

## Capacitor Based Battery Balancing System

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### Abstract

Battery systems as a vital part of the electrical vehicles are facing major difficulties, the most important matter is the cells unbalancing. The cells unbalancing leads to individual cell voltages differ over time, decreasing the battery pack capacity that consequently will fail of the total battery system in the long run. In addition, cell equalization acts an important role on the battery life preserving. Several cell balancing topologies have been proposed for battery pack equalization such as; switched shunt resistors, inductor/transformer base, shuttling capacitor and energy converters. Quite a few researches focused the capacitor base cell balancing. This paper is presents a review, comparisons and develop the capacitor based topologies for balancing battery string. With the aid of MATLAB/Simulink<sup>®</sup> modeling, the switched capacitor topologies have been proposed including circuits, cells balancing simulation, implementations, balancing speed, complexity and system efficiency, as well as, propose a new control strategy for the single switched capacitor.

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*Keywords:* *Battery balancing, Switched capacitor, MATLAB/Simulink, Battery management system, Cell equalization.*

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### 1 Introduction

BATTERY management system (BMS) acts an important part of the electric vehicles (EVs). It protects the battery system from damage, predicts and increases battery life, and maintains the battery system in an accurate and reliable operational condition. Battery pack cells Imbalance is a vital matter in the battery system life. Without the balancing system, the individual cells voltages will drift apart over time. The capacity of the total battery pack will also decrease more quickly during operation then fail the battery system [1].

Quite a lot of cell balancing/equalization methods have been proposed in [1-20] and reviewed in [1-7]. The balancing topologies can categories as passive and active balancing; The

passive balancing methods as proposed in [8-9] removing the excess energy from the fully charged cell(s) through passive, resistor, element until the charge matches those of the lower cells in the pack or a charge reference. The resistor element can either in fixed mode or switched resistor [2].

The active cell balancing methods remove the charges from higher energy cell(s) and deliver it to lower energy cell(s). It has different topologies according to the active element used for storing the energy such as capacitor and/or inductive component as well as the energy converters as [1-20]. Not a lot of cell balancing researches illustrate the switched capacitor cell balancing topologies such [10-18] that is may be due to the switched capacitor methods has a long equalization time, but on the contrary, they have a simple control strategy and high efficiency. Switched capacitors methods can be classified into four configurations as shown

in Fig. 1; switched capacitor (SC), double-tiered switched capacitor (DTSC), single switched capacitor (SSC) and modularized switched capacitor (MSC). Different switched capacitor balancing circuits' configurations are shown in figures 2-5.

This paper focuses on the switched capacitor balancing methods. First, give brief description of the switched capacitor methods from different

viewpoints. Second, simulate different switched capacitor balancing models using MATLAB/Simulink, as well as comparers between various switched capacitor balancing methods based on circuit configuration and simulation results. Finally, suggest several improvements will be proposed to overcome the switched capacitor long equalization time drawback.

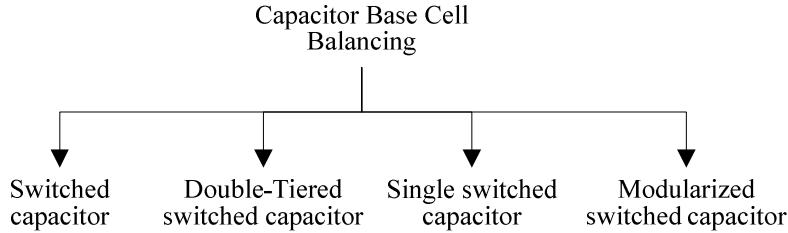


Figure 1: Switched capacitor cell balancing methods.

## 2 Capacitive shuttling balancing methods

Switched capacitor cell balancing, also known as “Charge Shuttling” equalization, [10-18] utilize basically an external energy storage devices, capacitor(s) for shuttling the energy between the battery pack cells so as to the balancing. The capacitor shuttling can be categorized into four shuttling configuration; the basic switched capacitor, double-tiered switched capacitor, single switched capacitor and modularized switched capacitor topologies.

### 2.1 Switched Capacitor

The switched capacitor [1-5], [10-13] is shown in Fig. 2. As illustrated it requires  $n-1$  capacitors and  $2n$  switches for balancing  $n$  cells. Its control strategy is simple because it has only two states. In addition, it does not need intelligent control and it can work in both recharging and discharging (at light loads currents) operation with high efficiency. The disadvantage of the switched capacitor topology is relatively long equalization time and more expensive than the switched shunt resistor balancing method.

### 2.2 Double-Tiered Capacitor

This balancing method [14-16] is also a derivation of the switched capacitor method, the difference is that it uses two capacitor tiers for energy shuttling as shown Fig. 3. It needs  $n$  capacitor and  $2n$  switches to balance  $n$  cells.

More tiers means more paths between batteries, which yields less impedance to the transport of charge over a particular distance across the battery pack [14].

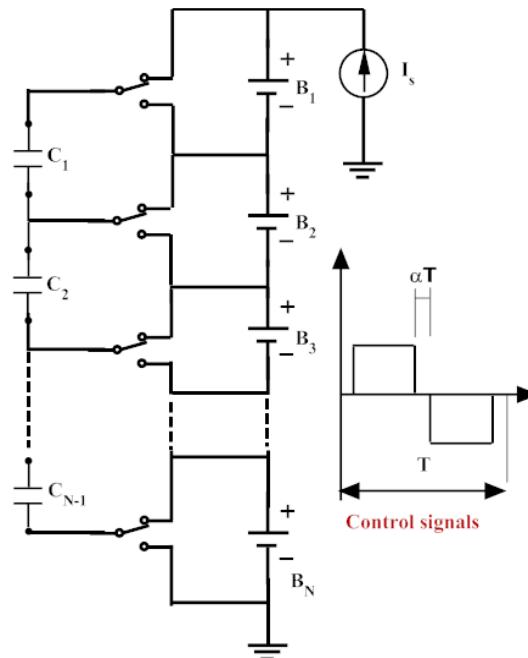


Figure 2: Switched capacitor (SC). [2]

The advantage of double-tiered switched capacitor more the switched capacitor method is that the second capacitor tier reduces the balancing time for more than a half. In addition, as the switched capacitor topology the double-tiered switched capacitor can work in both recharging and discharging operation.

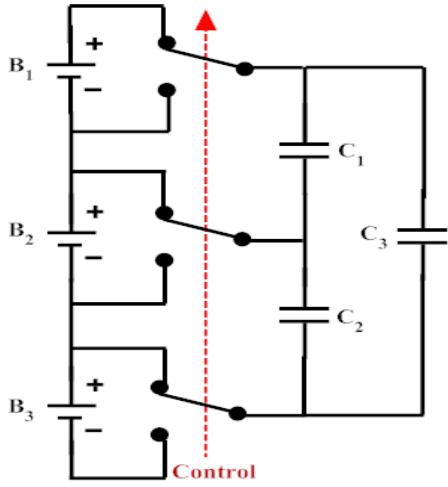


Figure 3: Double-Tiered switched capacitor (DTSC). [2]

### 2.3 Single Switched Capacitor

The single switched capacitor balancing topology [1-2], [4-5], [17], [23] can consider as a derivation of the switched capacitor, but it uses only one capacitor as shown Fig. 4. The single switched capacitor needs only 1 capacitor and  $n+5$  switches to balance  $n$  cells.

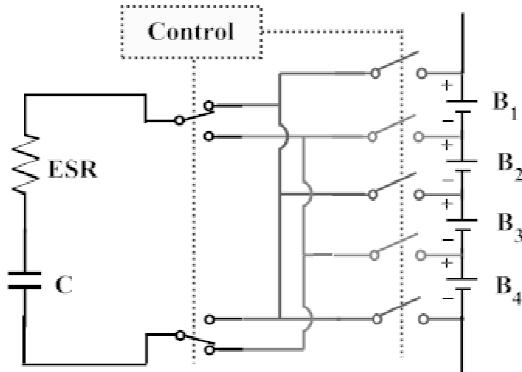


Figure 4: Single switched capacitor (SSC). [2]

A relatively simple control strategy is always used; the controller selects the higher and the lower charge cells then controls the corresponding switches for shuttling the energy between them. However, more advanced control strategies can be used for fast the balancing speed, which will be discussed later in the proposed control strategy.

### 2.4 Modularization Switched Capacitor

Another topology utilizes the switched capacitor method is based on battery pack modularization [18] shown in Fig. 5. It utilizes the modules

technique by dividing the battery pack into modules; inside each module it treats with sub-module cells with a separate equalization system. As well as, another equalization system is applied for balancing between the modules. That is to reduce the switches voltage and/or the current stress. MSC advantage it can operate in charging and discharging mode and has less balancing time than the switched capacitor. The main disadvantage of the MSC is that for balancing between modules utilizing switched capacitor will has a high cost due to high capacitor voltage value.

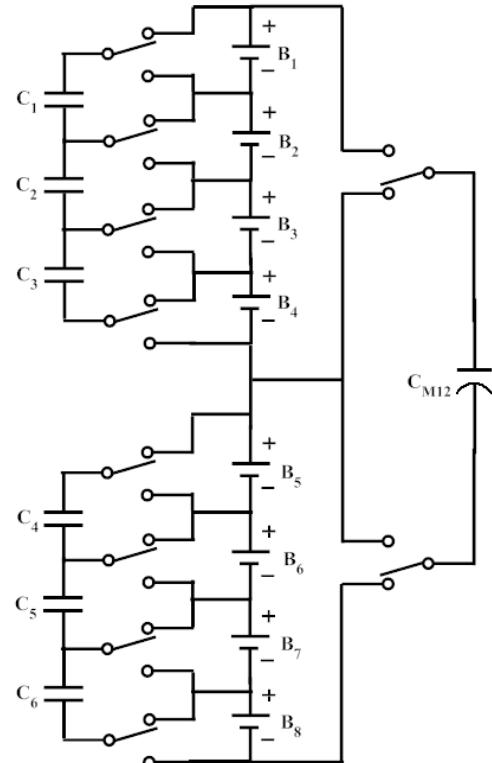


Figure 5: Modularized switched capacitor (MSC). [2]

## 3 Switched Capacitor Balancing Topologies Simulation Results

MATLAB/Simulink becomes the most used software for modelling and simulating the dynamic systems, here it is used for simulating the switched capacitor balancing methods. First step for constructing the cell balancing system is simulate one cell battery model, Lithium polymer (Li-Po) batteries have been tested and their model parameters estimated according to [21], after that a complete battery model “*Extended partnership for a new generation of vehicles EPNGV*” as in [22] was simulated. This battery model features by; it has SoC, SoH and cycle number prediction, variable parameters in function of SoC,

temperature and cycle number with a parameters variation between the pack cells.

Switched capacitor battery balancing methods have been simulated using Simulink with the suitable control systems with no load current drawn. Figures 6-8 illustrate the SC, DTSC and SSC balancing simulation results respectively. Four 12 Ah Lithium-Ion cells are used for the simulation comparison with a 5% state of charge (SoC) difference between each two neighboured

cells, initial SoC 80, 75, 70 and 65%, means that the higher SoC difference is 15%. As well as, the variation in the batteries model parameters are proposed. Some simulation results are illustrated in figures 6-8. Switched capacitor simulation results are shown in Fig. 6, the cells voltage, one capacitor voltage, cells SoC and cells currents. Double-Tiered switched capacitor simulation results are shown in Fig. 7. In addition, the single switched capacitor results are illustrated in Fig. 8.

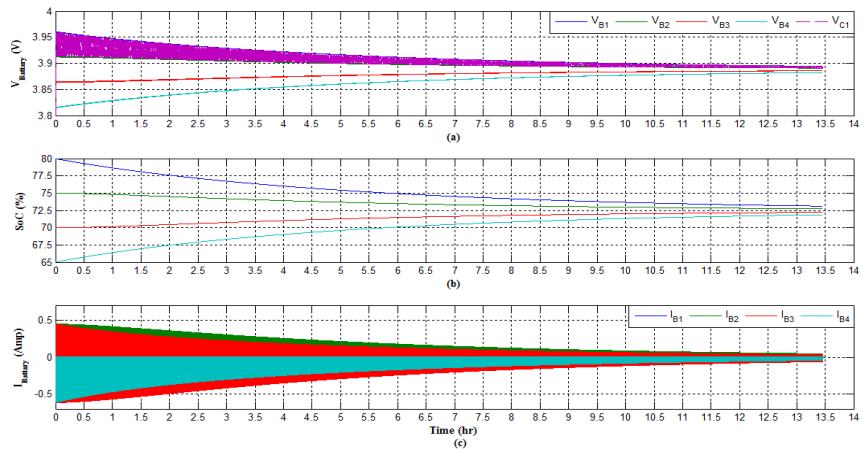


Figure 6: Switched capacitor simulation results. a) Cells and capacitor  $C_1$  (between cells 1&2) voltages, b) Cells SoC, c) Cells currents

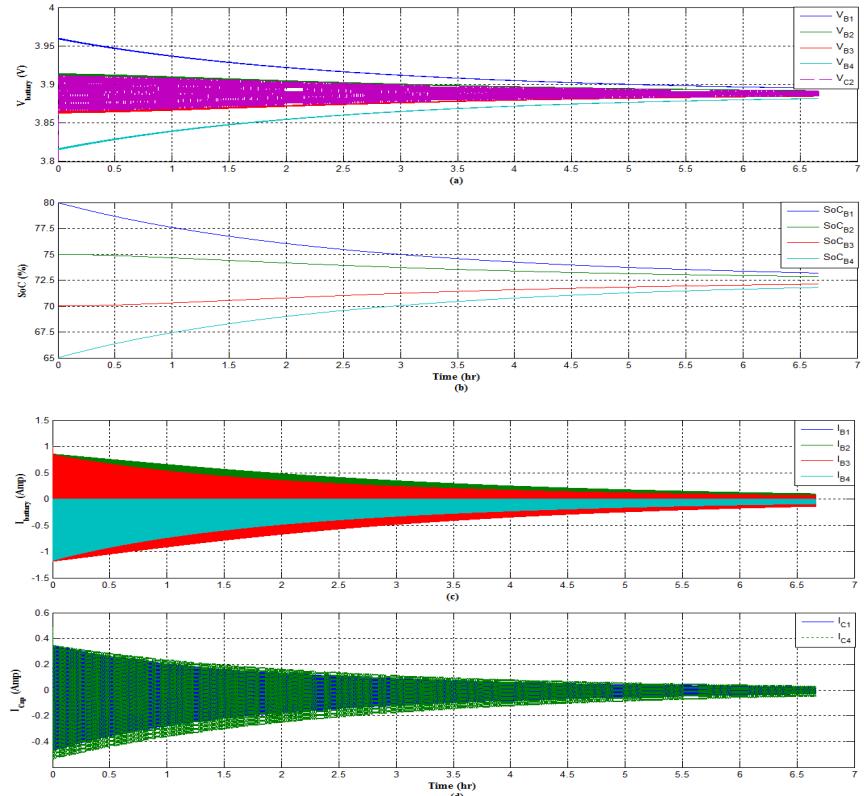


Figure 7: Double-Tiered switched capacitor simulation results. a) Cells and capacitor  $C_2$  (between cells 2&3) voltages, b) Cells SoC, c) Cells currents and d) Capacitors  $C_1$  and  $C_4$  (second tier capacitor) currents

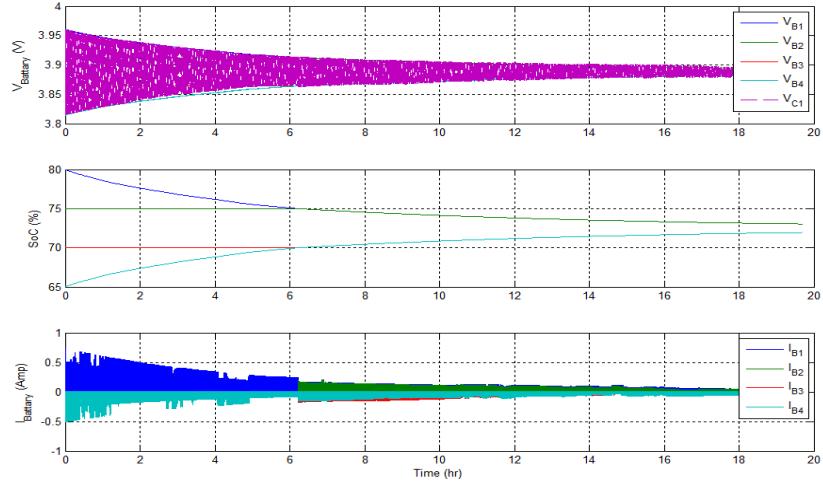


Figure 8: Single switched capacitor simulation results. a) Cells and capacitor voltages, b) Cells SoC, c) Cells and the capacitor currents

As an initial conclusion from the previous circuits and the simulation results it is clear that;

- The SSC has only one capacitor and the MSC method utilizes more capacitors and switches than the traditional switched capacitor.
- Both SC and DTSC have a straightforward control strategy, on the contrary, the SSC and MSC they are need relatively complex control.
- The SC and DTSC methods which have a simple control and have a great problem that; when the SoC difference between the cells is small, as well the voltage difference, the equalization current becomes smaller that will increases the equalization time significantly.
- The DTSC compared to the SC method, the first one has one more capacitor and importantly the DTSC decreases the balancing speed up to 50%, some times more, of the traditional SC.

## 4 Single Switched Capacitor Control

Single switched capacitor can have more intelligent control to optimize its performance that will reducing the capacitor size and cost as well, or maximizing the energy transfers between the cells, so that minimizing the balancing time. That can be done by intelligently controlling the switching frequency after extracting the switching cost function(s).

Conventionally control for the SSC is selecting the high energy, voltage, cell and low energy cell and shuttling the energy between them. The switches control can be classically performed using a fixed frequency (F) and duty cycle (D) that controls the switched capacitor equivalent resistance  $R_{equ}$  presented in equation (1) as a general case [22-23]. For normal duty cycle control, typically T is fixed,  $D_1$  and  $D_2$  are both fixed, typically both set as close to  $D = 50\%$  and the resistances are nearly equal, so  $\tau_1$  and  $\tau_2$  are nearly equal  $(ESR+R_{Cell})^*C$ . In this method a low equivalent resistance is paramount for effective equalization [22]. But that will not be very effectively when the voltage difference between the cells is small, the equalization current becomes smaller also, that will increases the equalization time significantly.

$$R_{equ} = \frac{1}{fc} \cdot \frac{1 + \exp\left(-\frac{DT}{\tau}\right)}{1 - \exp\left(-\frac{DT}{\tau}\right)} \quad (1)$$

### 4.1 Proposed control strategy:

The high charge cell – capacitor – low charge cell energy shuttling by somehow is a function of the capacitor value (C), switching frequency (F), series equivalent resistor ( $R_{Seq}$ ), voltage different between the unbalanced cells ( $V_{diff}$ ) and finally the duty cycle, on-period, (D). The proposed SSC balancing strategy will based on these factors as discussed later.

The capacitor voltage during charging period with an initial voltage  $V_i$  and final voltage  $V_f$  can be expressed as in equation (2), and the corresponding capacitor current can be formulated as (3) these

equations will be used for extracting the switched capacitor shuttling energy between two cells. There are some assumptions before extracting the transferred energy function: First the capacitor will switch from the lower charge cell  $V_i$  and connect to the higher charge cell  $V_f$ . The cells internal resistors are equal so the series equivalent resistor ( $R_{Seq}$ ) of the switched capacitor circuit will be the sum of the capacitor ESR and one cell internal resistor so the time constant  $\tau$  is equal to  $(ESR + R_{Cell}) \cdot C$ . This SSC energy is calculated during one charging period only, in other word, in time equal to one duty cycle  $DT$ .

$$V_{c_{charging}} = (V_f - V_i) \left(1 - e^{-\frac{t}{\tau}}\right) + V_i \quad (2)$$

$$= V_{diff} \left(1 - e^{-\frac{t}{\tau}}\right) + V_i$$

$$i_c = C \frac{dV_c}{dt} = \frac{V_{diff}}{R_{Seq}} \cdot e^{-\frac{t}{\tau}} \quad (3)$$

$$Energy = \int_0^{DT} i_c \cdot v_c dt$$

$$= C \cdot V_{diff} \left\{ \left[ \frac{V_{diff}}{2} \cdot e^{-2\frac{D}{\tau \cdot F}} - V_f \cdot e^{-\frac{D}{\tau \cdot F}} \right] - \left[ \frac{V_{diff}}{2} - V_f \right] \right\} \quad (4)$$

Equation (4) gives the energy transferred from the higher charge cell to the capacitor during the period  $D_1T$  or  $DT$ . This energy is a function of the capacitor value  $C$ , switching frequency  $F$ , cells voltages and voltages difference  $V_{diff}$ , series equivalent resistor  $R_{Seq}$ , and duty cycle  $D$  with different relation. Figures 9-13 show the transferred energy as a function of  $C$ ,  $F$ ,  $V_{diff}$ ,  $R_{Seq}$  and  $D$  relations respectively.

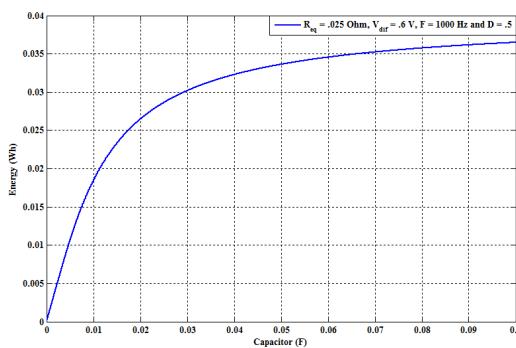


Figure 9: SSC transferred energy as a function of capacitor value.

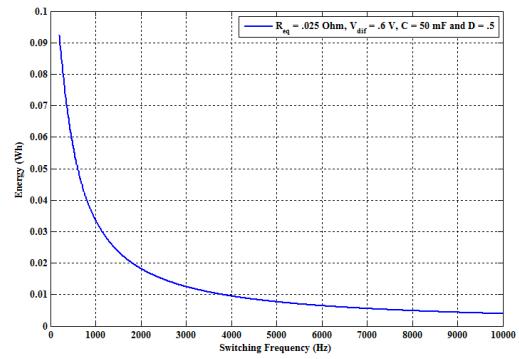


Figure 10: SSC transferred energy as a function of switching frequency.

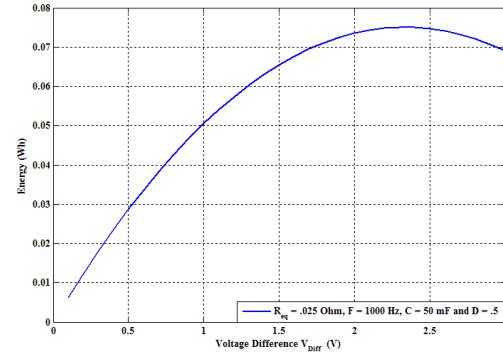


Figure 11: SSC transferred energy as a function of Voltage difference.

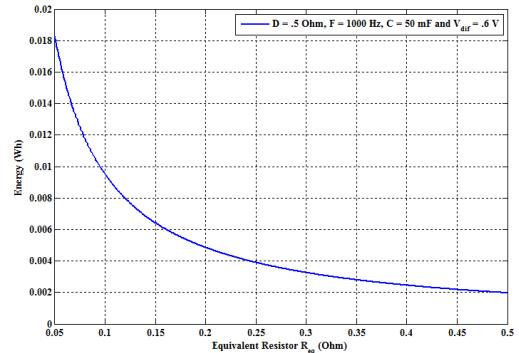


Figure 12: SSC transferred energy as a function of equivalent resistor.

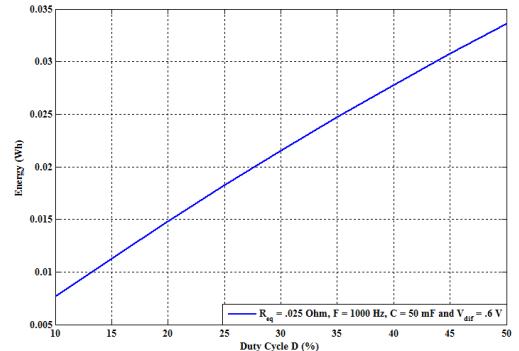


Figure 13: SSC transferred energy as a function of duty cycle D.

As shown in figures 9-13 and equation (4) the energy transferred has different relations with  $C$ ,  $F$ ,  $V_{\text{diff}}$ ,  $R_{\text{Seq}}$  and  $D$ . The aim of the proposed SSC cell balancing control strategy based on maximizing this energy transfer with these parameters ( $C$ ,  $F$ ,  $V_{\text{diff}}$ ,  $R_{\text{Seq}}$  and  $D$ ), as well as, keeping that energy maximum as possible with any variation of these parameters such as  $V_{\text{diff}}$  along the balancing period.

#### 4.1.1 Proposed SSC strategy steps:

1. Extracting the transferred energy between the cells and the capacitor function, it can be easily maximizing this transferred energy and reducing the balancing time as well. That can be done by controlling the switching frequency during the equalization process.
2. Selecting optimal capacitor (minimum) with manufacture ESR by maximizing the energy function with different switching frequency, energy as a function of ( $C$ ,  $F$ ), with any arbitrary  $V_{\text{diff}}$  and  $D$  because these two parameters will vary during balancing periods.
3. After select the capacitor value with given ESR, maximizing the energy transfer with that given  $C$  and  $R_{\text{Seq}}$  values and now the energy will be function of ( $F$ ,  $D$ ) at different  $V_{\text{diff}}$ .
4. By measuring the higher and lower cells voltage, applying the corresponding  $F$  and  $D$  along the balancing time to get maximum energy transfer so that reducing the balancing time.
  - A. Dividing the balancing period into zones according to voltage difference  $V_{\text{diff}}$ . Then decide the required maximum current allowed to pass through the capacitor and the corresponding equivalent resistor  $R_{\text{equ}}$  value. To get this resistor value select  $D$  value and allowable switching frequency range as illustrated in Fig. 14.
  - B. From this frequency range maximize your energy function with the optimal switching frequency.

#### 4.1.2 Protective Steps

1. At the balancing starts, if the capacitor voltage lowers than the low charge cell voltage, the capacitor must switched firstly with the lower voltage cell first till to prevent high balancing current.

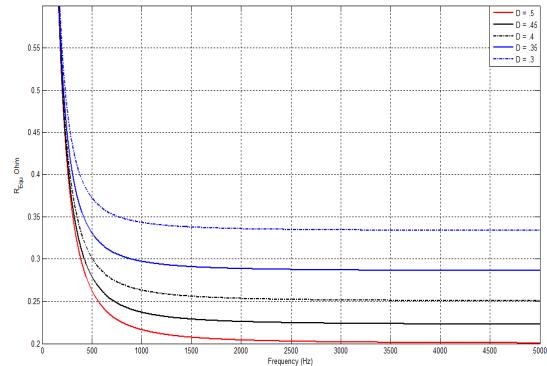


Figure 14: SSC equivalent resistor  $R_{\text{equ}}$  as a function the switching frequency  $F$  and the duty cycle  $D$ .

2. Another solution to avoid high balancing current if the cells have high voltage difference is to add resistor in series with the switched capacitor and that resistor are shunted with a switch for controlling its value and out the resistor totally when the voltage difference become in an acceptable values. By adding this resistor it can be easily controlling the switched capacitor current.

## 5 Conclusion

Battery system application in electric vehicle is a very important issue, the cell balancing as an important task of the BMS that increase battery pack life, the safety of the battery system as well benefit from the whole battery pack energy. Switched capacitor battery balancing topologies, SC, DTSC, SSC and MSC have been reviewed; simulated using MATLAB/Simulink and detailed comparison have been presented. The single switched capacitors balancing method has been discussed in details with an optimal control strategy for reducing the system cost and balancing time by increasing the energy transfer between the cells and the capacitor.

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