Scholar Journal of Applied Sciences and Research

Sch J Appl Sci Res 2018
Volume 1: 8

Suitability of Switched Capacitor Converters for Electric Vehicle Energy Storage

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Abstract

Novel topologies and intelligent balancing strategies for electric vehicle and plug-in hybrid electric vehicle energy storage system applications are proposed in this paper. The focus is on switched capacitor bidirectional DC/DC converter topologies, to reduce balancing time and number of switches required.

Keywords: Battery storage, Control, Electric vehicles, Energy management, Power electronics, Switched capacitor converters, Voltage equalizers.

Introduction

An electric vehicle (EV) battery is able to store large amounts of energy (in the order of 1kW/kg; 100Wh/kg). However, it is not suitable for supplying a large amount of power in a very short time, due to low power output density. The lead acid, alkaline, and lithium-ion (Li-ion) batteries are generally used for portable utilities and industry applications. As for the lithium-ion battery, it has the advantage of high working cell voltage, low environmental population, low self-discharge rate, and high power density in volume as well as high specific energy and energy density. Therefore, the voltage in a single battery cell is inherently low. Series-connected lithium-ion battery packs are usually employed for EVs, hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs). The battery cell voltage imbalance in a series connection could result in differences in cell internal resistance (R_{in}), unbalanced state-of-charge (SOC) between cells, and the gradients of ambient temperature of the battery during charging and discharging [1-3].

Thus, battery cell voltage equalization control is imperative, to regulate charging and discharging current to the allowable limitations of cells in the battery series. This in turn is determined by the cell physical design and materials. Without equalization, the individual battery voltages will slowly drift apart over time and battery capacity decreases rapidly. Thereafter, battery life cycles shorten, eventually leading to total destruction of the battery system [4,5].

Lithium-ion battery chemistries cannot suffer overcharge in the charging state, since it will cause vaporizing active materials in the internal area of the battery and increase pressure, which gives rise to a higher risk of explosion. The maximum overvoltage threshold is unstable close to the fully charged terminal voltage, typically, in the range of 4.1 to 4.2 V/cell. Li-ion batteries must also be prevented from being discharged to very low voltage limit; typically, about 2.0 to 2.5 V/cell. Over discharge will melt copper in the electrolyte, which damages the battery or causes battery cell short circuiting. Cell balancing control is designed to obtain maximum usable capacity from the Li-ion battery string. Thus, battery string charging and discharging are limited by any

Article Information

Article Type: Research
Article Number: SJASR193
Received Date: 15 October, 2018
Accepted Date: 26 October, 2018
Published Date: 06 November, 2018

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Citation: Amjadi Z (2018) Suitability of Switched Capacitor Converters for Electric Vehicle Energy Storage. Sch J Appl Sci Res. Vol: 1, Issu: 8 (01-05).

one single cell reaching its end-of-charge voltage (about 4.1 to 4.2 V/cell) and low voltage threshold (about 2.0 to 2.5 V/cell), respectively [6-8].

For EV applications, Li-ion batteries could be supplemented by ultra-capacitors (UCs). An ultra capacitor has low storage capacity, but possesses the ability to supply a large burst of power with short charge/discharge times. Due to the low voltage of a single UC cell, which is typically 2.5 to 3.0V, in a fully charged state; series connected UC strings with the bus voltage in the range of 300V-400V is necessary for high voltage applications such as EV, HEV, and PHEV [9,10]. The battery is used to supply a large amount of power at light loads, thereby increasing the total efficiency, whereas the UC bank is used for satisfying EV/HEV acceleration and regenerative braking requirements. Such a scenario also helps improve the on-board battery life time. The combination of battery and UC results in reduced size and weight of the overall energy storage system [11-13].

Equalization Circuit Topologies: Modeling and Analysis

Cell voltage equalizer for electric double layer capacitors

This cell voltage equalizer consists of 10 switches and 6 capacitors, C_1–C_6. Each switch consists of two back-to-back MOSFETs for current flow in both directions [14]. A typical system schematic is shown in Figure 1.

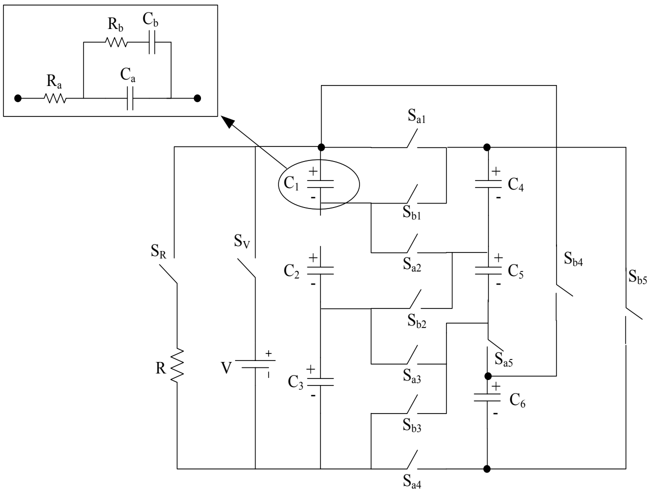
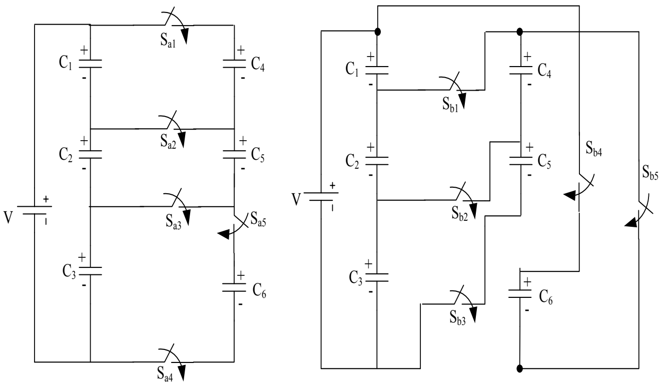


Figure 1: A typical system schematic with cell voltage equalizer and equivalent circuit of EDLC.



(a) (b)

Figure 2: Equivalent circuit of cell voltage equalizer, (a) first state; only SA is on and SB is off, (b) second state; SA is off and SB is on.

Figure 1 includes the equivalent circuit models of capacitors C_1–C_6. Equivalent circuit of EDLC consists of two capacitors, C_a and C_b in parallel, and two resistances, R_a and R_b. When S_V is ON and S_R is OFF, system is charged by voltage source, V. Otherwise, system transfers its stored energy to resistance, R. When system is charged, it is shown by two states. For better understanding of operation of switches, S_{a1}–S_{a5} is called S_A, and S_{b1}–S_{b5} is called S_B. Switch S_A is ON and S_B is OFF in the mode of operation depicted in Figure 2. In this state: $V_{C1}=V_{C4}$, $V_{C2}=V_{C5}$, and $V_{C3}=V_{C6}$.

In the second mode of operation, S_A is OFF and S_B is ON. This mode of operation is depicted in Figure 2(b). During this state: $V_{C1} = V_{C6}$, $V_{C2} = V_{C4}$, and $V_{C3} = V_{C5}$. First and second states appear one after another, and the process repeats, until all capacitor voltages become equal.

During the discharging process, S_V is OFF and S_R is ON. The system transfers its stored energy to resistance, R. In long term, voltage across resistance, R, slowly decreases, and in short term, it can be assumed to be constant. Discharging process equalizer is operated in the same manner. Therefore, each capacitor voltage can be maintained equal.

Cell equalizers for ultracapacitors

An alternative topology utilizes equalization operation for ultracapacitor (UC) energy management. A typical electric vehicle energy storage system could consist of up to about 600 UC cells. A typical arrangement of the UC cells is as shown in Figure 3. The equalization operation is represented in Figure 4. The principle of operation is fairly simple, wherein power is transferred from a higher voltage capacitor to a lower voltage capacitor.

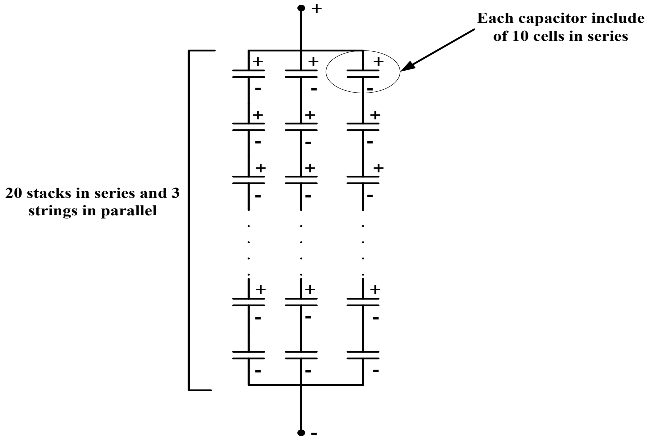


Figure 3: Ultracapacitor stacks with three strings in parallel.

In the first step, the higher voltage capacitor charges the balancing capacitor (BC). Thereafter, BC charges the lower voltage capacitor. In both operation modes, S_1 and S_2 are on. Each switch consists of two anti-series MOSFETs, for current flow in both directions [15]. The equivalent circuit of the cell equalizer is shown in Figure 5. Here, C_1, U_1, and R_1 represent the capacitance, voltage before S_1 and S_2 are on, and the internal resistance of the BC, respectively. Also, C_2,

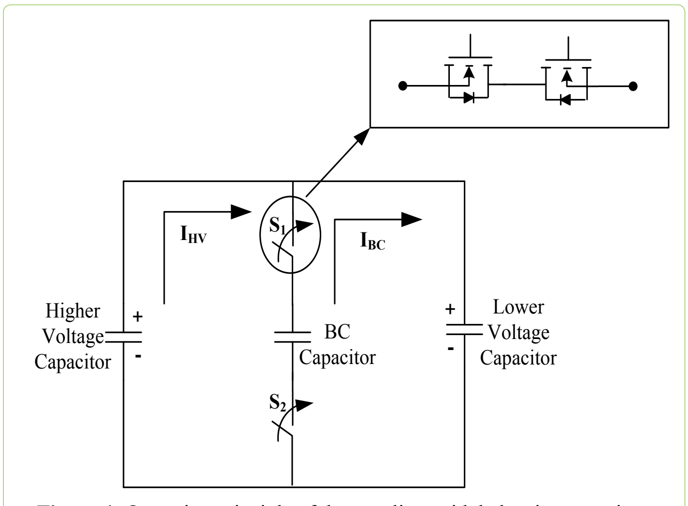


Figure 4: Operating principle of the equalizer with balancing capacitor.

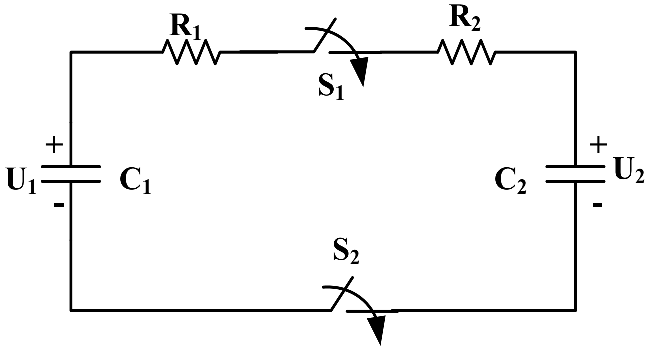


Figure 5: Equivalent equalization circuit, with BC and UC stack capacitors in parallel.

U_2, and R_2 are the capacitance of the UC stack, to be charged or discharged, voltage before S_1 and S_2 are on, and its internal resistance, respectively. Voltages U1 and U2 versus time can be expressed as:

$$U_1(t)=\frac{C_1U_1+C_2U_2}{C_1+C_2}+\frac{C_2}{C_1+C_2}(U_1-U_2)e^{\frac{-(C_1+C_2)t}{(R_1+R_2)C_1C_2}} \tag{1}$$

$$U_2(t)=\frac{C_1U_1 \quad C_2U_2}{C_1+C_2}-\frac{C_2}{C_1+C_2}(U_1-U_2)e^{\frac{-(C_1+C_2)t}{(R_1 \quad R_2)C_1C_2}} \tag{2}$$

In order to achieve faster equalization, three BCs can be chosen for three strings of stacks. Thus, there exist three modes in the UC equalization operation energy management system, namely, charging, discharging, and static modes [15]. Each mode is described in the sub-sections to follow.

Equalization during charging mode: Ultracapacitors inherently possess quick-charge characteristics. Typically, UCs fully charge in about 15-20 minutes, using large currents. The balancing capacitor is controlled to parallel the stack with highest capacitor voltage between the strings in series. The voltage of larger capacitor increases slowly. However, the voltages of other stacks increase comparatively rapidly. During charging, BC switches from one stack to a new stack, with highest voltage between strings. U_{full} represents fully charged voltage of UC stack, C_{new} is new highest voltage stack during charging, u_{new} is voltage of C_{new}, C_{old} is the stack used in parallel with BC, before BC switches to new highest voltage stack, and u_{old} is voltage of C_{old}. Assume that $\Delta u = U_{full} - u_{new}$ and $\delta u = u_{new} - u_{old}$. When $\delta u \geq f(\Delta u)$, it means the BC is disconnected from C_{old}, and is connected to the new highest voltage stack (C_{new}). Therefore, $f(\Delta u)$ can be written as:

$$f(\Delta u)=\begin{cases} \frac{\Delta u}{4} & 6V \leq \Delta u \\ \frac{\Delta u}{3} & 2V \leq \Delta u < 6V \\ \frac{\Delta u}{2} & 1V \leq \Delta u < 2V \\ \frac{1}{2} & \Delta u < 1V \end{cases} \tag{3}$$

Thus, the stacks are charged appropriately, and at the same time, are protected from over-charging. Thereafter, the BC is ready to enter discharging mode [15].

Equalization during discharging mode: Similar to charging, ultracapacitors have a tendency to quickly discharge, using large currents. The BC is controlled to parallel the stack with lowest capacitor voltage between the strings in series. The larger capacitor voltage decreases gradually, while voltages of other stacks decrease comparatively quickly. In discharging mode, BC switches between the old stack to new stack, with lowest voltage between strings [15].

Equalization during static mode: In the static mode, energy is transferred from high voltage stacks to low voltage stacks, and there exists no charging or discharging current flowing in or out of the stacks. Consider the UC stack with maximum and minimum voltages as C_{max} and C_{min}, respectively. Also, consider voltage of C_{max} and C_{min} as U_{max} and U_{min}, respectively. U_{avg} is average voltage of the entire UC stack. U_{BC} and I_{BC} represent the BC voltage and current flow, respectively. I_g and U_g are minimum balance current and minimum voltage difference limit value, respectively. Details of the equalization process are shown in the flowchart of Figure 6. During the equalization process, the stack capacitance is equal to the sum of BC capacitance and stack capacitance [15].

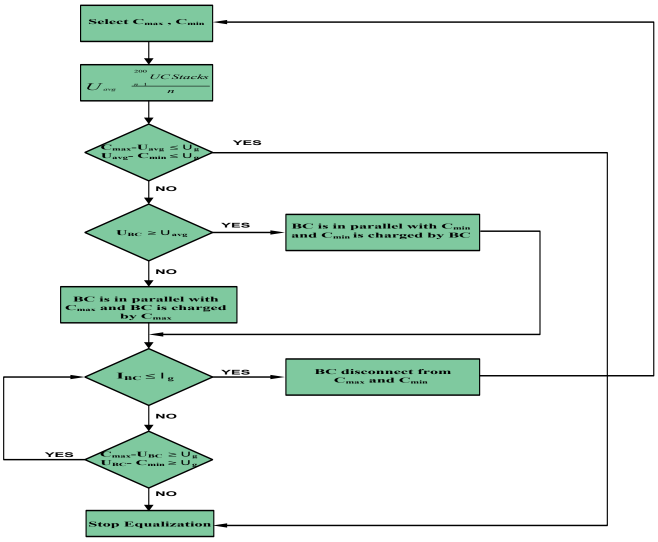


Figure 6: Overall algorithm for ultracapacitor cell equalization.

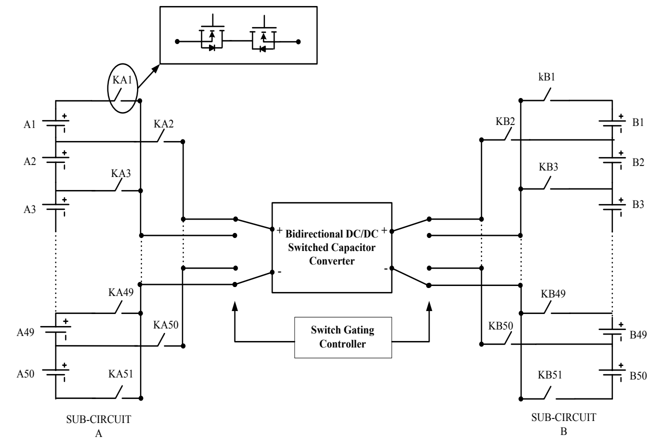


Figure 7: Battery cell equalizer with isolated switched capacitor bidirectional DC/DC converter.

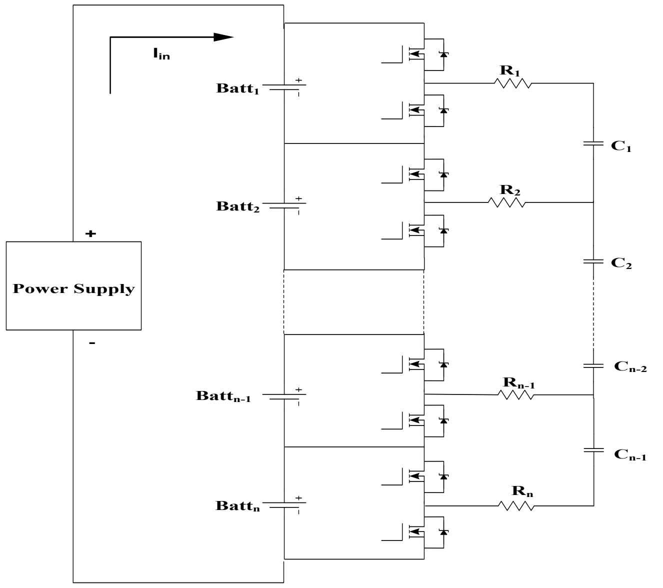


Figure 8: Block diagram of a typical switched capacitor converter based cell equalizer.

Isolated DC/DC converter topology for battery cell equalization: In this topology, the battery equalizer consists of a bidirectional DC/DC converter and two pairs of balancing voltage buses. Typically, the power electronic battery management system could consist of up to about 100 cells, coupled with 102 MOSFETs. The polarities of the balancing buses are not fixed; they could either be positive or negative. Each cell can be connected to balancing buses by switches. This flexibility of the polarity of balancing buses leads to reduction in the number of switches by almost 50%.

The batteries and switches could be divided into two sub-circuits, *A* and *B*. Consider the scenario, wherein sub-circuit *A* consists of 50 battery cells (A_1, A_2...A_{50}) and 51 switches, (KA_1, KA_2...KA_{51}). Also, consider sub-circuit *B*, consisting of 50 battery cells (B_1, B_2...B_{50}) and 51 switches (KB_1, KB_2...KB_{51}) [16,17]. A typical schematic of such a switched capacitor based power electronics intensive battery cell equalizer is shown in Figure 7.

As aforementioned, each corresponding switch consists of two MOSFETs, for current flow in either direction, based on battery cell load conditions. The overall equalization process is best described by considering the following probable scenario:

Initially, the highest cell voltage in sub-circuit *A* and lowest cell voltage in sub-circuit *B* is selected. Energy gets transferred from sub-circuit *A* to *B*, through the DC/DC converter. If the highest cell voltage in sub-circuit *A* is higher than lowest cell voltage in sub-circuit *B*, then the highest cell voltage in sub-circuit *B* and lowest cell voltage in sub-circuit *A* is selected. Thus, energy gets transferred from sub-circuit *B* to *A* via the bidirectional switched capacitor DC/DC converter. If the highest cell voltage in sub-circuit *B* is higher than lowest cell voltage in sub-circuit *A*, then the overall process is repeated every 30 seconds, until all battery cell voltages are equalized.

If the battery cells of sub-circuit *A* are selected for balancing, then KA_n number of switches are on (where $n = 1, 2...51$). If n is an odd number, KA_n is of positive polarity. In addition, $KA_{(n+1)}$ is of negative polarity. KA_n is of negative polarity and $KA_{(n+1)}$ is of positive polarity, otherwise.

Figure 8 shows an equalizer arrangement that consists of *n* battery cells in parallel with a switched capacitor converter. In addition, the power circuit also consists of (*n*-1) capacitor cells and ideal switches in series with resistor, *R*. It must be noted that the power supply and the switched capacitor equalizer are operated simultaneously.

As is clear from Fig. 8, the MOSFTEs are controlled by the capacitors, whereby they are charged and discharged through different paths. As is obvious, the balancing current is directly proportional to the capacitance value that the converter switches [16,17].

Conclusion

This paper presented the viability of using switched capacitor converter topologies and corresponding intelligent balancing strategies for electric and plug-in hybrid electric vehicle energy storage systems. Switched capacitor converter based battery and/or ultracapacitor cell voltage equalization depicts the following major advantages: (a) switching losses of MOSFETs can be significantly reduced, (b) low electromagnetic interference (EMI) emission, and (c) reduced size, cost, and weight of the overall energy storage and management system.

References

1. Amjadi Z, Williamson SS (2010) Power-electronics-based solutions for plug-in hybrid electric vehicle energy storage and management systems. IEEE Trans on Industrial Electronics 57: 608-616.
2. Venkatasetty HV and Jeong YU (2002) Recent advances in lithium-ion and lithium-polymer batteries," in Proc. 17th Annual Battery Conf. Applications and Advances; pp: 173-178.
3. McDowell J, Brenier A, Broussely M, Lavaur P (2002) Industrial lithium-ion batteries: from the laboratory to real telecom application. IEEE Annual International Telecommunications Energy Conf; pp: 373-378.
4. Amjadi Z and Williamson (2014) Digital Control of a Bidirectional DC/DC Switched Capacitor Converter for Hybrid Electric Vehicle Energy Storage System Applications. IEEE Transactions on Smart Grid 5: 158-166.
5. Lee YS and Cheng MW (2005) Intelligent control battery equalization for series connected lithium-ion battery strings. IEEE Trans. on Industrial

Electronics 52: 1297-1307.

6. Moore SW and MacLean G (2001) Control and management strategies for the Delphi high power lithium battery. 18th International Battery, Hybrid and Fuel Cell Electric Vehicle Symp and Exhibition, Montreal, Quebec. pp: 1-10.
7. Amjadi Z and Williamson SS (2010) Modeling, simulation, and control of an advanced Luo converter for plug-in hybrid electric vehicle energy storage system. IEEE Transactions on Vehicular Technology 60: 64-75.
8. Affanni A, Bellini A, Franceschini G, Guglielmi P, Tassoni C (2005) Battery choice and management for new-generation electric vehicles. IEEE Trans on Industrial Electronics 52: 1343-1349.
9. Park HS, Kim CE, Kim CH, Moon GW, Lee JH (2009) A modularized charge equalizer for an HEV lithium-ion battery string. IEEE Trans on Industrial Electronics 56: 1464-1476.
10. Dong GX, Yan YS, Wei Y, Jun H (2008) Analysis on equalization circuit topology and system architecture for series-connected ultra-capacitor. IEEE Vehicle Power and Propulsion Conf, Harbin, China. pp: 1-5.
11. Amjadi Z and Williamson SS (2010) A novel control technique for a switched capacitor converter based hybrid electric vehicle energy storage system. IEEE Trans on Industrial Electronics 57: 926-934.
12. Amjadi Z and Williamson SS (2010) On the suitability of interleaved switched capacitor converter as an interface for electric vehicle dual energy storage system. World Energy Congress, Montreal, Canada.
13. Schupbach RM, Balda JC, Zolot M, Kramer B (2003) Design methodology of a combined battery-ultracapacitor energy storage unit for vehicle power management. IEEE Power Electronics Specialists Conf, June 1: 88-93.
14. Lukic SM, Cao J, Bansal RC, Rodriguez F, Emadi A (2008) Energy storage systems for automotive applications. IEEE Trans on Industrial Electronics 55: 2258-2267.
15. Cassani PA, Williamson SS (2010) Design, testing, and validation of a simplified control scheme for a novel plug-in hybrid electric vehicle battery cell equalizer. IEEE Trans on Industrial Electronics 57: 3956-3962.
16. Hung ST, Hopkins DC, Mosling CR (1993) Extension of battery life via charge equalization control. IEEE Trans on Industrial Electronics 40: 96-104.
17. Pascual C and Krein PT (1997) Switched capacitor system for automatic series battery equalization. IEEE Applied Power Electronics Conf and Expo 2: 848-854.

Citation: Amjadi Z (2018) Suitability of Switched Capacitor Converters for Electric Vehicle Energy Storage. Sch J Appl Sci Res. Vol: 1, Issu: 8 (01-05).