# Passive and Active Battery Balancing comparison based on MATLAB Simulation

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**Abstract-Battery systems are affected by many factors, the most important one is the cells unbalancing. Without the balancing system, the individual cell voltages will differ over time, battery pack capacity will decrease quickly. That will result in the fail of the total battery system. Thus cell balancing acts an important role on the battery life preserving. Different cell balancing methodologies have been proposed for battery pack. This paper presents a review and comparisons between the different proposed balancing topologies for battery string based on MATLAB/Simulink® simulation. The comparison carried out according to circuit design, balancing simulation, practical implementations, application, balancing speed, complexity, cost, size, balancing system efficiency, voltage/current stress … etc.**

**Keywords –** Battery balancing review, MATLAB/Simulink simulation, Battery management system, Cell equalization.

## I. INTRODUCTION

**B**ATTERY management system (BMS) is an important part of the electric vehicle (EV). It protects the battery system from damage, predicts and increases battery life, and maintains the battery system in an accurate and reliable operational condition. The BMS performs several tasks such as measuring the system voltage, current and temperature, the cells state of charge (SoC), state of health (SoH), and remaining useful life (RUL) determination, protecting the cells, thermal management, controlling the charge/discharge procedure, data acquisition, communication with on-board and off-board modules, monitoring and storing historical data and the most important task is the cell balancing.

Imbalance of cells in battery systems is very important matter in the battery system life. Because without the balancing system, the individual cell voltages will drift apart over time. The capacity of the total 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 such [1-34] and reviewed in [1-5].

The cell imbalance falls into two major categories according to [34], they are internal and external sources. Internal sources include manufacturing variance in charge storage volume, variations in internal impedance and differences in self-discharge rate. While the external sources are mainly caused by some multi-rank pack protection ICs, which drain charge unequally from the different series ranks in the pack. In addition the thermal difference across the pack results in different self discharge rates of the cells.

The balancing topologies can categories as passive and active balancing as shown in Fig. 1. The passive balancing methods removing the excess charge from the fully charged cell(s) through passive, resistor, element until the charge matches those of the lower cells in the pack or charge reference. The resistor element will be either in fixed mode as [5-6] or switched according the system as [1-5], [7-9].

The active cell balancing methods remove charge 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 controlling switches or converters as [1-5] and [9-34].

This paper discusses the several proposed balancing methods from different viewpoints as well simulates some balancing methods using MATLAB/Simulink. First, it gives brief description of these topologies. Second, it simulates some of these balancing topologies using Simulink. Finally, it comparers between the balancing topologies based on circuit design, application, implementations, balancing speed, complexity, cost, size, balancing system efficiency, … etc.
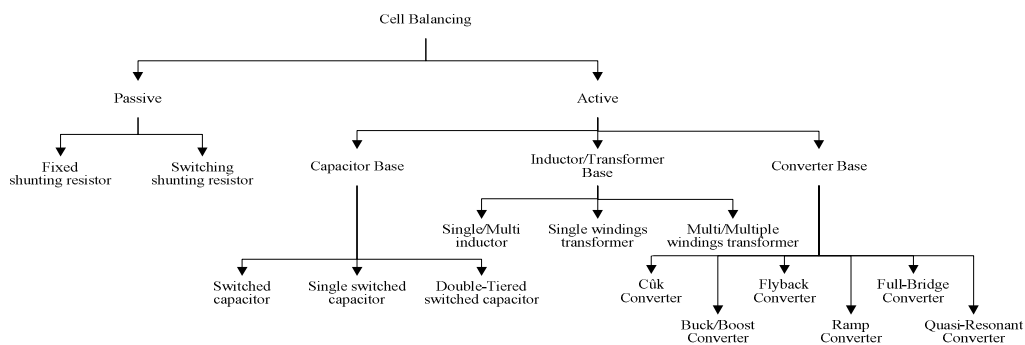


Fig. 1. Passive and Active cell balancing topologies.

## II. SHUNTING RESISTOR BALANCING

Shunting resistor cell balancing methods are the most straightforward equalization concept. They are based on removing the excess energy from the higher voltage cell(s) by bypassing the current of the highest cell(s) and wait to until the lower voltage cell(s) to be in the same level. The shunting resistor methods can be categorized into two sub-categories as shown in Fig. 2.

The first method is fixed shunt resistor as presented in [5-6], as shown in Fig. 2-a. This method uses continuous bypassing the current for the all cells and the resistor is adjusted to limit the cells voltage. It can be only used for Lead-acid and Nickel based batteries because they can be brought into overcharge conditions without cell damage [3]. It's Features are simplicity and low cost but it has continuous energy dissipated as a heat for all cells.

The second method is controlled shunting resistor [7-8], is shown in Fig. 2-b. It is based on removing the energy from the higher cell(s) not continuously but controlled using switches/relays. It could work in two modes. First, continuous mode, where all relays are controlled by the same on/off signal. Second, detecting mode, where the cells voltages are monitored. When the imbalance conditions are sensed, it decides which resistor should be shunted. this method is more efficient than the fixed resistor method, simple, reliable and can be used for the Li-Ion batteries.
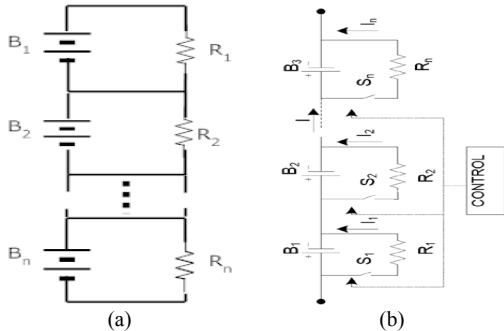


Fig. 2. Shunting resistor a) fixed resistor and b) control shunting resistor [9].

The main drawback in these methods the excess energy from the higher cells is dissipated as heat, and if applied during discharge will shorten the battery's run time. The two methods can be implemented for the low power application with dissipating current is smaller than 10mA/Ah.

### III. CAPACITIVE SHUTTLING BALANCING METHODS.

Capacitive cell balancing, also known as "Charge Shuttling" equalization, [10-16] utilize basically an external energy storage devices, capacitor(s) for shuttling the energy between the pack cells so as to the balancing. The capacitor shuttling can be categorized into three shuttling topologies; the basic switched capacitor, single switched capacitor and double-tiered capacitor topologies see Fig. 1.

### A. Switched Capacitor

The switched capacitor [1-4], [10-11] is shown in Fig. 3. As illustrated it requires n-1 capacitors and 2n switches to balance 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 operation. The disadvantage of the switched capacitor topology is relatively long equalization time.
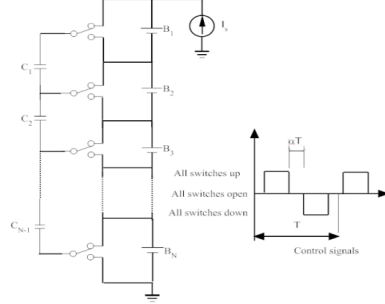


Fig. 4. Switching capacitor cell balancing topology.

### B. Single Switched Capacitor

The single switched capacitor balancing topology [1], [3-4], [12] 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.
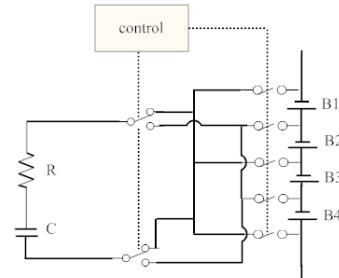


Fig. 4. Single switching capacitor cell balancing topology.

A simple control strategy is used; the controller selects the higher and the lower cell and the corresponding switches for shuttling the energy between them. However, more advanced control strategies can be used to fast the balancing speed.

### C. Double-Tiered Capacitor

This balancing method [13-14] is also a derivation of the switched capacitor method, the difference is that it uses two capacitor tiers for energy shuttling as shown Fig. 5. It needs n capacitor and 2n switches to balance n cells. The advantage of double-tiered switched capacitor more the switched capacitor method is that the second capacitor tier reduces the balancing time to quarter. In addition, as the switched capacitor topology, single switched capacitor and the double-tiered switched capacitor can work in both recharging and discharging operation.
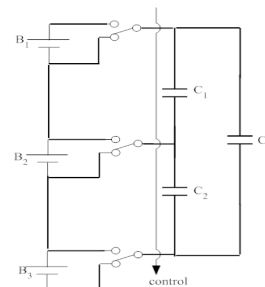


Fig. 5. Double-tiered switching capacitor cell balancing topology.

Another topology utilizes the switching capacitor method is based on battery modularization [15] shown in Fig. 6. 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 another equalization system between the modules. That is to reduce the switches voltage and the current stress.
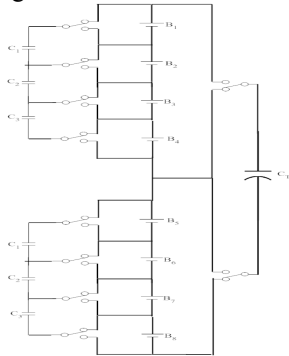


Fig. 6. Circuit modularized switched capacitor [15].

## IV. INDUCTOR/TRANSFORMER BALANCING METHODS.

Energy conversion cell balancing topology uses inductors or transformers as proposed in [16-23] to move energy from a cell or group of cells to another cell or group of cells. They offer a smaller balancing executing time and their disadvantage is relatively high cost for the transformers and that will be described separately. In addition, by [5] since the switching frequency is quite high, filter capacitors must be placed across each battery to filter the high frequency.

### A. Single/Multi-Inductor

Utilizing one or more inductor for cell balancing [16-18] is shown in Fig. 7. The single-inductor balancing system, shown in Fig. 7-a proposed in [17], utilizes one inductor for transferring energy between the whole pack. The control system senses the voltage of the cells and selects the two cells which will be used for energy transferring. In the multi-inductor system [16], [18], uses n-1 inductor for balancing n cells (see Fig. 7-b) and the controller senses the voltage difference of the two neighboring cells, then applying a PWM with a condition that the higher cell must be switched on at first. The main disadvantage in this method, it takes a long time for transferring the energy from the first cell to the last one especially for long string battery pack. Single-inductor has less equalization time than the multi-inductor topology.
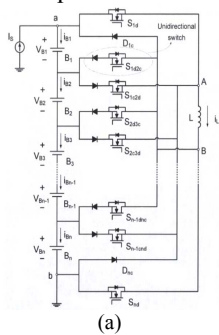
### B. Single-Windings Transformer

Single windings transformer as well, known as "switched transformer" [1-3], [9], [19-20], is actually a selectable energy converter [3]. This method has two techniques for cell balancing. First technique "pack-to-cell topology" as shown in Fig. 8, is based on carrying the energy from the whole battery pack through the switching transformer and transferring that energy to the weak cell(s) using the corresponding switch(s). The second technique "cell-to-pack topology" is based on transferring the energy from the high energy cell(s) through the transformer into the battery pack.
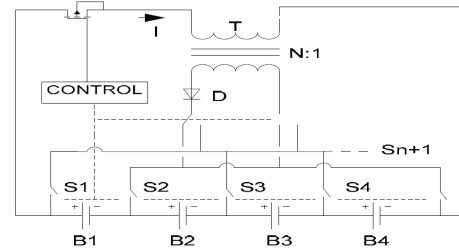


Fig. 8. Single windings transformer balancing topology.

### C. Multi-Windings Transformer

Multi-windings transformer [1-3], [9], [21-22] is shown in Fig. 9. This balancing method can fall into two topologies; the first multi-windings transformer, shown in Fig. 9-a, as well it is known as "shared transformer". The second one is multiple transformer balancing which as shown in Fig. 9-b.

First topology, the multi-windings transformer "shared transformer" topology [1-3], [21-22] has a single magnetic core with one primary windings and multi secondary windings one for each cell. It has two circuit configurations [2]; flyback and forward configurations, as shown in Fig. 9.

The flyback structure, the switch connected to the primary side is switched on. So, some energy is stored in the transformer. Then when it is switched off, the energy is transferred to the secondary of the transformer. Most of the induced current will be provided to the cell(s) with lowest voltage (least reactance) via the diode(s).

In forward structure, when the voltage difference is detected, the switch connected to the cell with highest voltage is switched on, and energy is transferred from this cell to others via the transformer and the anti-parallel diodes of the switch. The circuit is complex and the cost is high, also the multi-windings transformer saturation problem.



| (a) | (b) |

Fig. 7. Single/Multi inductor battery balancing topologies a) multi-inductor [16] and b) single-inductor [17]
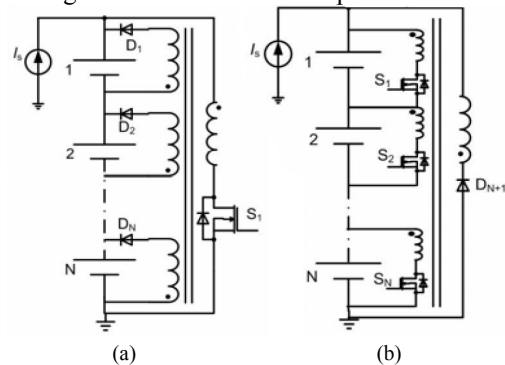


| (a) | (b) |

Fig. 9. Multi-secondary windings transformer a) flyback structure b) forward structure [2].

Second topology, the multiple transformer balancing as in [1-3], [9] is shown in Fig. 10, uses several multiple core transformers, one core for each cell. Compared to the multi-windings transformer scheme, this method is better for modular design and battery pack extension without changing the magnetic core, while it is still expensive.
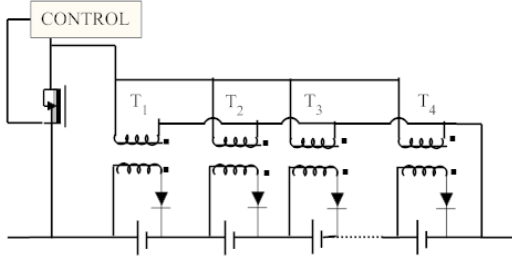


Fig. 10. Multiple transformer balancing topology.

As the switching capacitor modularization method there is same topology for the inductor/transformer modularization [15], [23]. It utilizes the modules technique by dividing the battery pack into groups or modules that will reduce the voltage and/or the current stress in the switching components.

## V. ENERGY CONVERTERS BALANCING METHODS.

Energy converters [24-32] used for cell balancing fall in several categories such as; Cûk, Buck or/and Boost, Flyback, Ramp, full-bridge and, Quasi-Resonant converters. They are featured by fully control of balancing process. Unfortunately, the system is facing its relatively high cost and complexity.

### A. Cûk converter

The bi-directional Cûk converter [24], [25] as shown in Fig. 11 can be considered as individual cell equalizers (ICE) topology, which balances each pair of the neighboring cells. It requires (n−1) ICEs to balancing n cells. Each ICE has two inductor, two switches and one capacitor. Since the Cûk converter transfer the energy between two neighbored cells so it will take relatively long equalization time especially for long string battery pack.
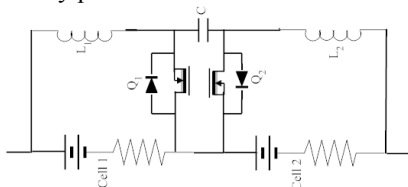


Fig. 11. Cûk converter balancing topology.

### B. Buck or/and Boost converter

A step down (Buck), step-up (Boost) and Buck-Boost energy converters [1-2], [26-27] are widely used in cell balancing systems. These methods have several balancing topologies such as boost converter used for removing the excess energy from single cell to the total pack, or buck-boost converter used for removing exceed energy from the highest cells to the DC link, storage element, and retransfer the energy to the weak cells. The cells voltage sensing as well intelligent controller are needed for the converters operation. Converters balancing methods are relatively expensive and complex but they are suitable for modular design.
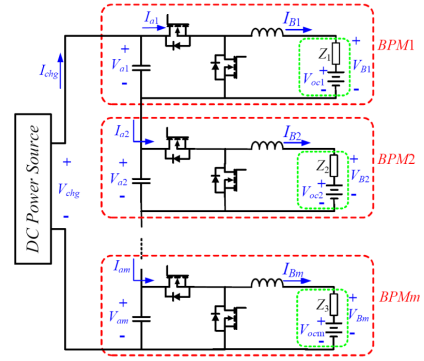


Fig. 12. Buck-Boost energy converters cell balancing topology [26].

### C. Flyback converter

Flyback converters [2], [28-29] are used in isolated structure and they can be unidirectional or bi-directional, as shown in Fig. 13. The unidirectional structure, energy of the more charged cell is stored in the transformer when the coupled switch is on and transferred to the pack when it is off. The bidirectional flyback converter is more flexible in energy transmission where the energy also can be transferred from the pack to the cells. Its drawback is derived from the uniformity of the multi winding as well the magnetic losses.
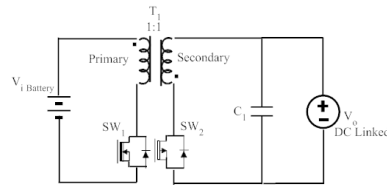


Fig. 13. Flyback energy converter battery balancing.

### D. Ramp converter

Ramp converter cell balancing topology [1], [33] is shown in Fig. 14 shares the same idea as multi-windings transformers. It only requires one secondary winding for each pair of cells instead of one per cell. The ramp converter operation can be summarized as; on the first half cycle, most of the current is used to charge the odd number of lowest voltage cells. While on the other half cycle it supplies the even cells, so that it called ramp converter.
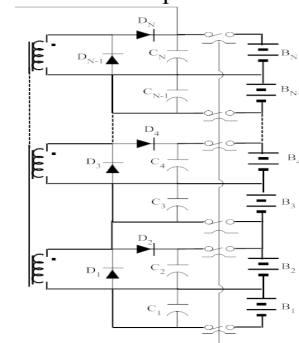


Fig. 14. Ramp converter cell balancing topology.

### E. Full-bridge converter

Full-bridge PWM energy converter [32] can be considered as a fully controlled energy converters are shown in Fig. 15, they can used as AC-DC which is suitable for the plug-in hybrid electric vehicle (PHEV) for or DC-DC converter, both

need an intelligent control and superior for modulated battery packs and high power rating. The main drawback of Full-bridge converter is relatively high cost and complex control.
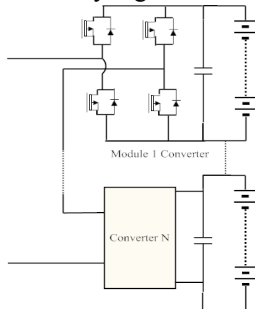


Fig. 15. Full-bridge energy converter cell balancing topologies.

### F. Quasi-Resonant converter

The resonant converter [1], [30-31] shown in Fig. 16, can be either zero-current quasi-resonant (ZCQR) or zero-voltage quasi-resonant (ZVQR) converters. Instead of using intelligent control to generate a PWM signals, resonance circuits are used for both transfer energy and drive the switches. $L_r$ and $C_r$ are constructed as the resonant tank to achieve the zero current switching function for the symmetrical and bi-directional battery equalizer.

The main advantage of the resonant converter is that they can reduce the switching losses thus increasing the balancing system efficiency. Unfortunately, the resonant converters have a very complex control as well high converter cost.
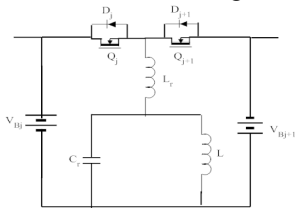


Fig. 16. Zero-current quasi-resonant converter balancing topologies.

## VI. BALANCING TOPOLOGIES SIMULATION RESULTS AND COMPARATIVE ANALYSIS.

MATLAB/Simulink becomes the most used software for modelling and simulation of the dynamic systems. First step for constructing the cell balancing system is simulate one cell battery model, Lithium polymer (Li-Po) batteries have been tested and their parameters estimated according to [35], after that a complete battery model "Extended partnership for a new generation of vehicles EPNGV" as in [36] 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 cells.

Different Battery balancing systems have been simulated using Simulink such as, fixed resistor, shunting switching resistor, switched capacitor, single switched capacitor, double-tiered switched capacitor, multi-inductor, single-windings transformer and buck-boost converter with a control system.

The simulation has been performed according to these conditions; 4 Li-Po cells having capacity of 12 Ah with initial SoC 80, 78, 76 and 74%. The following figurers illustrate various balancing topologies simulation results such as switching shunting resistor, single switching capacitor.
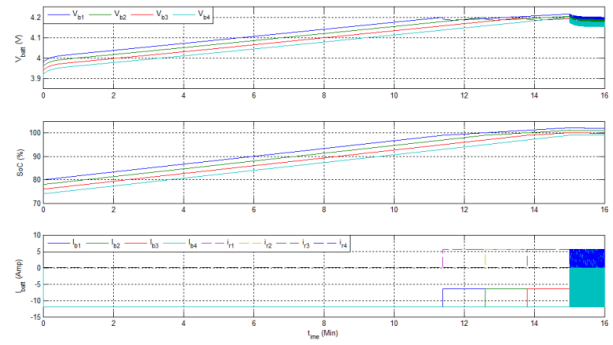


Fig. 17. Switching shunt resistor 4 cells balancing simulation a) the cells voltage, b) the cells SoC and c) the cells and the resistors currents.

Fig. 17. Shows switching shunt resistor balancing simulation for 4 cells, it illustrates the cells voltage, SoC as well as the cells current and the resistors currents. The previous figure clears that; the balancing occurred during charging, so that the battery nearly fully charged it will shunted by the coupled switch and waiting for the other cells to reach the fully charged state. In addition, the topology gives a fasting equalization time.
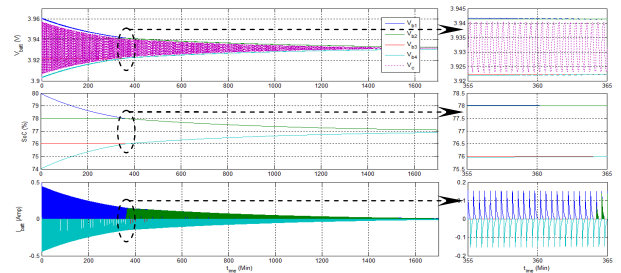


Fig. 18. Single switched capacitor simulation balancing a) the cells and capacitor voltage, b) the cells SoC and c) the cells currents.

Fig. 18 shows the simulation results for the single switching capacitor balancing for 4 cells. It illustrates the cells voltage, capacitor voltage, the cells SoC and currents. It's clear that for a 6% SoC difference between the higher and lower cells the system took very long time for complete balancing. In addition, after a period from balancing starts the voltage difference between the cells is decreasing so that the balancing current is decreasing too. As a result, the balancing time increases, by adding an intelligent control into the system the equalization speed could be improved.

A comparison between the balancing methods is planned in Table 1 and Table 2. Generally for low power application the switching shunt resistor is good with its low cost, small size and very simple control. For simple, active control selecting the switching capacitor is the right choice and it's good for HEV application but it takes long equalization time. In case of fast equalization time switched inductor and transformer is suitable but there is a need to a complex control system as well magnetic losses. Energy converter superior for medium and high power application (HEV and PHEV) with fully control in the balancing procedure unfortunately their high cost, complex control and large size.

Table 1.
Comparison of Different Cell Balancing Topologies.

| Fig. No. | Equalization speed | Control Complexity | Implementation | size | Cost | Charge discharge type | applications | Approx. Eff. | V & I stress | | Passive/Active elements for n cells and m module | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | V | I | R | L | C | SW | D | IC |
| 1-a | S | Very Simple | P | E | E | Fixed | Low Power | P | 0 | 0 | n | 0 | 0 | 0 | 0 | 0 |
| 1-b | G | Simple | G | E | E | Charge | Low Power | S | S | S | n | 0 | 0 | n | 0 | 0 |
| 2 | S | Medium | VG | G | G | Bidirectional | Medium/High | G | E | P | 0 | 0 | n-1 | 2n | 0 | 0 |
| 3 | S | Complex | VG | VG | VG | Bidirectional | Medium/High | VG | E | P | 1 | 0 | 1 | n+5 | 0 | 0 |
| 4 | G | Medium | VG | G | G | Bidirectional | Medium/High | G | E | P | 0 | 0 | n | 2n | 0 | 0 |
| 5 | S | Complex | G | G | G | Bidirectional | Medium/High | S | G | G | 0 | 0 | n-1 | 2n+2m | 0 | 0 |
| 6 | VG | Complex | E | G | G | Bidirectional | Medium/High | G | G | E | 0 | 1 | 0 | 2n | 2n-2 | 0 |
| 7 | VG | Complex | E | G | G | Bidirectional | Medium/High | G | G | E | 0 | n-1 | 0 | 2n-2 | 0 | 0 |
| 8 | G | Complex | G | G | S | Charge | Medium/High | S | G | E | 0 | 2 | 0 | n+6 | 1 | 1 |
| 9-a | G | Medium | G | S | S | Charge | Medium/High | S | P | E | 0 | n+1 | 0 | 2 | 0 | 1 |
| 9-b | G | Complex | VG | S | S | Charge | Medium/High | S | S | S | 0 | 2n | 0 | 1 | n | n |
| 10 | S | Complex | G | S | S | Bidirectional | Medium/High | S | G | G | 0 | 2n+2m | 0 | m | n | n+m |
| 11 | S | Complex | E | G | G | Bidirectional | Medium/High | G | E | VG | 0 | n+1 | n-1 | n+1 | 0 | 0 |
| 12 | G | Complex | G | G | G | Bidirectional | Medium/High | G | E | E | 0 | n | n | 2n | 0 | 0 |
| 13 | G | Complex | G | S | S | Bidirectional | Medium/High | S | E | VG | 0 | 2n | 0 | 2n | 0 | n |
| 14 | S | Complex | S | S | S | Bidirectional | Medium/High | S | E | VG | 0 | n/2 | n | n | n | 1 |
| 15 | VG | Complex | VG | S | S | Bidirectional | High | VG | E | E | 0 | 0 | m | 4m | 0 | 0 |
| 16 | S | Medium | S | S | S | Bidirectional | Medium/High | G | E | E | 0 | 2n-2 | n-1 | 2n-2 | 0 | 0 |

R: Resistor, L: Inductor, C: Capacitor, D: diode, SW: Switch, IC: Iron core.
E: Excellent, VG: Very good, G: Good, S: Satisfactory and P: Poor.

TABLE 2.
Advantage and Disadvantage of Cell Balancing Topologies.

| Scheme | Advantage | Disadvantage |
|---|---|---|
| 1. Fixed Resistor | • Cheap. Simple to implement with a small size. | • Not very effective. Inefficient for its high energy losses. |
| 2. Shunting Resistor | • Cheap, simple to implement and Fast equalization rate.<br>• Charging and discharging but not preferable for discharging.<br>• Suitable for HEV but for EV a 10mA/Ah resistor specified. | • Not very effective; Relatively high energy losses<br>• The requirement for large power dissipating resistors.<br>• Thermal management requirements. |
| 3. Switched Capacitor | • Simple control. Charging and discharging modes.<br>• Low voltage stress, no need for closed loop control. | • Low equalization rate.<br>• High switches number. |
| 4. Single Switched Capacitor | • Simple control. Charging and discharging modes.<br>• One capacitor with minimal switches. EV and HEV app. | • Satisfactory equalization speed.<br>• Intelligent control is necessary to fast the equalization. |
| 5. Double Tiered Switched Capacitor | • Reduce balancing time to quarter than the switched capacitor.<br>• Charging and discharging modes. EV and HEV applications. | • Satisfactory equalization speed.<br>• High switches number. |
| 6. Modularized Switched capacitor | • Low voltage and current stress.<br>• Charging and discharging modes | • Complex control is needed.<br>• Satisfactory equalization speed. |
| 7. single Inductor | • Fast equalization speed. | • Complex control is needed. Switches current stress.<br>• Filtering capacitors are needed for high switching frequency. |
| 8. Multi Inductor | • Fast equalization speed.<br>• Good efficiency | • Less complex control. Needs accurate voltage sensing.<br>• Charging mode only. Switches current stress.<br>• Filtering capacitors are needed for high switching current. |
| 9. Single Windings Transformer | • Fast equalization speed.<br>• Low magnetic losses. | • High complexity control. Expensive implementation.<br>• To add one or more cells the core must be change. |
| 10. Multi Windings Transformer | • Rapidly balancing. No closed-loop controls are required.<br>• Suitable for both EV and HEV applications | • High cost. Complexity control.<br>• The core will be changed if cell or more are added. |
| 11. Multiple Transformers | • Fast equalization speed. Can be modularized<br>• EV and HEV applications. New cells easily added. | • High cost. Complexity control.<br>• Satisfactory efficiency due to magnetic losses. |
| 12. Modularized Switching Transformer | • Fast equalization speed. Suitable for both EV and HEV.<br>• Low voltage and current stress. | • High cost.<br>• Complexity control. |
| 13. Cûk Converter | • Suitable for both EV and HEV applications.<br>• Efficient equalization system. | • Complexity control. Accurate voltage sensing needed.<br>• Satisfactory equalization speed. |
| 14. Buck-Boost Converter | • Good equalization speed.<br>• Easy for modular design. | • High cost<br>• Intelligent control needed. |
| 15. Flyback Converter | • Easy implemented for large number of cells.<br>• EV and HEV application. Suitable modularized system. | • Voltage sensing needed.<br>• Satisfactory equalization speed. |
| 16. Ramp Converter | • Soft switching along with a relatively simple transformer. | • Complex control. Satisfactory equalization speed. |
| 17. Full-Bridge Converter | • Fast equalization speed.<br>• Ideal for transportation applications | • High cost<br>• Intelligent control needed. |
| 18. Quasi-Resonant Converter | • Low switches current stress that increases its efficiency.<br>• Simple implementation. | • High cost<br>• Complex and intelligent implementation needed. |

# VII. CONCLUSION

Battery system application in electric vehicle is a very important issue, the cell balancing as an important part in the BMS the cells so as to increase the life, the safety of the battery system as well Benefit from the whole battery pack energy. Several battery balancing topologies have been reviewed, simulated using MATLAB/Simulink which is the most used software for modelling and simulation of dynamic systems and detailed comparison have been presented. The cell balancing topologies differ in their cost, size, control complexity, implementation and suit application. Each topology has its own advantage and disadvantage as planned.

## REFERENCE

[1] Jian Cao, Nigel Schofield and Ali Emadi, "Battery balancing methods: A comprehensive review," IEEE Vehicle Power and Propulsion Conference, VPPC 08. pp. 1-6, 2008.

[2] K. Zhi-Guo, Z. Chun-Bo, L. Ren-Gui and C. Shu-Kang, "Comparison and Evaluation of Charge Equalization Technique for Series Connected Batteries," 37th IEEE Power Electronics Specialists Conference, pp. 1-6, 2006.

[3] S. Moore and P. Schneider, "A Review of Cell Equalization Methods for Lithium Ion and Lithium Polymer Battery Systems," in Proceedings of the SAE 2001 World Congress, 2001.

[4] M. J. Isaacson, R. P. Hollandsworth, P. J. Giampaoli, F. A. Linkowsky, A. Salim and V. L. Teofilo, "Advanced lithium ion battery charger," 15th Annual Battery Conference on Applications and Advances, pp. 193-198, Jan. 2000.

[5] N. H. Kutkut, and D. M. Divan, "Dynamic Equalization Techniques for Series Battery Stacks," IEEE Telecommunications Energy Conference, INTELEC '96, pp. 514-521, 1996.

[6] B. Lindemark, "Individual Cell voltage Equalizers (ICE) For Reliable Battery Performance," IEEE 13th International Telecommunications Energy Conference, INTELEC '91, pp. 196-201, 1991.

[7] A. Thomas. Stuart, and Wei Zhu, "Fast Equalization for Large Lithium Ion Batteries," IEEE Aerospace and Electronic Systems Magazine, Vol. 24, pp. 27-31, 2009.

[8] Xiujuan Zhang, Peide Liu, and Darui Wang, "The Design and Implementation of Smart Battery Management System Balance Technology," Journal of Convergence Information Technology, Vol. 6, No. 5, pp. 108-116, May 2011

[9] Dorin V. Cadar, Dorin M. Petreus and Toma M. Patarau, "An Energy Converter Method for Battery Cell Balancing," IEEE 33rd International Spring Seminar on Electronics Technology (ISSE), pp. 290-293, 2010.

[10] S. West, and P.T. Krein, "Switched-Capacitor Systems For Battery Equalization," IEEE Modern Techniques and Technology (MTT 2000). Proceedings of the VI International Scientific and Practical Conference of Students, Post-graduates and Young Scientists, pp. 57–59, 2000.

[11] C. Pascual, and P.T. Krein, "Switched Capacitor System for Automatic Series Battery Equalization," IEEE Applied Power Electronics Conference and Exposition, APEC '97 Conference Proceedings, 12th Vol. 2, pp. 848-854, 1997.

[12] Carmelo Speltino, Anna Stefanopoulou and Giovanni Fiengo, "Cell Equalization in Battery Stacks Through State Of Charge Estimation Polling," American Control Conference (ACC), pp. 5050-5055, 2010

[13] A.C. Baughman, and M. Ferdowsi "Double-Tiered Switched-Capacitor Battery Charge Equalization Technique," IEEE Transactions on Industrial Electronics, Vol. 55. pp. 2277-2285, 2008.

[14] A. Baughman, and M. Ferdowsi, "Double-Tiered Capacitive Shuttling Method for Balancing Series-Connected Batteries," IEEE Conference on Vehicle Power and Propulsion, pp. 109-113, 2005.

[15] P. Hong-Sun, K. Chol-Ho, P. Ki-Bum, M. Gun-Woo and L. Joong-Hui, "Design of a Charge Equalization Based on Battery Modularization," IEEE Trans. on Vehicular Technology, Vol. 58, pp. 3938-3946, 2009.

[16] T. H. Phung, J. C. Crebier, A. Chureau, A. Collet And N. T. Van Nguyen, "Optimized Structure for Next-to-Next Balancing of Series-Connected Lithium-ion Cells," 26th Annual IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1374-1381, 2011.

[17] P. Sang-Hyun, K. Tae-Sung, P. Jin-Sik, M. Gun-Woo, and Y. Myung-Joong, "A New Battery Equalizer Based on Buck-boost Topology" IEEE 7th International Conf. on Power Electronics, pp. 962-965, 2007

[18] C.S. Moo, Y.C. Hsieh, I.S. Tsai, and J.C. Cheng, "Dynamic Charge Equalisation for Series-Connected Batteries," IEEE Proceedings Electric Power Applications, Vol. 150, No. 5, pp. 501-505, 2003.

[19] Abusaleh M. Imtiaz, Faisal H. Khan and Haresh Kamath, "A Low-Cost Time Shared Cell Balancing Technique for Future Lithium-Ion Battery Storage System Featuring Regenerative Energy Distribution," IEEE 26th Annual Applied Power Electronics Conference and Exposition (APEC), pp. 792-799, 2011.

[20] Jong-Won Shin, Gab-Su Seo, Chang-Yoon Chun, and Bo-Hyung Cho, "Selective Flyback Balancing Circuit with Improved Balancing Speed for Series Connected Lithium-ion Batteries," the 2010 International Power Electronics Conference (IPEC), pp. 1180-1184, August 2010.

[21] Markus Einhorn, Werner Roessler and Juergen Fleig, "Improved Performance of Serially Connected Li-ion Batteries With Active Cell Balancing in Electric Vehicles," IEEE Transactions on Vehicular Technologies, Vol. xx, No. 99, pp. 1-10, May 2011

[22] Kyung-Hwa Parky, Chol-Ho Kim, Hee-Keun Cho, and Joung-Ki Seo, "Design Considerations of a Lithium Ion Battery Management System (BMS) for the STSAT-3 Satellite," Journal of Power Electronics, Vol. 10, No. 2, pp. 210-217, March 2010.

[23] Hong-Sun Park, Chong-Eun Kim, Chol-Ho Kim, Gun-Woo Moon and Joong-Hui Lee, "A Modularized Charge Equalizer for an HEV Lithium-Ion Battery String," IEEE Transactions on Industrial Electronics, Vol. 56, No. 5. pp. 1464-1476, 2009.

[24] Jingyu Yan, Zhu Cheng, Guoqing Xu, Huihuan Qian and Yangsheng Xu "Fuzzy Control for Battery Equalization Based on State of Charge" IEEE 72nd Vehicular Technology Conference Fall, pp. 1-7, 2010.

[25] L Yuang-Shung, D. Chun-Yi, C. Guo-Tian, and Y. Shen-Ching, "Battery Equalization Using Bi-directional Cûk Converters in DCVM Operation," IEEE, 36th Power Electronics Specialists Conference, PESC '05, pp. 765–771, 2005.

[26] Wei Hong, Kong-Soon Ng, Jin-Hsin Hu and Chin-Sien Moo, "Charge Equalization of Battery Power Modules in Series," The 2010 International Power Electronics Conference, pp. 1568-1572, 2010.

[27] Chin-Sien Moo, Kong Soon Ng and Yao-Ching Hsieh, "Parallel Operation of Battery Power Modules," IEEE Transactions on Energy Conversion, Vol. 23, No. 2, pp. 701-707, June 2008.

[28] Chol-Ho Kim, Hong-Sun Park, Chong-Eun Kim, Gun-Woo Moon, and Joong-Hui Lee, "Individual Charge Equalization Converter with Parallel Primary Winding of Transformer for Series Connected Lithium-Ion Battery Strings in an HEV," Journal of Power Electronics, Vol. 9, No. 3, pp. 472-480, May 2009.

[29] S.Chakraborty, A.K. Jain, and N. Mohan, "novel converter topology and algorithm forsimultaneouscharging and individual cell balancing of multiple Li-ion batteries," 26th Annual International Telecommunications Energy Conference, pp. 248-253, 2004.

[30] L. Yuang-Shung, T. Cheng-En, K. Yi-Pin and C. Ming-Wang, "Charge Equalization Using Quasi-Resonant Converters in Battery String for Medical Power Operated Vehicle Application," The International Power Electronics Conference (IPEC), pp. 2722-2728, 2010.

[31] Yuang-Shung Lee, Guo-Tian Cheng, "Quasi-Resonant Zero-Current-Switching Bidirectional Converter for Battery Equalization Applications," IEEE Transactions on Power Electronics, Vol. 21, No. 5, pp, 1213-1224, 2006.

[32] L. Maharjan, S. Inoue, H. Akagi, and J. Asakura, "State-of-Charge (SOC)-Balancing Control of a Battery Energy Storage System Based on a Cascade PWM Converter," IEEE Transactions on Power Electronics, Vol. 24, pp. 1628-1636, 2009.

[33] T. Gotwald, Z. Ye and T. Stuart, "Equalization of EV and HEV batteries with a ramp converter," IEEE Transactions on Aerospace and Electronic Systems, vol. 33, no. 1, pp. 307-312, Jan. 1997.

[34] W. F. Bentley, "Cell balancing considerations for lithium-ion battery systems," 12th Annual Battery Conference on Applications and Advances, pp. 223-226, 1997.

[35] Mohamed Daowd, Noshin Omar, Bavo Verbrugge, Peter Van Den Bossche, and Joeri Van Mierlo, "Battery Models Parameter Estimation based on MATLAB/Simulink®," EVS-25 Shenzhen, China, Nov. 2010.

[36] Mohamed Daowd, Noshin Omar, Peter Van Den Bossche, and Joeri Van Mierlo, "An Extended PNGV Battery Model for Electric and Hybrid Vehicles," Journal of International Review of Electrical Engineering (IREE), in press 2011.