 0.6 to 0.7 volts depending on the internal tolerance of diodes. Rectifier diodes used in this experiment have high current rating of 3A, it is used to rectify current as well as gives low voltage drop. Four forward biased diodes are connecting in series to equalize the voltage across each SC and their forward equivalent resistance Rd< 250Ω. Current will flow in forward direction and will produce resistance in both forward bias and reverse bias, amount of resistance vary in both operations which is small in forward bias and large in reverse bias. The number of series connected diodes used to equalize SC voltage depends on the nominal voltage of SC which is calculated using following formula. Also basic circuit diagram for rectifier diode balancing is shown in figure 4.

$$N = U_{cell}/U_{d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

Where,

N = Number of diodes require
U_{cell} = Nominal Supercapacitor voltage
U_d = Diode voltage drop (0.6….0.7)
Where Cell nominal voltage is 2.7V and number of diodes across each cell (N) can be calculated as,

$N = 2.5/0.6\text{-}0.7 \approx 4$

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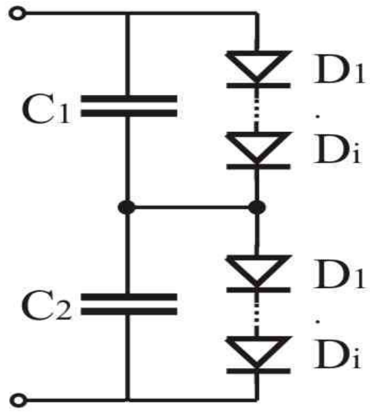

Figure 4: Basic concept for Rectifier diode balancing method

4. EXPERIMENTAL SETUP

Two set of tests are used to verify results using Multisim and LabVIEW results, where string of 3 SCs and 6SCs are used and readings of cell voltage without balancing and with balancing circuits are compared. Block diagram of project is shown in Figure 5.

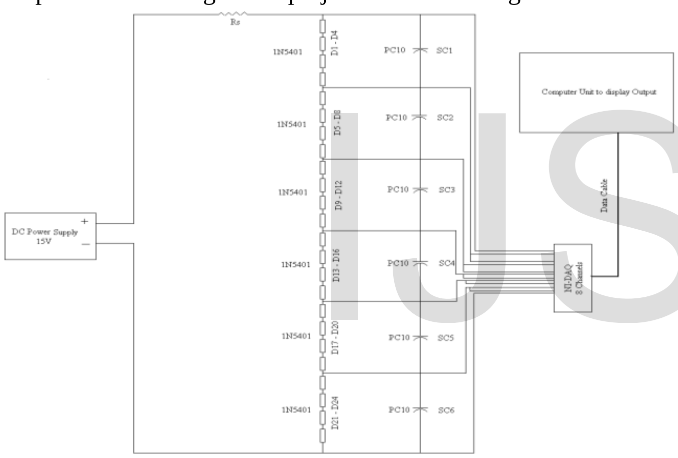

Figure 5: Experimental set up

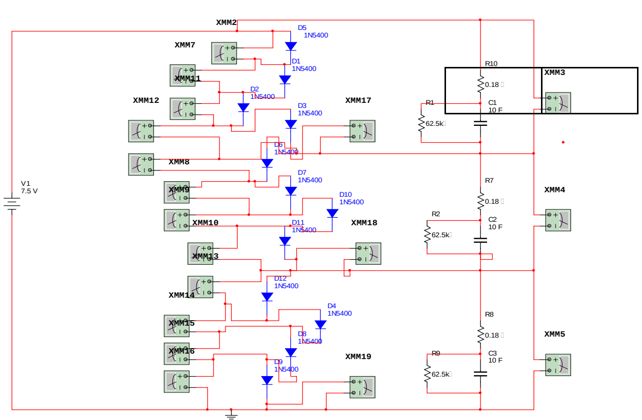

Figure 6: Multisim design for 3SCs

Figure 7: Hardware setup of experiment

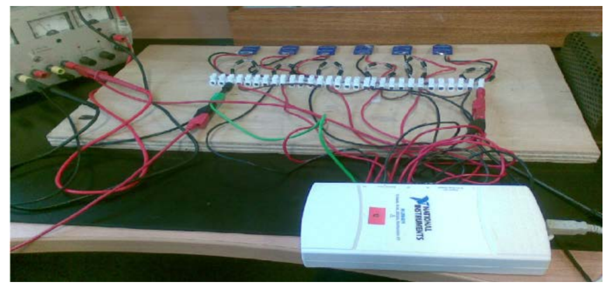

Figure 8: Real time circuit design

A. Simulation of 6 SCs without voltage balancing Circuit

Classical equivalent model of SC is chosen to simulate the voltages of SCs during charging and discharging. Over the long period of time unequal voltages are noticed when 6 SCs are connected to the DAQ. In both charging and discharging modes voltages have non identical behaviors. As from internal tolerances output can vary 10% from the rated values as shown in datasheet, but the results obtained by 6 SCs without using voltage balancing circuit during charging and discharging varies 20% to 30% values reflects this in table 1.

Vsc1	Vsc2	Vsc3	Vsc4	Vsc5	Vsc6
2.913	2.402	1.802	2.907	2.563	2.598

Table 1: Simulation results of 6 SCs without balancing circuit

If experiment continues then after long period of time results get closer to actual values but this technique is also not working in this case as shown in figures 9 and 10 respectively.

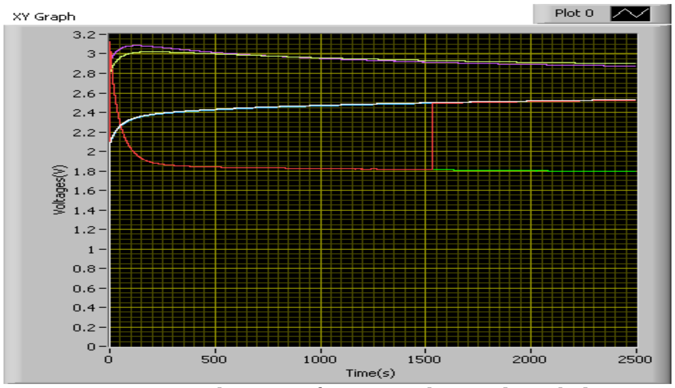

Figure 9: Charging of 6 SCs without voltage balancing Circuit

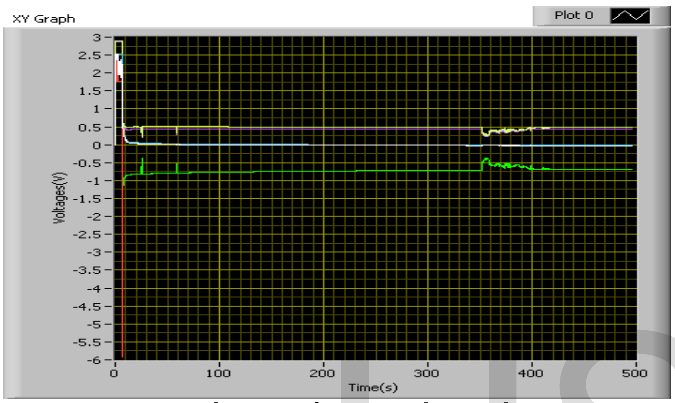

Figure 10: Discharging of 6 SCs without Balancing Circuit

B. *Simulation of different numbers of SCs using voltage balancing circuit*

To balance the voltage of SC string different combinations of SCs are used, starting from three SCs then increase it to five SCs and finally six SCs are used to achieve voltage balancing across each cell. All three combinations are described with simulation results.

C. *Voltage balancing of 3 SCs*

Three SCs are used in parallel with three set of rectifier diodes each containing four diodes connected in series. Initially for some period of time voltages were not equal and showing variations as shown in figure 11, after some time voltages keep constant for the long period of time until final reading taken. Very little variation observed on one of the SC which was for very small period of time but after some time voltage equalizes as shown values in table 2. But without balancing circuit when 6 SCs were connected over the same period of time no voltage balancing was found even between two SCs.

VSc1	VSc2	VSc3
2.50515	2.49679	2.49547

Table 2: Voltage values of 3 SCs using balancing circuit

Above table shows the values of voltage equalization among three SCs which are very much closer to the rated values of SC. Although due to internal tolerances there are some variations which may reduce over the long period of time. Voltage balancing of three SCs during charging and discharging is shown in figures 11 and 12 respectively.

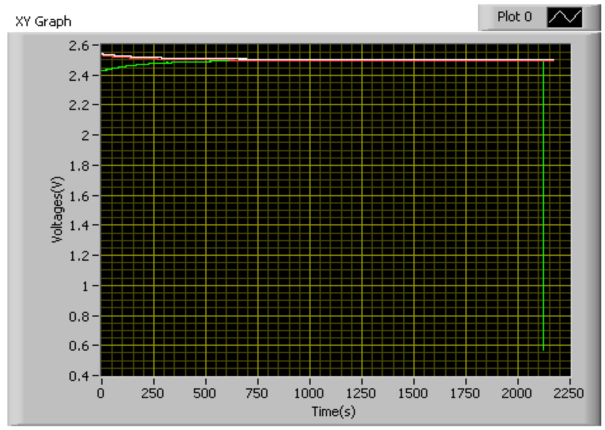

Figure 11: Voltage balancing of 3 SCs during charging

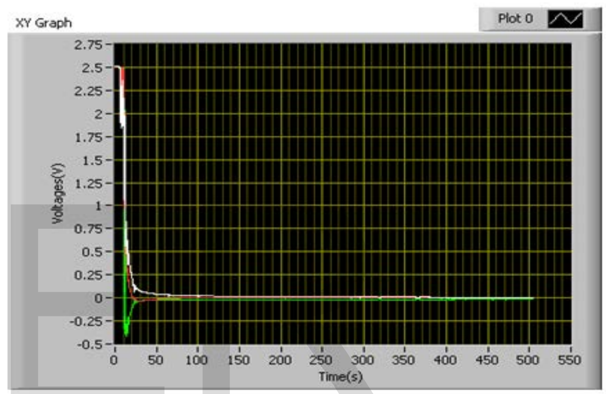

Figure 12: Voltage Balancing of 3 SCs during discharging

D. *Voltage balancing of 5 SCs*

After getting voltage equalization among three SCs voltage equalization among five SCs is determined using same technique. Five SCs are connected in parallel with five diode stacks each stack containing 4 diodes in series. As it is the continuation of voltage balancing of 3 SCs so two SCs are the difference between both circuits. When initially connected to the supply every SC started with very high values but after some time it start equalizing according to the rated values although over the period of time when it started all SCs were equally charging but higher than the rated values. One more important point in 5 SCs balancing is that they equalize much quicker than 3 SCs. So after increasing two SCs instead of negative effect on voltage balancing it is much quicker than the previous equalization. Values of voltage equalization of 5 SCs are shown in table 3.

Sc1	Sc2	Sc3	Sc4	Sc5
2.50656	2.48776	2.49649	2.50652	2.49655

Table 3: Voltage values of 5 SCs using balancing circuit

There are very minor variations among the voltage values of SCs which are well within the 10% of tolerance. Charging and

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discharging graphs of 5SCs are shown in figures 13 and 14 respectively.

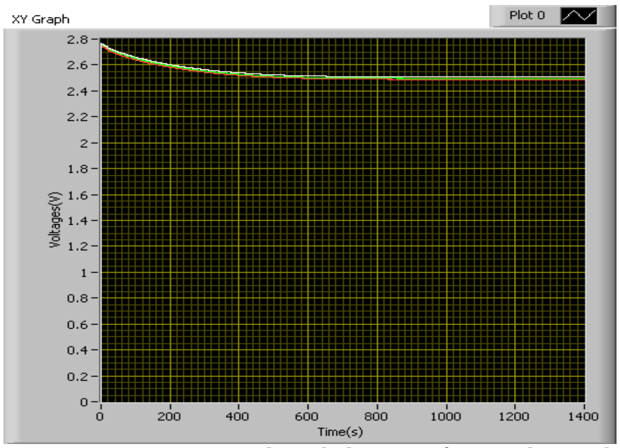

Figure 13: Voltage balancing of 5 SCs during charging

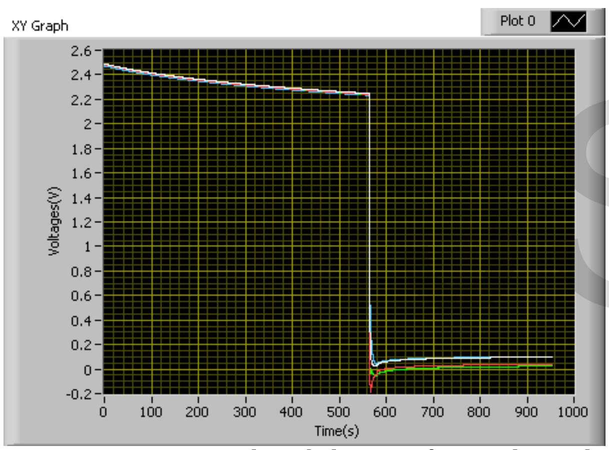

Figure 14: Voltage balancing of 5 SCs during discharging

E.Voltage balancing of 6 SCs

Voltage balancing for six SCs is determined in this section. Initially without balancing circuit six SCs were connected but the output results were showing unequal voltages on each SC. after connected balancing circuit voltage equalization is achieved, results are similar to the rated voltage. Voltage values are shown in table 4.

VSc1	VSc2	VSc3	VSc4	VSc5	VSc6
2.506	2.498	2.495	2.50643	2.487	2.495

Table 4: Voltage values of 6 SCs using balancing circuit

Using six SCs over the same period of time voltages during charging and discharging are well within the rated voltage range of 10% tolerance. As shown in figures 15 and 16 respectively.

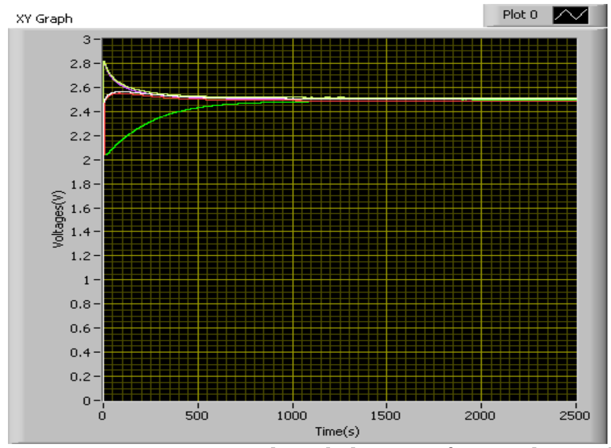

Figure 15: Voltage balancing of 6 SCs during charging

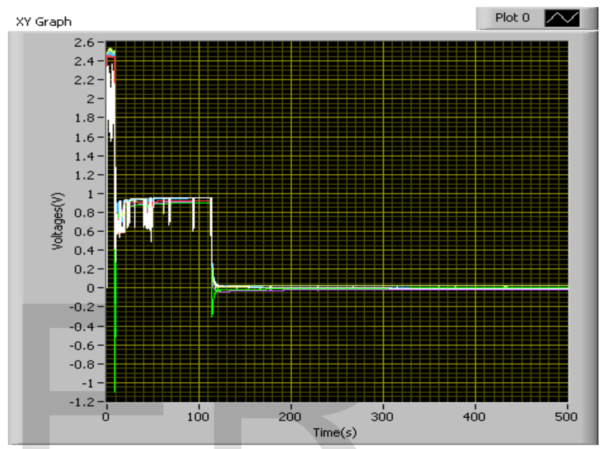

Figure 16: Voltage balancing of 6SCs during discharging

C. Comparison of Voltages without balancing circuit and with balancing circuit using 6 SCs

	VOLTAGE	
	Without Balancing Circuit	With Balancing Circuit
VSc1	2.91352	2.50600
VSc2	2.40210	2.49852
VSc3	1.80250	2.49576
VSc4	2.90720	2.50643
VSc5	2.56320	2.48782
VSc6	2.59852	2.49572

Table 5: Comparison of Voltages

5. CONCLUSION

Simulation and circuit design approaches are used in this paper for voltage balancing and results were achieved as shown in Table 5. Voltages across each cell has significant difference with and without balancing circuit which also verifies rectifier diode method is capable of equalizing voltage across each cell. One of the tasks to improve these results can be fast equalization in the string; however this design is tested for 6SCs which gave good equalization results over long period of time. Proposed balancing method has very simple design with few components compare to some other used methods and easy to operate.

As this equalization method purely consists of passive components which tend to transfer energy between connected SCs, it is assumed this system will take little bit longer than active balancing techniques to balance complete stack. One of the advantages to use rectifier diode balancing method is to negate thermal effects by reducing resistive components.

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