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A Review of Battery Cell Equalization Techniques for Use in Real World Applications

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Abstract: The usable energy available from a lithium-based battery energy storage system is affected by factors both internal and external. One of the most influential and potentially dangerous factors is cell charge deviation. This issue is directly addressable with the use of a battery management system and even more through the use of a cell equalization subsystem. There is a wide variety of cell equalization methods that can be used in low, medium, or high-power applications ranging from residential energy backup systems to electric vehicles and industrial load-shifting grid-tied systems. This paper presents a variety of cell equalization methods and compares each of the distinct cell equalization topologies by evaluating different criteria such as equalization rate, power capabilities, complexity and cost. The result of this comparative study is summarized in a set of comprehensive tables that can serve as a guideline to engineers in selecting the best solution for an application. The use of these comparative tables is also illustrated by looking at different real-world case studies.
Keywords: Electric vehicle (EVs); green power; intelligent transportation; battery management; automobile motors

I. INTRODUCTION

The battery management system (BMS) is a crucial element within any Lithium based energy storage system. These energy storage systems include the battery systems found in electric vehicles (EV), grid-tied energy storage systems, and even high-performance power tools. The main objectives of the BMS are battery protection, keeping the battery in an accurate and reliable state as well as predicting and extending battery life [1]. The BMS achieves these objectives by continuously performing various battery-specific functions. These functions may include that of measurement voltages, temperatures and currents throughout the battery system, the state of charge (SoC) and state of health (SoH) of the cells and the system, thermal management, charge/discharge control, communication with external systems, data acquisition and battery cell equalization [2].

Over time series-connected battery cells will differ in terms of SoC, this imbalance of cells is a vital issue for the life and capacity of a Lithium battery system. The usable capacity of a battery is determined by the lowest and highest charged cells when the battery is in discharging mode and in charging mode respectively. This is due to the under-voltage and over-voltage limits of the Lithium battery cell. The imbalance between cells is caused by internal and/or external factors. Internally cells vary due to minor manufacturing inconsistencies such as internal impedance, charge storage volume, and self-discharge rates. The external factors are mainly due to thermal differences throughout the battery system and external circuitry (protection units) connected to each cell[3].

Battery cell imbalance is corrected through the use of a battery cell equalization/balancing unit that forms part of the BMS. Numerous cell equalization methods have been researched and proposed. These methods are categorized as either passive or active equalization as can be seen in Fig. 1 [4]–[7].

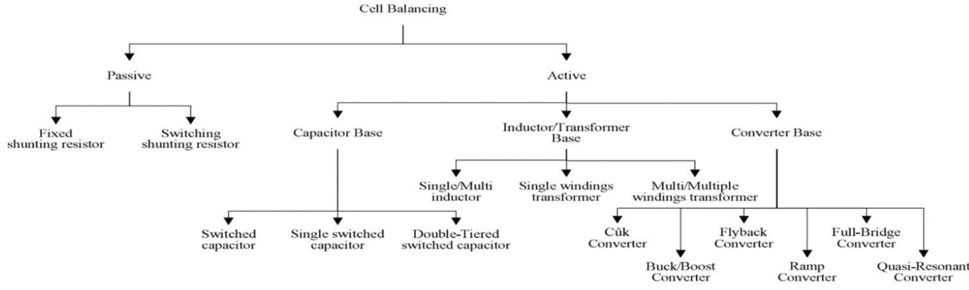

Fig. 1. Cell equalization categorization

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Passive cell equalization methods make use of passive resistors in parallel with the battery cells to remove excess energy from higher-charged cells through heat dissipation. These passive resistors are either fixed in the circuit or can be switched in and out of the circuit[8]–[10]. Active cell equalization methods operate by transferring excess energy from higher-charged cell(s) to lower-charged cell(s). The active cell equalization method can be further divided into three subcategories according to the elements used such as capacitors, inductive storage elements, or converters (controlled switches) [10], [11].

This paper will discuss several cell equalization topologies from both the passive and active cell equalization categories. Firstly, each of the cell equalization topologies will be discussed individually. The focus being respective circuit configurations, basic components required, advantages and disadvantages as well as a brief look at the control strategy for each of the topologies. Previous papers only discussed and compared cell equalization methods at a low level. This paper aims to generate usable information tables that will serve as a guide to engineers to select the most appropriate topologies for an application, thus reducing time spent during the research phase. In this paper, a scaled number-based comprehensive comparison is presented featuring all the cell equalization topologies with regard to equalization rate, equalization efficiency, control complexity, size, cost, application, and circuit design. The addition of case studies will illustrate to the reader how these tables can be used in selecting the best-suited cell equalization topology through the implementation of a simple Pugh method (decision matrix).

II. CELL EQUALIZATION TOPOLOGIES

This section will look at cell equalization methods and the different topologies of each of these methods. The basic operation of each of these topologies will be discussed along with the advantages and disadvantages of each topology.

A. Resistor Based

The resistor-based cell equalization method is the only equalization method classified under the passive cell equalization branch as can be seen in Fig. 1 [8], [10]–[12]. Resistor-based cell equalization methods are the most commonly used topology in a wide variety of Li-Ion battery applications including power tools, electric vehicles, and backup energy storage systems. This is due to the exceptional reliability, simplicity, and ease of integration with new or existing energy storage systems [11]. The resistor-based cell equalization method has two distinct sub-structures namely fixed shunt resistor (FSR) and switched shunt resistor (SSR).

The fixed shunt resistor topology has fixed resistors permanently connected in parallel with each series-connected cell. This topology was designed for lead-acid and nickel-cadmium batteries and is not suitable for Li-Ion batteries. Thus, this topology will not be considered for this paper.

Switched Shunt Resistor (SSR)

The SSR equalization method utilizes a resistor, which can be switched in and out of the circuit to get rid of excess energy through heat dissipation for equalization of the series-connected cells, as shown in Fig. 2 [10]–[12]. The most commonly used design practice is to choose a resistor size so that the dissipating current is equal to or lower than 10mA/h, this is an equalization rate of 1% per hour.

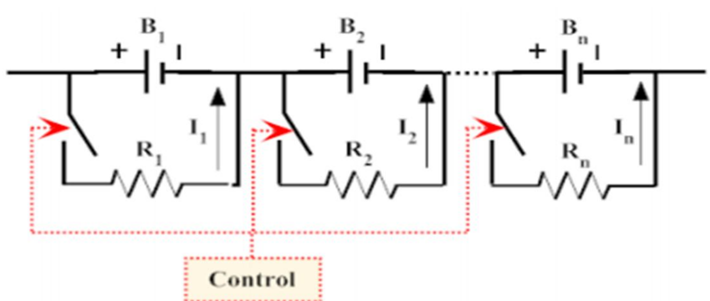

Fig. 2. Switched Shunt Resistor Topology

The SSR topology can be coupled with two control strategies, continuous or detect operation. The continuous control strategy involves all the switches being controlled by a single control signal, i.e. all switches are turned on and off simultaneously. As each of the cells have a different voltage level, the power is dissipated through the shunt resistor will be higher for the higher-charged cells. This will result in less charging current flowing to the higher-charged cells. The detect control strategy requires additional components as this strategy relies on the measurements of each cell voltage. The measured voltages are used to identify the cells with higher voltages. The shunt resistors for these higher-charged cells are connected in parallel to the cells through individual switches.

This will allow the lower-charged cells to receive more charge current, thus speeding up the equalization process. The activation time is determined by the voltage difference between the higher and lowest cell voltages.

The control strategy for the detection topology is more complex and more expensive than that of the continuous topology, but it has a quicker equalization rate and is also more efficient.

It is recommended that the SSR topology is used when the battery is in charging mode. This will dissipate incoming energy to the higher charged cells, which will result in a slower charge rate for these respective cells instead of wasting the stored energy within the cells.

B. Capacitor Based

The capacitor-based cell equalization method makes use of external capacitors as an additional storage element to shuffle excess energy between all the series-connected cells in the battery pack. This is a considerable increase in efficiency over the resistor-based topologies as excess energy is not wasted in the form of heat. The capacitor-based cell equalization method has the highest energy efficiency of all the cell equalization methods, close to 99% [4]–[7], [9], [13]. The capacitor-based cell equalization method or "charge shuffling" method can be separated into four topologies or district variants. These topologies are; the switched capacitors (SC), single switched capacitor (SSC), double-tiered switched capacitor (DTSC), and common node switched capacitors (CNSC). Due to the nature of the capacitor, these types of topologies operate in three stages, capacitor charging, capacitor discharging, and dead time. The dead time occurs between each transition from charging and discharging of the capacitors. All of the above-mentioned topologies can operate when the battery is in standby, charging or discharging modes. This does not necessarily mean an increase in equalization rate over the resistor-based topologies, however, unbalanced cells can be addressed more often during operation although the method requires a larger and more complex configuration.

1) Switched Capacitor (SC)

The SC cell equalization topology is capable of working with little to no additional intelligence [14]–[20]. The configuration shown in Fig. **3**, shows that for *n* number of cells, *n-1* external capacitors are required with *2n* switches. The equalization rate for this topology is the lowest of all (up to 5 times lower than resistor-based topologies), especially in the event where the cells with the highest and lowest charge are on opposite ends of the battery pack as seen in Fig. **3**.

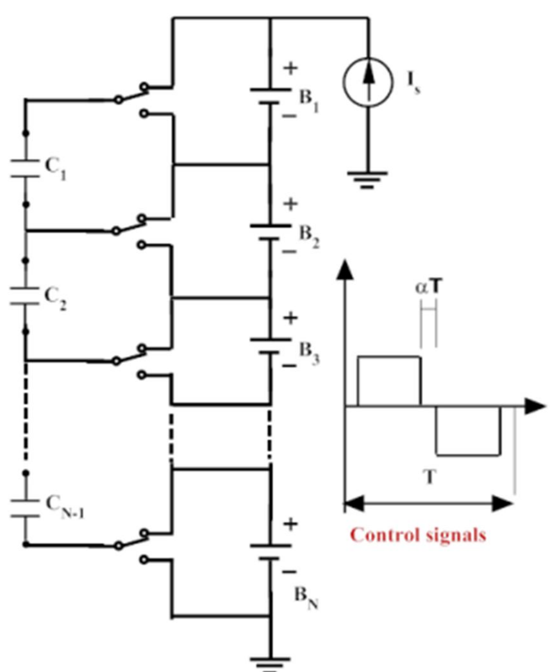

Fig. 3. Switched Capacitor Topology

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All the capacitors are activated and deactivated (charge/discharge) simultaneously, as a result during the active state the capacitors will charge to match the voltage of the respective parallel cells. This means that each of the higher-charged cells will transfer more energy to its respective parallel capacitors than the lower-charge cells. This is followed by the capacitors then transferring the stored energy to the neighbouring (possibly lower-charged) battery.

2) Double Tiered Switched Capacitor (DTSC)

The DTSC topology is an evolution of the basic SC topology, with an additional capacitor added to a second tier [21], [22]. The basic operation of this topology is similar to that of the switched capacitor topology, with all first-tier capacitors switched in and out of the main circuit simultaneously. The second-tier capacitor functions as a bridge between non-adjacent battery cells, allowing energy to be transferred via the bridge, thus significantly reducing the equalization time.

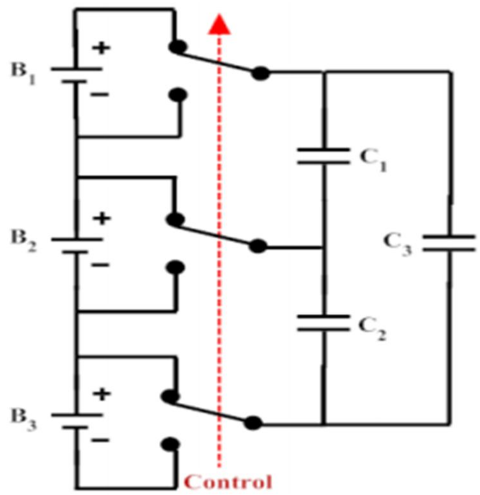

Fig. 4. Double Tiered Switched-Capacitor Topology

The addition of the second-tier capacitor allows an additional charge shuffling path, which in turn can increase the total equalization rate by up to a factor of 4.

3) Common Node Switched Capacitor (CNSC)

The CNSC topology is a deviation of the SC and double-tiered switched capacitor topologies [13]. As shown in Fig. 5, *2n* switches are required with *n* capacitors with all secondary terminals of these switches connected to a common node.

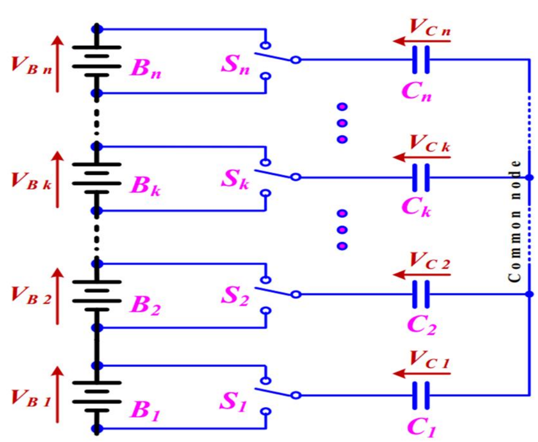

Fig. 5. Common Node Switched-Capacitor Topology

This topology makes use of a simple control strategy that measures the charge of each of the series-connected cells. All high-side switches are switched simultaneously to transfer energy from the cell to its corresponding capacitor, however, if two adjacent cells have equal charge the respective switches are not activated. This ensures that energy is only transferred between unbalanced cells which increases the equalization rate and efficiency.

Single Switched Capacitor (SSC)

The SSC topology is a targeted cell equalization topology [23]–[27]. Fig. 6 shows the hardware layout of the SSC topology, which requires a single capacitor and *n+5* switches for *n* cells.

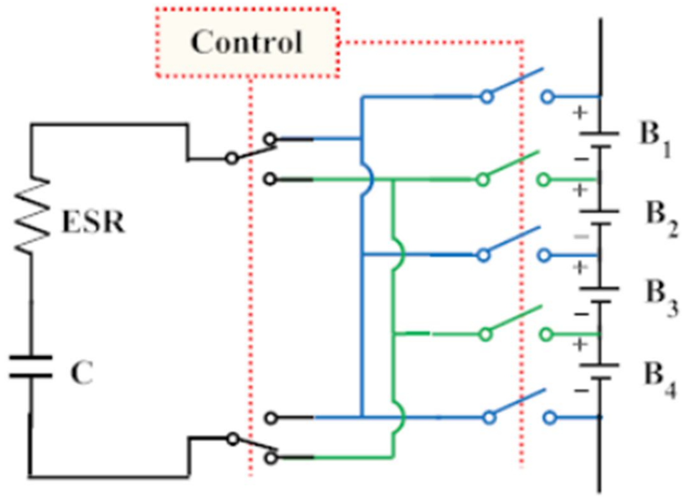

Fig. 6. Single Switched-Capacitor Topology

This topology requires a non-complex control strategy that identifies the highest and lowest charged cells. The corresponding switches are then activated and deactivated in turns starting with the higher-charged cell followed by the lower-charged cell. Thus, energy is transferred directly between any two cells. In the event all cells are equally charged, no charge shuffling will take place, thus increasing efficiency.

C. Inductive Base

The inductive base cell equalization methods can be subdivided based on the main equalization element being either an inductor or transformer.

The inductor-based cell equalization method is very similar to the capacitor-based cell equalization method but utilizes inductors as external energy reservoirs rather than separate energy storage elements. The high-side and low-side switches are controlled using pulse width modulation (PWM) signals. The high-side and low-side switches can be active at the same time, with the high-side PWM signal leading to the low-side PWM signal. The advantage of the inductor-based equalization method is a higher equalization current and equalization rate when compared to the previously mentioned resistor-based and capacitor-based methodologies. The disadvantage when compared to the other topologies is the relatively higher capital cost. Similar to the capacitor-based topologies, the inductor-based cell equalization can be divided into the single-switched inductor (SSI) and multi-switched inductor (MSI) topologies respectively.

1) Multi Switched Inductor (SSI)

The MSI topology utilizes a common inductor for each set of neighbouring cells. Each set of neighbouring cells is also accompanied by a set of switches which is oppositely controlled with a PWM pulse width modulated) signal. During the first half of the PWM signal (<50% duty cycle), this first switch will close. This causes current to flow, charging the inductor (storing energy), The charge rate is determined by the SoC of each respective cell, higher charge cells will result in higher current flow to the inductor. During the second half of the PWM signal, the first switch will open and the alternative switch will close, discharging the inductor thus transferring the

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energy to the adjacent cells[28]–[38]. With the addition of a low-level control strategy, energy transfer can be seized once charge equalization is reached.

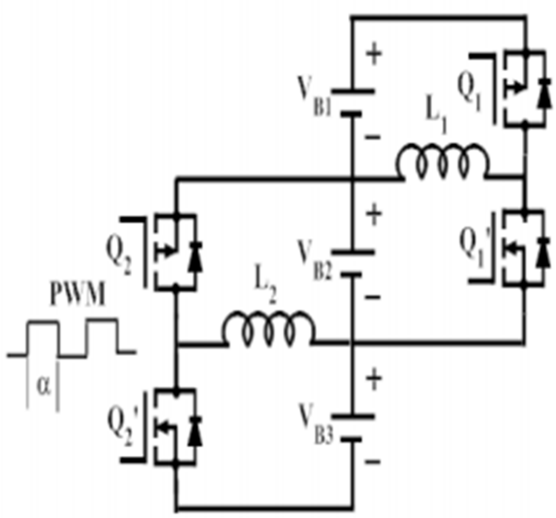

Fig. 7. Multi Switched Inductor Topology

The basic components required are *n-1* inductors and *2n-2* switches, as shown in Fig. **7**. The size of the inductor as well as the equalization rate is dependent on the switching frequency.

2) Single Switched Inductor (SSI)

The SSI topology is represented in Fig. **8** [28]–[38]. This configuration requires one inductor with *2n* switches and diodes.

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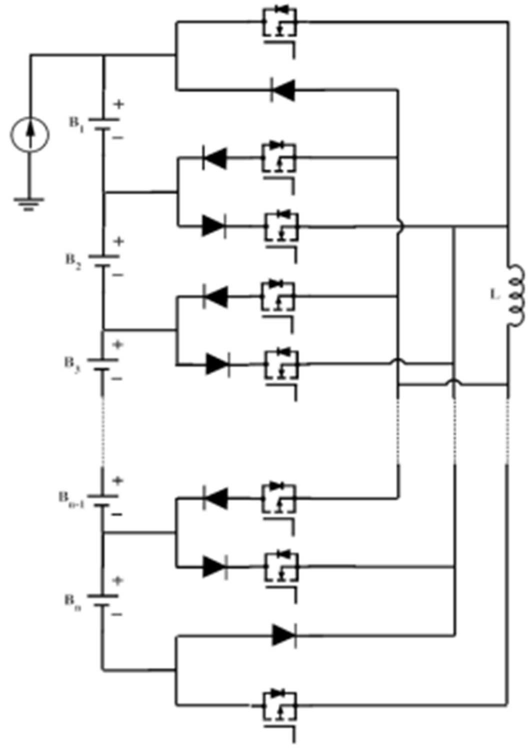

Fig. 8. Single Switched Inductor Topology

This topology is also a targeted cell equalization topology, which means that individual cells are identified for the transfer of energy. The accompanying control strategy may have a great impact on the equalization rate. The control strategy can identify the single highest and lowest charged cells for energy transfer or transfer energy between multiple higher and lower charged cells simultaneously.

The transformer-based cell equalization method is a unique approach when it comes to energy transfer. The balancing topologies, which are single winding transformers (SWT) and multi winding transformers (MWT) respectively, have selectable energy transfer techniques. The different energy transfer techniques are “cell-to-pack” and “pack-to-cell”. The “pack” can also be substituted with an auxiliary battery which in turn eliminates the need for a dc-dc converter in some applications.

3) Single Winding Transformer (SWT)

The SWT topology configuration can be seen in Fig. **9** and is made up of *n+4* switches and *2* windings (primary and secondary), the winding ratio is determined by the ratio of the pack voltage to the cell voltage [39]–[46].

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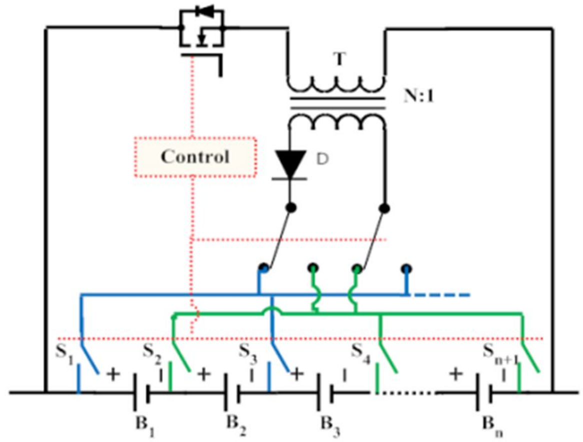

Fig. 9. Single Winding Transformer Topology

This topology implements a one-to-many or many-to-one strategy depending on the energy transfer technique. For "cell-to-pack" the highest cell is discharged and the energy is redistributed equally throughout all the cells in the battery pack. For the "pack-to-cell" energy transfer technique the entire pack is discharged and the energy is transferred to the lowest charged cell.

Multi Winding Transformer (MWT)

The MWT topology consists of up to *n* switches and *n+1* windings (*1* primary and *n* secondary) [39]–[46]. This topology, which can be seen in Fig. **10**, can better be described as a "fly-forward" and "fly-back" converters instead of "cell-to-pack" and "pack-to-cell" respectively.

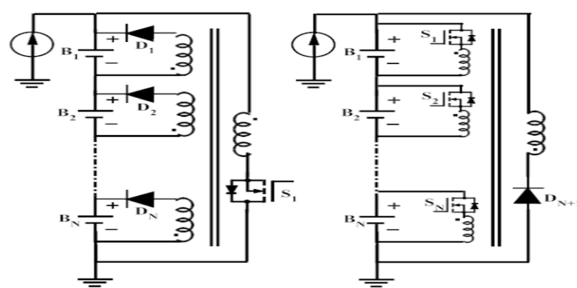

Fig. 10. Multi Winding Transformer Topology

The "fly-forward" structure discharges all cells, with the higher-charged cells transferring energy at a relatively higher current rate. This excess energy is then redistributed across the battery pack. The "fly-back" structure works in reverse fashion with the battery pack being discharged and the energy distributed across each series cell. The lower charged cells will sink energy at a higher current rate.

D. Converter Based

In recent times the idea to use basic electronic converters as a means to equalize the energy between the series-connected cells of a battery pack has been revisited. These electronic energy converters include; Ćuk converters, Buck/Boost converters, Ramp converters, Quasi-Resonant converters, and Bridge converters. Each of these converters requires complex control strategies, which in turn makes these converters very bulky and very expensive. Most of these converter-based cell equalization topologies are therefore better suited for high-power applications where energy is transferred between high-current cells or between series-connected battery modules.

1) Ćuk Converter

The Ćuk converter is a bi-directional energy converter capable of equalizing the charge between two neighbouring cells [47]–[50]. Each circuit is only capable of transferring energy between two cells, thus *n-1* circuits are required. This equalization technique also utilizes the alternating switch strategy, while utilizing the body diodes to discharge the external energy storage elements to the lower-charged cell.

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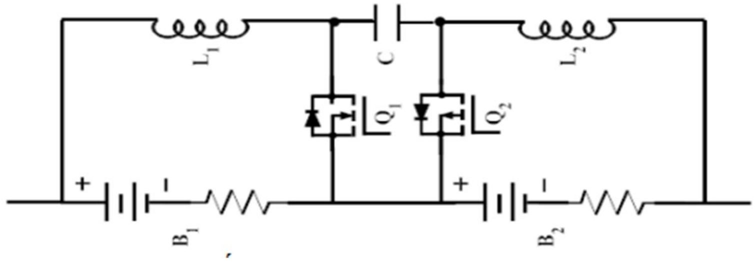

Fig. 11. Ćuk Converter Topology

Fig. **11**, shows each Ćuk converter circuit consists of *2* inductors, *1* capacitor, and *2* switches. Due to the energy only being transferred between neighbouring cells the equalization rate is very low.

2) Buck-Boost Converter

The buck/boost energy converters are some of the most widely used energy converters in power electronics [51]–[60]. There are a variety of cell equalization topologies available such as the buck dc converter, shown in Fig. **12**, which operates in a "pack-to-cell" or "source-to-cell" manner to increase the charge of the lower charged cells.

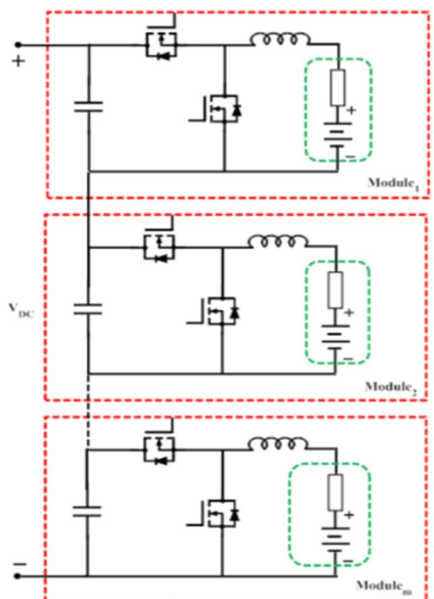

Fig. 12. Buck Converter Topology

Another topology is the buck-boost converter, which transfers energy from higher-charged cells to lower-charged cells via an auxiliary battery or external energy storage device (Figure 13). Both these topologies discharge each of the respective cells, either to a designated external energy storage component or via a single buck-boost dc/dc converter to an auxiliary battery. The second half of the equalization cycle charges each of the adjacent cells by discharging the external energy storage components or by discharging the auxiliary battery. The lower-charged cell will sink more energy that higher-charged cells.

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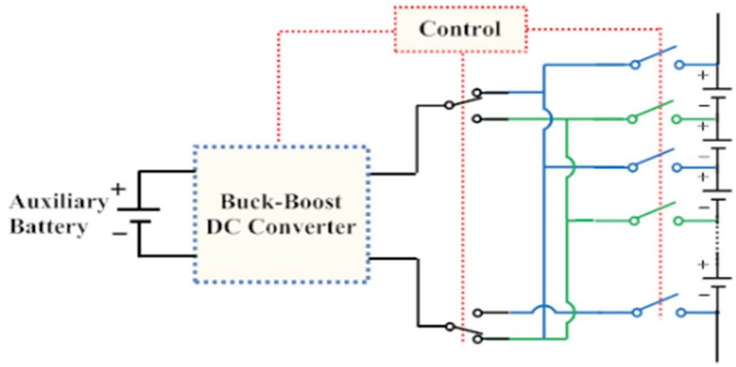

Fig. 13. Buck-Boost Converter Topology

All of these topologies require voltage-sensing components together with an intelligent controller. These topologies have high energy efficiency, typically greater than 92%, very fast equalization rates, and are best suited for cell equalization in modular designs.

3) Ramp Converter

The ramp converter equalization topology is a deviation of the MWT topology, with the key difference being that a single winding is required per pair of neighbouring cells rather than per individual cell, see Fig. **14**.

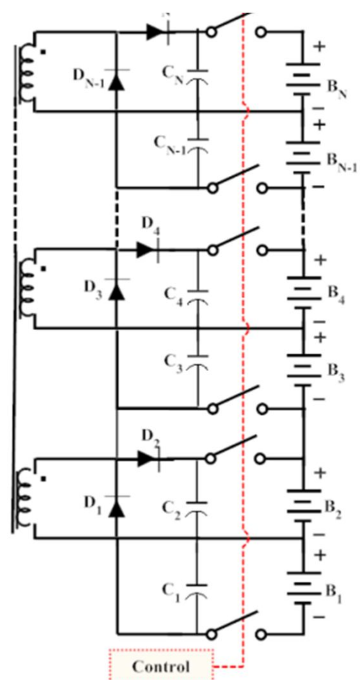

Fig. 14. Ramp Converter Topology

The operation of this topology takes place in two stages. The first half of the cycle transfers energy from the pack to the odd-numbered cell with the lowest charge, while the second half of the cycle shifts the energy to the even-numbered cells [61]–[63].

4) Quasi-Resonant Converter

The zero-current or zero-voltage quasi-current converters utilize resonance circuits as a means to drive the switches instead of the traditional PWM signals [64]–[68]. The same resonance circuits are also used to transfer energy via an inductor and capacitor resonant tank.

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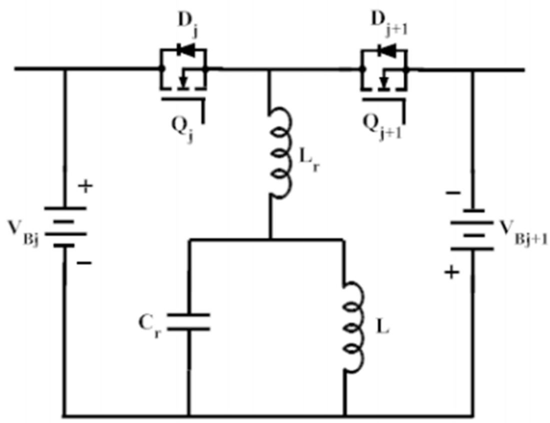

Fig. 15. Quasi-Resonant Converter Topology

This cell equalization topology is capable of symmetrical and bi-directional zero-current switching. This means minimal switching losses for increased efficiency, however, when compared to the capacitor-based and inductive-based cell equalization methods the design complexity and costs of this topology are very high.

5) Full-bridge Converter

The final converted topology is the fully controllable full-bridge energy converter [69]–[73]. This converter topology is capable of operation in dc or ac mode. This topology is best suited for use in modular battery design due to its high power and current rating.

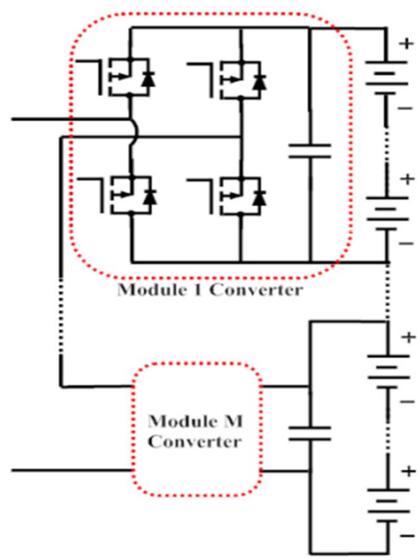

Fig. 16. Full-bridge Converter Topology

The control strategy for this topology is dependent on the functionality and whether it is being used together with ac or dc secondary circuit. This will only add to the already complex design and control strategies and this equalization topology is also relatively more expensive than the capacitor and inductive-based methods.

III. RESULTS AND DISCUSSION

To do a comprehensive comparison of all the cell equalization topologies discussed in the previous section, Table 1 is a summary of the advantages and disadvantages of each of the cell equalization topologies and Table 2 introduces a score-based comparison of each of the topologies. In general, for low to medium-powered battery systems the switched resistor topology (passive equalization) is preferred due to the low cost, small size, and simplicity even though the equalization of cells through heat generation decreases the charging efficiency of the battery system. This topology is often preferred in normal electric vehicles for the same reasons. The capacitor-based equalization topologies are the best fit for low or medium-power applications where high energy efficiency is a top priority. In the case where faster equalization is a key factor the inductor-based topologies or the transformer-based topologies will be the top choice. For the higher-powered applications, the energy converter topologies are superior with the added benefit of full controllability. This is also true for modular energy storage systems, with size, cost, and complexity being the biggest drawbacks.

Table 2 refers to all the cell equalization techniques and additionally states the complexity of the control system required, the preferred modes of operation as well as the preferred power application. The control strategy has three levels, **simple** (can be implemented by hobbyists), **medium** (requires extensive electronic knowledge) and **complex** (requires validated engineering design). Low-power applications refer to battery capacity and are considered to be less than 15kWh, medium power ranges from 15kWh to 150kWh (below 1000V) and high-power applications alongside typical EV batteries are any batteries with a capacity greater than 150kWh. Operational modes refer to the battery system being in charging mode, discharging mode, or all modes which include standby mode where energy is flowing in or out of the battery. The equalization speed of the various topologies was measured relative to the approximate equalization rate which is measured in minutes per watt-hour. The efficiency of each of the equalization topologies was ranked according to estimated energy loss during the complete equalization cycle. The reaming criteria were structured in comparison to the preceding equalization topologies, thus the first equalization topology was placed in the center of a hierarchical comparison table. The second equalization topology was compared criteria-wise based on information obtained from academic references as shown in the previous section. Based on this the equalization method was ranked higher or lower per criteria. After this was repeated for all the equalization topologies, scores were assigned based on each equalization topology's rank and relevance to all other topologies.

Table 1. Cell Equalization Topologies Advantages and Disadvantages

Topology	Advantages	Disadvantages
SSR	Inexpensive, simple to implement, and fast equalization rate. See Table 2 Charging and discharging but not preferable for discharging. Suitable for HEV	Not very efficient; high energy losses The requirement for large power-dissipating resistors increases mass and size. Thermal management requirements.
SC	Simple control. Charging and discharging modes. Low voltage stress, no need for closed-loop control.	Low equalization rate. The high number of switches increases size and mass.
DTSC	The balancing rate is four-time higher than the SC. Charging and discharging modes.	Satisfactory equalization rate. See table 2. High switches number.
CNSC	Charging and discharging modes. EV and HEV applications.	Satisfactory equalization speed. High switches number.
SSC	Simple control. Charging and discharging modes. One capacitor with minimal switches.	Satisfactory equalization speed. Intelligent control is necessary for fast equalization.
SSI	Fast equalization speed.	Complex control is needed. Switches current stress. Filtering capacitors are needed for high switching frequency.
MSI	Fast equalization speed. Good efficiency	Less complex control. Filtering capacitors are needed for high switching currents.
SWT	Fast equalization speed. Low magnetic losses.	High complexity control. Expensive implementation. To add one or more cells the core must be changed.
MWT	Fast equalization speed. Can be modularized. EV and HEV applications. New cells are easily added.	High cost. Complexity control. Satisfactory efficiency due to magnetic losses.
CUK	Suitable for both EV and HEV applications. Efficient equalization system.	Complexity control. Accurate voltage sensing is needed. Satisfactory equalization speed.
Buck	Good equalization speed. Easy for modular design.	High cost Intelligent control is needed.
Buck-Boost	Good equalization speed. Easy for modular design.	High cost Intelligent control is needed.
Ramp	Soft switching along with a relatively simple transformer.	Complex control. Satisfactory equalization speed.
Quasi	Low switches current stress increases their efficiency. Simple implementation.	High cost Complex and intelligent implementation is needed.
Full-bridge	Fast equalization speed. Ideal for transportation applications	High cost Intelligent control is needed.

Table 2. Cell Equalization Topology Comparison

Name	Speed	Ef f	Control	Size	Cos t	Operate	Power App	Im p	Stres s	Components n cells, m modules

		min/Wh								V	I	R	L	C	SW	D	IC
SSR	3	10	2	Simple	5	5	Charge mode	Low - Medium	5	2	2	*N*	*0*	*0*	*n*	*0*	*0*
SC	2	90	5	Simple	3	4	All modes	Medium - High	4	4	4	*0*	*0*	*n-1*	*2n*	*0*	*0*
DTSC	3	48	5	Simple	3	3	All modes	Medium - High	4	4	4	*0*	*0*	*n*	*2n*	*0*	*0*
CNSC	3	42	5	Simple	3	3	All modes	Medium - High	4	4	4	*0*	*0*	*n*	*2n*	*0*	*0*
SSC	3	42	5	Medium	4	4	All modes	Medium - High	4	4	4	*1*	*0*	*1*	*n+5*	*0*	*0*
SSI	4	7	4	Medium	3	3	All modes	Medium - High	4	4	5	*0*	*1*	*0*	*2n*	*2n-2*	*0*
MSI	4	12	4	Medium	3	2	All modes	Medium - High	4	4	5	*0*	*n-1*	*0*	*2n-2*	*0*	*0*
SWT	4	7	3	Medium	3	2	Charge mode	Medium	2	2	4	*0*	*2*	*0*	*n+6*	*1*	*1*
MWT	4	12	3	Medium	2	1	Charge mode	Medium	2	2	4	*0*	*n+1*	*0*	*2*	*0*	*1*
CUK	3	2	4	Complex	3	2	All modes	Medium - High	3	4	4	*0*	*2n-2*	*n-1*	*2n-2*	*0*	*0*
Buck	5	0.9	5	Complex	3	3	All modes	Medium - High	5	4	4	*0*	*m*	*m*	*2m*	*0*	*0*
Buck Boost	5	0.5	5	Complex	3	2	All modes	Medium - High	5	4	4	*0*	*1*	*1*	*n+7*	*0*	*0*
Ramp	3	3.5	3	Complex	2	1	All modes	Medium - High	2	3	3	*0*	*n/2*	*n*	*n*	*n*	*1*
Quasi	3	0.7	4	Complex	2	1	All modes	High	4	1	1	*0*	*2n-2*	*n-1*	*2n-2*	*0*	*0*
Full Bridge	5	0.5	5	Complex	2	2	All modes	High	3	2	2	*0*	*0*	*m*	*4m*	*0*	*0*

5 = Excellent, 4 = Very Good, 3 = Good, 2 = Satisfactory, 1 = Poor

V = Voltage, I = Current, R = Resistor, L = Inductor, C = Capacitor, SW = Switch, D = Diode, IC = Intelligence Circuit

Both Table 1 and Table 2 can be used as a guideline when choosing a suitable cell equalization topology to be added to the battery management system for a specialized battery application. Herewith follows a few examples of specialized applications and the best-suited cell equalization topologies found by making use of Table 1 and Table 2.

Solar Vehicle Challenges are international events where teams design and build solar-powered endurance racing electric vehicles. In some events, teams have to travel between 3000km and 5000km without charging the 5kWh battery from an external power source. This means that these lightweight vehicles require an ultra-efficient electrical system. The priorities for this low-power battery system are weight, size, and equalization efficiency. Referring to Table 1 and Table 2, most of the converter-based topologies as well as the transformer-based topologies can be eliminated due to the size and weight of the equalization systems. Resistor-based topologies can be eliminated due to the low equalization efficiency. The most suitable systems are the capacitor-based and the inductor-based cell equalization methods such as the double-tiered switched capacitor (DTSC) or the multi-switched inductor (MSI), because of the exceptional efficiency and high balancing rate when compared to component-based variations.

Grid-tied energy storage systems together with rooftop solar systems are being used throughout the commercial, industrial and domestic sectors as a means to minimize dependency on the electrical grid or load shifting for a more carbon-neutral electric infrastructure. The battery systems required can range from medium to high-powered applications and normally consist of multiple battery modules. The cell equalization priority is to increase the operational life of the battery system while implementation simplicity is also important. After consulting Table 1 and Table 2 the most suitable cell equalization topologies for this application are the buck-boost converter topology or the multi-winding transformer topologies.

One of the biggest revolutions in battery systems is the use of second-life batteries in emergency backup energy storage systems. Second-life batteries refer to battery cells that have been recycled from previously functional battery systems but have still been tested to have more than 70% useable battery capacity. These battery cells are assembled into extremely cost-effective battery systems, usually for use in large backup applications, with modules and cells of varying state of health (SoH) parameters. The equalization system required for this application must, first of all, operate during all operational states of the battery system. Thereafter priorities of the equalization system will be high power transfer between cells as well as a high equalization rate. Based on these criteria the most suitable cell equalization topology as deducted from tables 1 and 2 is the single or multi-winding transformer SWT/MWT) topology. The selection between these two topologies will be determined by the capacity of the application.

A new trending topic within the mining industry is the use of electrified vehicles, not only for use deep within the mines but more recently rubble removal vehicles. In this application mining vehicles are fitted with a relatively small all-electric hybrid energy storage (battery and supercapacitor), that will allow the empty vehicle to reach the top of the mining pile by discharging the battery. The now fully loaded vehicle will now travel downhill which will allow the electric motors to produce power that will be synced to both the supercapacitor bank and battery bank. This high-powered energy storage system requires very high equalization speed and high efficiency. Thus the only logical choice will be the full-bridge equalization topology. The workings of the full-bridge cell-to-pack topology will allow charging of the battery from the supercapacitor "auxiliary" bank.

For low-cost, low-powered applications such as electric wheelchairs and electric bicycles the switched shunt resistor (SSR) is the best solution as this topology is easiest to design and implement. Extremely cost-effective and reliable.

The key to choosing the best cell equalization topology is to prioritize or rank each of the attributes based on a specialized system and eliminate the topologies that do not meet the preferred requirements.

IV. CONCLUSION

The battery management system is a crucial part of the energy storage system and part of the BMS is the cell equalization unit. Cell equalization is a key subsystem as it contributes to battery system performance enhancements, while also extending battery life and ensuring battery safety. Numerous battery equalization techniques have been researched and presented by academics and application experts. There is no single equalization technique that fulfils all requirements, however, using the cell equalization technique best suited to a specific battery application can have numerous benefits. These benefits include extended battery life in emergency backup systems, cost reduction for small cost-sensitive energy storage systems such as e-bikes or implementation simplicity and cost reduction for large-scale production battery systems. Furthermore, the concepts discussed in this paper are also linked to real-world applications based on the characteristics of each cell equalization topology. The use of Table 1 and Table 2 can aid in the cell equalization selection, design, production, and implementation of a balanced battery system infrastructure.

This paper presented a review of four equalization methods, resistor-based, capacitor-based, inductive-based and converter-based, each with its distinct topologies. The basic operation of each topology was explained followed by a comparative analysis together with the advantages and disadvantages of each topology. This paper can, therefore, not only be used for cell equalization selection but serve as a reference in identifying the potential of each cell equalization method to develop new and enhanced or hybrid topologies by focusing on overcoming the disadvantages and limitations of the topologies discussed.

V. DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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