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Review of Battery Cell Balancing Methodologies for Optimizing Battery Pack Performance in Electric Vehicles

ZACHARY BOSIRE OMARIBA[1,2], LIJUN ZHANG[1], AND DONGBAI SUN[1,3]

[1]National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing 100083, China
[2]Computer Science Department, Egerton University, Njoro 20115, Kenya
[3]School of Materials Science and Engineering, Sun Yat-sen University, Guangzhou 510275, China

Corresponding author. Lijun Zhang (ljzhang@ustb.edu.cn)

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ABSTRACT Batteries are gaining entry into every home and office for they are widely used because of their variant benefits. However, these batteries are prone to failure caused by charge imbalance in the batteries connected in either series or parallel, which can sometimes be catastrophic and hence they require to be properly monitored in a real-time manner. There exist many battery balancing schemes which are broadly grouped into either passive or active schemes. All these schemes have their own advantages and disadvantages, and hence it is upon the user to decide on which scheme will best work for them. However, research has proven that the hybrid scheme will be the best as it couples the benefits of all schemes. This study will review the various battery cell balancing methodologies and evaluate their relationship with battery performance. At present there are a few studies tackling the mechanical vibration of battery balancing performance. This study shows that battery balancing performance during long-term should be evaluated from various temperature and vibration frequencies.

INDEX TERMS Battery cell balancing, electric vehicles, hybrid schemes, and performance optimization.

I. INTRODUCTION

In the transport industry, large battery packs provide high output power without producing harmful emissions like nitrogen oxides, carbon monoxide, and hydrocarbons which are associated with gasoline-powered combustion engines. In an ideal situation, each individual battery in the pack equally contributes to the system, but, when it comes to batteries, all batteries are not made the same. Even if the batteries exhibit the same chemistry with the same physical size, shape, and weight, they can have different total capacities, different self-discharge rates, different internal resistances, and different aging which all have an effect on the overall battery life equation [1]–[3]. These differences make batteries to face a major challenge of battery life, which research has shown can be extended by cell balancing [4], and thus call upon the battery management system (BMS) to perform cell balancing always.

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The battery pack is limited in performance by the lowest capacity cell in the pack since once the weakest cell is depleted, the entire pack is effectively depleted. The health of each individual battery cell in the pack is determined based on its state of charge (SOC) measurement, which measures the ratio of its remaining charge to its cell capacity. The SOC uses battery measurements such as voltage, integrated charge, and discharge currents and temperature to determine the charge remaining in the battery. Precision single-chip and multi-chip BMS combine battery monitoring (including SOC measurements) with passive or active cell balancing to improve battery pack performance. Ordinarily, the performance criteria of the battery balancing system normally include aspects such as the impact of state-of-health (SOH), balancing speed, efficiency, cost, and volume [5]. These measurements result in healthy battery SOC independent of the cell capacity; minimized cell-to-cell SOC mismatch; and minimized effects of cell aging (aging results in lost capacity).

A battery pack consists of several battery cells in parallel and in series to provide sufficient operating voltage and capacity to support the application. However, if there is a mismatch between the voltage and capacity of the connected battery cells, the entire battery pack cannot operate efficiently [6]. For example, during discharge, as soon as the first cell reaches below the cutoff voltage, the discharge stops and the charge in the rest of the cells cannot be utilized. This type of mismatch can occur because of a mismatch in the capacities of the cells or the SOCs of the cells. The two methods of cell balancing are passive and active cell balancing which offers different features to the battery pack and solutions to the battery management system of electrical vehicles (EVs).

Batteries experience several kinds of degradation mechanism throughout their lifetime. When these batteries are cycled at high temperatures, degradation mechanisms leading to capacity loss are observed through the rise of the positive electrode impedance especially at low lithium content [7], [8]. The operating temperature, uniformity of the temperature distribution, vibration, and uniformity of vibration distribution are the four important factors which will be researched on in this study, at the scale of batteries in which batteries are embedded. This makes thermal management system to be crucial for a LIB pack as cycle life, driving a range of EVs, usable capacity and safety are heavily dependent on operating temperature [9]. For the purpose of ensuring the safety of the batteries, proper battery balancing should be conducted to ensure that the excessive temperature rise or drop, and vibration which can lead to uneven degradation in the battery life or explosion should be carefully monitored.

So far although research is commonly focusing on the evaluation of battery performances at room temperature, little is done concerning the balancing of the batteries at various temperatures they are cycled, as well as the load vibration frequencies. This is specifically believed to lead to biased and unfair assessments to battery real capabilities. For accelerated aging, tests carried out at variant temperatures from room temperature, and variant load vibration frequencies, a lack of knowledge is hence recognized regarding the impact of the temperature chosen together with vibration frequencies for evaluation of battery balancing performances during long-term cycling. Therefore with this review paper proposed, the impact of varying temperature and vibration in the assessments of lithium-ion battery (LIB) cells balancing performances during long-term cycling is aimed to be investigated.

II. BATTERY MODEL

A LIB consists of three main parts, which are a negative electrode, electrolyte, and positive electrode whereby the charge and discharge principle takes place when the heavily charged ions are transferred between the two electrodes and it takes place in the electrolyte [10]–[12]. The rechargeable lithium-ion cells perform electrical work by exchanging li-ions through the electrolytes between negative and positive electrodes which are separated by ion-permeable polymer membranes [13]. The battery model is required to define and study voltage u, current I, SOC, temperature, and vibration.

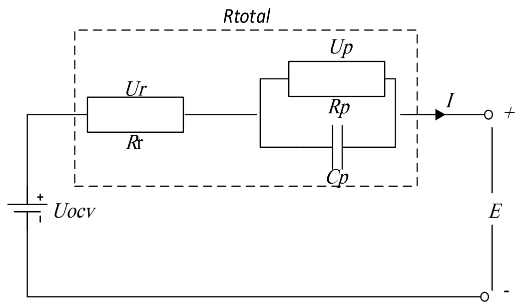


FIGURE 1. Thevenin battery model.

Several works of literature propose many battery models [14]–[16] which are made of the equivalent circuit combination of capacitance and resistance. These models include Thevenin equivalent circuit model, resistance-capacitance model, the RC model, internal resistance model, and the partnership for a partnership for the new generation of vehicles (PNGV) capacitance model [14]–[16]. Taking temperature into consideration the study of Thevenin equivalent circuit model will be applied as shown in Fig. 1.

The Thevenin battery model from Fig. 1 is used to analyze the battery discharging process.

where:

Uocv	is the open-circuit voltage,
Rr	represents the ohmic resistance,
Ur	is the voltage on *Rr*,
Cp	is the polarization capacitance,
Rp	is the polarization resistance,
Up	is the voltage on *Cp* and *Rp*,
E	is the terminal voltage,
I	is the discharging current,
Rtotal	is the sum of *Rr*, *Cp*, and *Rp*.

The influence of temperature is a major factor in battery performance, shelf life, charging, resistance, and voltage control. At very high temperature, there is more chemical activity inside a battery than at lower temperatures. The capacity of the battery is lowered when the temperature is too low, like the case when vehicles are operating in winter periods. If the battery is exposed to extreme weather it may stop working, melt, create sparks, create flames, expand, or even blow up in very extreme cases. Extreme cold affects the battery as the internal components expand as a result and electrons are inhibited, but when the temperature rises the electrons are excited. High temperature has, therefore, a deep impact on battery performance, safety, and cycle-life. Temperature control mechanisms are required to monitor the temperature and interrupt the current path when the temperature exceeds the required ones, otherwise, loos of energy through conduction, convection, and radiation can occur. The protection prevents the damage to batteries also saving their performance and work-life. This can be achieved by uniform heat distribution and protection from overheating. The effect of temperature to the voltage of a battery is an indirect effect which is associated with other properties of the material i.e. the conductor or semiconductor which changes with temperature. The resistance of the conductor increases with the increase of the temperature which is given by the relation:

$$R(T) = R_0[1 + \propto (T - T_0)] \tag{1}$$

where $\propto$ is the temperature coefficient, R_0 is the internal resistance of the conductor, T is battery temperature, and T_0 is the room temperature. Therefore we can observe that resistance increases with temperature rise, which implies that the voltage decreases. Thus voltage decreases with the rise of the temperature and vice versa.

The battery generates heat which can be either reversible or irreversible heat. The reversible heat commonly known as the reaction heat refers to the energy that is released or absorbed in the electrochemical reaction to maintain the energy balance of the reaction. While the irreversible heat includes the Joule heat and the concentration polarization heat. The simplified heat generation equation according to [17] is:

$$Q_t = Q_j + Q_r = I(E - U_{ocv}) + IT\frac{\partial U_{ocv}}{\partial T} \tag{2}$$

$$Q_j = I(E - U_{ocv}) = I^2R \tag{3}$$

where:

I	is operating current of the battery,
E	is battery voltage,
U_{ocv}	is open-circuit voltage,
Q_t	is total heat generation power,
Q_j	is irreversible heat generation power,
Q_r	is the reaction heat or reversible entropy heat.

The irreversible heat generation power Q_j is generally the sum of heat generated by Ohmic resistance when current is flowing, and the heat generated by concentration difference through material transfer in the battery. Qj can be expressed as the difference between the battery terminal voltage and the OCV voltage results from the voltage that is generated by the internal resistance when the current flows as shown in Eqn. 2, where R is the equivalent internal resistance of the battery. While the reaction heat Qr is the reversible entropy heat which depends on the direction of current and the sign of entropy coefficient. The entropy potential varies significantly with different chemical composition and is greatly influenced by SOC [17].

Three parameters namely heat generation, thermal diffusion, and heat conduction are found to majorly influence the battery temperature. This temperature affects battery test reliability when measuring the uncertainty of DC resistance [18]. The battery distributes heat to the exterior when it works under low temperatures, in addition to heat production. Thermal convection and heat radiation are basically the main approaches to battery heat loss. This thermal radiation is usually ignored because it is usually very small as compared to thermal convection. The dissipated heat can be expressed as:

$$Q_{dis} = -hA(T - T_\infty) \tag{4}$$

where h is the equivalent heat transfer coefficient, A is the surface area of the battery, T is the battery temperature, and $T\infty$ is the ambient temperature. This makes the heat balance equation to be obtained as follows:

$$mc\frac{dT}{dt} = Q_j + Q_r + Q_{dis} = I^2R + IT\frac{\partial U_{ocv}}{\partial T} - hA(T - T_\infty) \tag{5}$$

where m is the mass of the battery and c is the specific heat capacity.

From Eqn. 5 we can resolve that the total heat generated from the battery is basically influenced by resistance, current, entropy potential, the equivalent heat transfer coefficient, and battery temperature. The higher the current and resistance the greater the heat generated, and the higher the equivalent transfer coefficient, and battery temperature, the greater the heat dissipation, resulting into the reduction in the total heat generated, as well as the lower the ambient temperatures the lower the initial discharge voltage [8]. The battery model developed in this research will take into account changes in resistance, entropy coefficient during battery heating process, and the changes in load vibration frequencies so as to guarantee accuracy. According to the literature [18], vibration has an influence on the electrical performance of the cell as it increases the resistance, decreases the cell capacity and causes a slight deterioration of consistency. This makes the study of vibration influence on battery cells balancing in the battery pack to be crucial and thus requires to be incorporated in the design of LIBs.

From Eqn. 5, we can get the linear differential equation relating to the battery temperature as follows;

$$\frac{dT(t)}{dt} = \left(\frac{I\frac{\partial U_{ocv}}{\partial T}}{mc} - \frac{hA}{mc}\right)T(t) + \frac{I^2R}{mc} + \frac{hA_\infty}{mc} \tag{6}$$

By using the Laplace transform Eqn. 5, can be rewritten in discrete time as:

$$sT(s) - T(t_0) = \left(\frac{I\frac{\partial U_{ocv}}{\partial T}}{mc} - \frac{hA}{mc}\right)T(s) + \left(\frac{I^2R}{mc} + \frac{hAT_\infty}{mc}\right)\frac{1}{s'} \tag{7}$$

where t_0 is the initial time, and t is the current time. Under periodic sampling conditions, $t_0 = kT_0$, $t = (k+1)T_0$, and $k = 0, 1, 2, 3, \ldots, n$. Then Eqn. 7 becomes:

$$sT(s) - T(KT_0) = \left(\frac{I\frac{\partial U_{ocv}}{\partial T}}{mc} - \frac{hA}{mc}\right)T(s) + \left(\frac{I^2R}{mc} + \frac{hAT_\infty}{mc}\right)\frac{1}{s} \tag{8}$$

If Eqn. 8 is further rearranged, it becomes:

$$T(s) = \frac{T(kT_0)}{\frac{s + hA - I\frac{\partial U_{ocv}}{\partial T}}{mc}} + \frac{1}{\frac{s(s + hA - I\frac{\partial U_{ocv}}{\partial T})}{mc}} + \frac{I^2R + hAT_\infty}{mc} \tag{9}$$

By applying the inverse of the Laplace transform in Eqn. 9, we get:

$$T\left((k+1)\,T_0\right) = e^{-\frac{hA - I\frac{\partial U_{ocv}}{\partial T}}{mc}t}\,T\left(KT_0\right) + \frac{mc}{hA - I\frac{\partial U_{ocv}}{\partial T}}\left(1 - e^{-\frac{hA - \frac{I\partial U_{ocv}}{\partial T}}{mc}t}\right)I^2R + \frac{hAT_\infty}{mc} \qquad (10)$$

From Eqn. 10, the Laplace transform has been used to provide an alternative functional description to simplify the process of analyzing the battery heat behavior. In this case, the inverse Laplace transform solves the problem of removing the time variable from the partial differential equation while guaranteeing accuracy.

III. BATTERY CELL BALANCING

The major function of BMS is monitoring and balancing battery cells in a battery pack. There are two groups of factors that influence the cell imbalance which is said to be intrinsic or extrinsic. The intrinsic factors are those factors associated with manufacturing processes, that leads to variance in the amount of active material and internal resistance [19], while the extrinsic factors are those that include the manner of connection (serial/parallel), charge/discharge current, and heat dissipation [20]. The battery pack is said to be balanced if at, some SOC, all cells are at the same SOC. The BMS performs the battery cell balancing to ensure that the charge is maximized so that the battery can deliver the required amount of charge at all times [21]–[23], otherwise the imbalance may lead to increased losses and or heating effects [24], [25], reduced charge, low energy efficiency, and accelerated degradation [26].

If one cell fails in a battery pack, and it is not replaced immediately it will lead to disastrous consequences. But again, replacing the failed cell in a battery pack is not a permanent solution since the fresh cell has different chemical characteristics than the aged cell, which can again lead to failure. It is therefore advised to take cells that have common chemical characteristics, so that same age cells are assembled together in a battery pack. Because of these, the BMS employs cell balancing as a control measure to avoid the overcharge or over-discharge of battery cells [27], and this balancing must take place while the cells are charging or discharging. Cell balancing is done to ensure that the delivered energy to the cells during the charging process is maximized, and the energy released from the cells during the discharging process is also maximized [28]. The EVs battery pack contain a series of multi-cell batteries in order to achieve higher operating voltages. The high number of cells in a battery pack, are subject to failure and worse still this will affect reliability since higher failure rate is likely to take place than in the case of a single battery cell. This implies that when the cells are many, the chances of failure are higher which means that if you have got *n* battery cells in a pack, failure of the battery is equivalent to *n* times the failure rate of an individual cell.

Due to the variances in battery cells, charge and discharge occur at different rates. This results in a non-uniform voltage across the battery cells in series in the pack. This phenomenon can make cells to overcharge or undercharge respectively yielding to decrease in battery pack lifetime, safety hazards, and loss of pack capacity over time [29], [30]. To safeguard batteries from these and many other unforeseen issues, cell balancing or cell equalization technique is employed by the BMS to ensure that there is uniform charge level among different cell by basically dissipating excess charge as heat, or transferring the excess charge to the less charged battery cells [31]. According to the literature [32], the control objectives and algorithms should be embedded in each battery module to be used to bias individual cell state and impact pack performance. The cell voltage equalization will take place in either under passive or active balancing mode, wherein the former the excessive charge is dissipated as heat, while in the latter the excessive charge from highly charged cells is moved to the cells with less charge, thus making them stronger cells to support the weaker ones [33]–[35]. In the BMS, the cell balancer charger operates in three modes namely the cell charging balancing mode, the cell discharging balancing mode, and the idle mode by controlling the driving signals of the primary and secondary switches [36], due to the fact that EVs batteries are not always used to their full capacity in every driving cycle and thus it is not necessary to keep the SOC balanced at all times [37]. Fig. 2 illustrates the three cell balancing modes of the equalization charger.

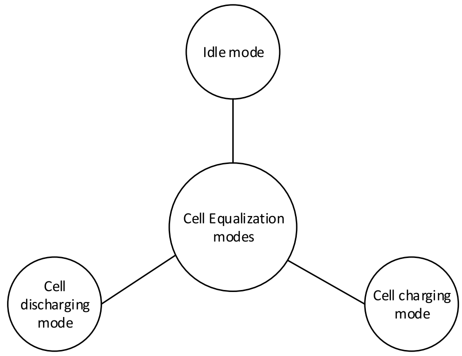


FIGURE 2. **Cell balancing modes.**

The cell charging balancing mode happens when the balancer charger transfers the pack energy to the cell with little energy thus operating on a pack-to-cell mode, while the cell discharging balancing mode operates when the balancer charger transfers the extra cell energy back to the pack operating in the cell-to-pack mode. The idling balancing mode refers to that situation when the cell charger balancer is not in operation.

A. CELL BALANCING SCHEMES

The importance of cell balancing is to equalize the voltage and SOC among the battery cells when they fully charged. As shown in Fig. 3 the two batteries have variations in cell charges, and this calls for cell balancing to bring the cells to the same SOC. The main cell balancing schemes are active

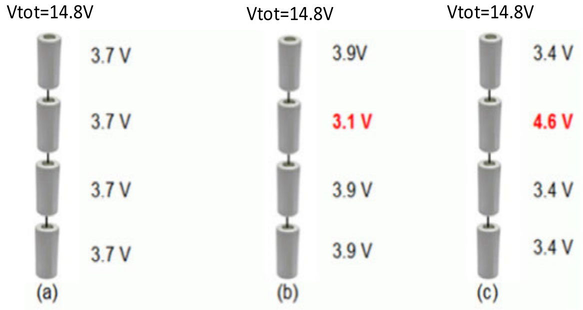


FIGURE 3. Example of Cell Charge Variations. (a) Fully charged cells with same SOC, (b) Imbalanced battery with one cell with low charge, (c) Imbalanced with one cell with high charge.

and passive methods [38]–[41]. The cell balancing algorithms are classified into a voltage-based algorithm and charge-based algorithm. The algorithms yield into either active or passive cell balancing methods that are applicable to balancing batteries

1) ACTIVE CELL BALANCING

Active cell balancing technique utilizes the capacitive or inductive charge shuttling to transfer charge from the cell with a high charge to the cell of low charge. This means that active balance methods equalize inconsistencies among cells in series by moving electrical energy from higher SOC cells to lower SOC cells [21], [42]–[44], with little loss [39]. In the charges of one cell are higher than the average charges of balancing module, the cell will have no option but to be deprived the extra charges which are moved to the cell with fewer charges [45]. This method is very efficient because the excess energy is transferred to the cell with low energy instead of being precipitated away, but it increases balancing circuit complexity [40], but the high performance of LIBs is rendered [46]. The active cell balancing method consists of the relays, DC-DC connectors, and the current transducers. Also, this method constitutes of five main subcategories namely: cell bypass, cell-to-cell, cell-to-pack, pack-to-cell, and cell-to-pack-to-cell [47]–[49]. The cell bypass method is subdivided into three methods: namely complete shunting method, shunt resistor method, and the shunt transistor method [40], [50], and this method is easy to implement, easy to modularize, and low cost but is used at the end of charging process [51]. All these methods in summary form are represented in TABLE 1.

Cell bypass: Ideally each individual cell in a battery pack has identical characteristics so that they all react identically to various characteristic parameters. However, in practice, the individual cell characteristic parameters vary from cell to cell due to, manufacturing differences [52], environmental conditions such as localized temperature in the pack, or an evolving damage state of the cell [53] and so on. Some cells will have increased self-discharge rates. Some will have higher voltages due to their temperature. Some will have higher internal resistances causing voltage variation and heating. In nearly every battery pack, individual cell characteristics will diverge from those of the other cells in their pack [54]. Cell bypass equalization methods bypass the current of those cells that reach their maximum/minimum voltage, waiting for the remaining cells to reach the maximum/minimum voltage as well. These methods are easy to implement, easy to modularize, and their cost is low; however, their existing control strategies only allow them to be used at the end of the charging/discharging process when their efficiency is low. Cell to cell methods: Cell-to-cell variations are important in pack conditions because they can result in different capacities for the battery cells or in local degradation in the pack. Therefore, cell-to-cell variations affect the SOC and SOH estimation and decrease BMS control performance, and also there are thermal gradients through a battery pack because actual battery packs stack many cells [47], [55]. Cell-to-cell methods pass the extra energy that is stored in the cells to the adjacent ones with lower stored energy. They may present higher efficiency, but whether their speed is slow or their control complexity is high. In Cell-to-pack methods, the energy is extracted from the most charged cell in the pack and equally delivered to all the cells through the pack terminals. This method is safe in the sense that no energy is lost in the form of heat as the extra charge that will cause heating is equally relieved from the cell to other cells in the pack. Pack-to-cell methods transfer energy from the pack to the least charged cell. This method ensures equilibrium charge is maintained all through the charging process, and no charge is lost.

Cell-to-pack-to-cell methods transfer energy by implementing both cell-to-pack and pack-to-cell methods. In cell-to-cell, cell-to-pack, pack-to-cell, and cell-to-pack-to-cell methods, conventional topologies based on DC/DC converters tend to be complex and expensive, and their efficiency can be low [41]–[48], [56]. These topologies are generally effective at preventing the over-charging or over-discharging of individual battery cells, which is important for pack safety and longevity. Usually, these balancing architectures employ either a fly-back transformer or multi-winding transformer. This creates space limitations: a fact that constrains the number of series-connected cells that can be balanced using these architectures [40]. In the literature [5], different active cell balancing architectures were studied, and a hierarchical active balancing architecture was proposed. The hierarchical active balancing architecture was found to reduce balancing time, and energy loss during balancing, avoid repeated charging and discharging, and reduced current rating of balancing circuit, unlike the conventional cell-to-cell architecture. In this method, the series-connected battery string is grouped into different packs, and a top layer is connected to the packs to directly deliver the energy from one pack to any other pack bi-directionally.

The main goal of an active balancing technique is to maintain an even distribution of charge among series-connected cells of a battery over time [57], with ideally no energy losses for the equalization process. This is coupled by the fact that the main idea behind all active balancing schemes is

TABLE 1. Advantages and disadvantages of various active cell balancing schemes.

Category	Scheme	Advantages	Disadvantages
Cell Bypass	Complete Shunting	Cheap, high efficiency, high speed, less control complexity, small size, low switch voltage stress	Used for low power applications, high switch current stress,
	Shunting Resistor	Low cost, easy implementation, high speed,	Used for low power applications, low efficiency
	Shunting Transistor	Low cost, high speed, less complex, small size, easily modular	Less efficiency allows low power applications
Cell-to-Cell	Single Switched Capacitor	Efficient, low complexity, the possibility of low and high power applications, less costly, low switch voltage stress-no need for closed-loop control	Low balancing speed, difficult modularity, high switch voltage stress, highly complex
	Double-tiered switching	Relatively cheap, lower balancing time, lower balancing capacity currents, allow high power applications, easily modularized	High cost, high size, relatively low speed, high switch current stress
	Cûk converter	Lower balancing currents, relatively efficient, relatively cheap, allows high power applications, low switch voltage/current stress	High control complexity, relatively big size, and low implementation
	PMW controlled converter	Allows high power applications, relatively cheap/efficient/small-sized/low-speed	High control complexity, relatively low switch voltage/current stress
	Quasi-Resonant converter	Good for high power applications, low switch voltage/current stress, relatively high efficiency, simple implementation	High control complexity, expensive, big-sized,
Cell-to-Pack	Shunting inductor	Allows high power applications, relatively cheap, small size, relatively low switch current/voltage stress	Very slow, highly complex, difficult modularity,
	Boost shunting	Good for high power applications, efficient, relatively cheap/high-speed/small-sized, easy for modular design, low switch voltage/current stress	High control complexity, high cost
	Multi-secondary winding transformer	Allows high power applications, relatively high switch voltage stress, low switch current stress	Expensive, less efficient, less speed, big size, difficult modularity, and control complexity
	Multiple transformers	Allows high power applications, can be modularized, fast equalization speed	High cost, less efficient, high complexity, relatively high switch voltage/current stress, big size
	Modularized-Switching transformer	Good for high power applications, relatively highly modular, low switching voltage/current stress	High cost, big size, high control complexity, and relatively low balancing speeds/less efficient
Pack-to-Cell	Voltage multiplier	High power applications, relatively low cost, high efficiency/speed/implementation, less complexity, easy modularity	High switch voltage/current stress
	Full-bridge converter	High efficiency, easy modularity, suitable for high power applications, high speed, low switch voltage/current stress	High control complexity, big size, high cost,
	Multiple transformers	High power applications, low complexity, fast equalization speed	Higher cost, slow, expensive, less efficient, big size
	Multi-secondary windings transformer	Allows high power applications, relatively high speed/implementation, low complexity, low switch current stress	Expensive, less efficient, big size, and control complexity, difficult modularity
	Switched transformer	Allows high power applications, low switch voltage/current stress, fast equalization speed	High cost, big size, less efficient, and high control complexity
Cell-to-Pack-to-Cell	PMW controlled converter	Can be used in high power applications, relatively high efficiency/speed/implementation	High cost, big size, less speed, relatively high switch voltage/current stress, and high control complexity
	Single switched capacitor	Relatively less costly, high efficiency, small size, low switch voltage stress, and applicable in high power applications	Low balancing speed, high control complexity,
	Single switched inductor	Relatively low cost, high efficiency, low switch voltage stress, and applicable in high power applications	Slow balancing speed, high complexity, big size,
	Bi-directional multiple transformers	Allows high power applications, easy modularity,	Expensive, less efficient, slow speed, high complexity, big size, relatively high switch voltage/current stress
	Bi-directional multi-secondary windings transformer	Allows high power applications, relatively high speed & implementation, low switch current stress	Expensive, less efficient, complex, big size
	Bidirectional switched transformer	Relatively high speed, allows high power applications, low switch current/voltage stress, and modularity	Expensive, less efficient, complex, big size,

Sources: [11-22][59][67]

to transfer the charge from cells having higher SOC to cells having lower SOC through switched capacitors which act as intermediate storage banks [58]. The active cell balancing technique maximizes the usable capacity of the battery by ensuring that it exploits all the energy stored in the battery and very little energy will be wasted as compared to the passive balancing method [59]. To achieve this, non-dissipative element such as a capacitor or an inductor is used as a tank

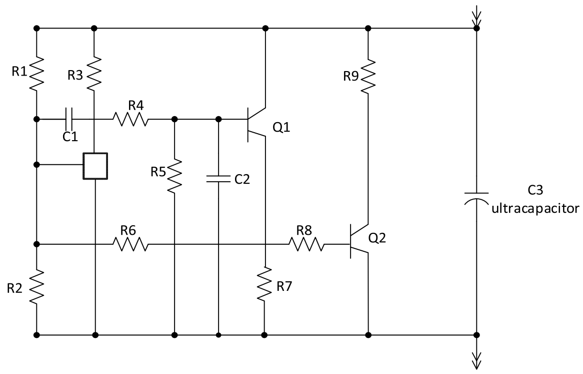


FIGURE 4. The active cell balancing circuit.

TABLE 2. Advantages and disadvantages of various passive cell balancing schemes.

Scheme	Advantages	Disadvantages
Fixed shunting resistor	Simplicity; Low costly	Has continuous energy dissipation as heat for all cell reducing life span; Effective for a small number of cells connected series; Excess heat generation; inefficiency.
Switched shunting resistor	More efficiency; Simplicity, Reliability; Less costly	Excess energy from higher cells is dissipated as heat hence short battery life; Implemented for low power applications

Sources: [4][6][13][47][63]

to transfer energy between the cells of the battery in every active balancing circuit. In this method, the circuit is placed in parallel with each cell and will bypass the current only when the cell goes above the rated voltage.

It is very ideal for high cycle applications or when stand by losses needs to be at a minimum, also active cell balancing, the battery cell lifetime and capacity can be further extended [60] of which make this scheme very advantageous over passive balancing. However, this method faces the challenge for the need of additional component which increases the cost and unreliability as well as the disadvantage of the length of time that the cells take to be equalized.

Fig. 4 shows the circuit of the active cell balancing model. From Fig. in active balancing, energy is drawn from the most charged cell and transferred to the least charged cells, usually through DC-DC converters. Since the active balancing scheme utilizes the capacitance or inductive charge shuttling to transfer charge from the cell with high charge to the cell with low charge [61], the battery balancer, or battery regulator based on active balancing topology is used to improve available capacity of a battery pack with multiple cells, and increase each cell's longevity.

Any cell that has more charge is relieved some charge which is supplied to the cell with a little charge, and from Fig. 4 the ultra-capacitor (supercapacitor) is used. This scheme, unlike passive balancing, does not precipitate the extra energy to the air as heat, hence it is more beneficial in energy saving and increasing the battery life. However, capacitors, or inductors adopted for active cell balancing, if they are small it results in small balance current. The active balancing scheme realizes cell by transferring redundant charge from the cell with high voltage to the cell with lower voltage and the middle voltage *Vmid* cell can be used as a reference. The terminal voltage *Vcell* of each cell is compared to *Vmid*, and if the voltage difference is higher than the threshold voltage ($+Vth$) this cell needs to be discharged or and if less than threshold voltage ($-Vth$), this cell needs to be charged hence discharging or charging balancing, while any other case means no balancing is required [62].

Fig. 5 represents the various cell balancing techniques that are applicable to passive, and active cell balancing schemes respectively. The advantages and disadvantages of the various active cell balancing techniques are shown in TABLE 1.

There are several different active cell balancing topologies available and are more complicated and more expensive than passive balancing as shown in Fig. 5.

2) PASSIVE CELL BALANCING

The passive cell balancing method is relatively simple compared to the active cell balancing method. In this method, the cells with excess energy are discharged through dissipative bypass route as heat until the charge matches those of the lower cells in the pack or charge reference [21], [40], [43], [63] and this will impact the battery run time. The dissipative nature of passive balancing means that there is no distribution of energy between cells since cell energy is wasted as heat [64], a task accomplished by the use of resistors. Therefore, the charge is lost or discharged through a resistor to the air rendering this method to be less efficient and generates a lot of heat. The conventional cell balancing approaches are passive where the excess charge of cells with high SOC is dissipated as heat across a resistor, resulting in reduced energy efficiency [65], [66]. However, this method is good for low-cost system applications in which no active control is utilized to equalize. It cannot be used for lithium-based batteries as there is a high risk of explosion [48]. In this method, the resistor is placed in parallel with each cell and the resistor size determines the balance rate. The passive battery cell balancing circuit and flowchart is shown in Fig. 6 and Fig. 7 respectively.

There are basically two types of passive cell balancing topologies. They include the fixed shunting resistor and switched shunting resistor. Passive balancing consists of a resistor in parallel to each cell, controlled by the cell voltage monitoring chip [35]. The intent is simply to discharge the cells at higher SOCs (or higher remaining charge) to match the rest of the cells. Passive balancing is still the dominant method in use today, but still has man disadvantages as well as advantages as shown in TABLE II.

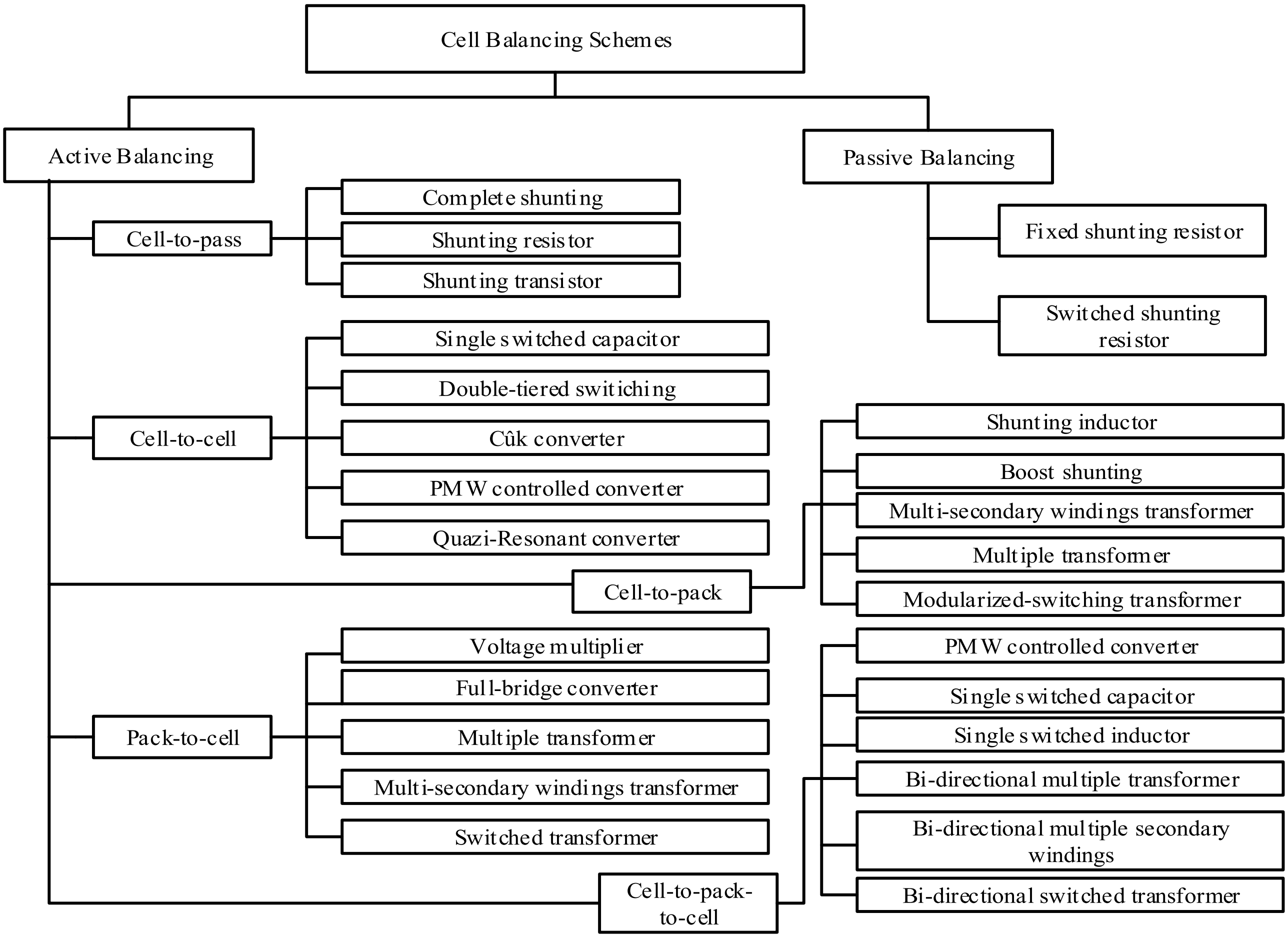


FIGURE 5. Active and passive cell balancing techniques.

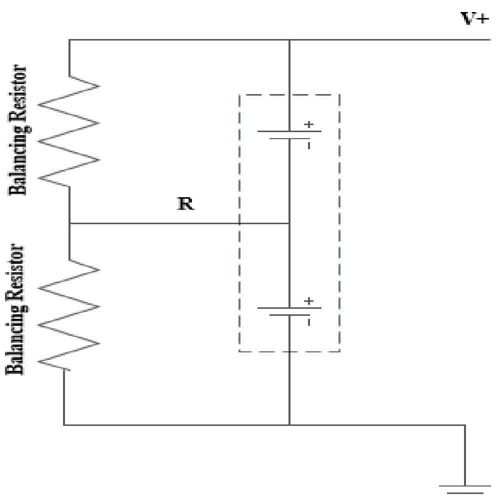


FIGURE 6. Passive balancing circuit.

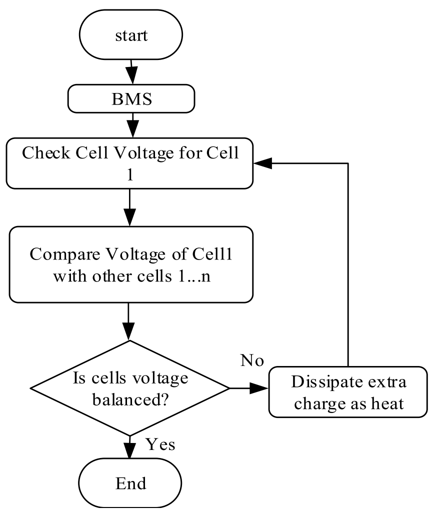


FIGURE 7. Passive cell balancing flowchart.

B. TYPES OF BATTERY CELL IMBALANCE THAT AFFECT CHARGE/DISCHARGE VOLTAGE

There is various battery cell imbalance that affects charge or discharge voltage of the battery cells namely; SOC imbalance, impedance differences, and total capacity differences. These cell imbalances are classified into two major categories [68], namely the internal sources and the external sources and are further illustrated as shown in Fig. 8. The

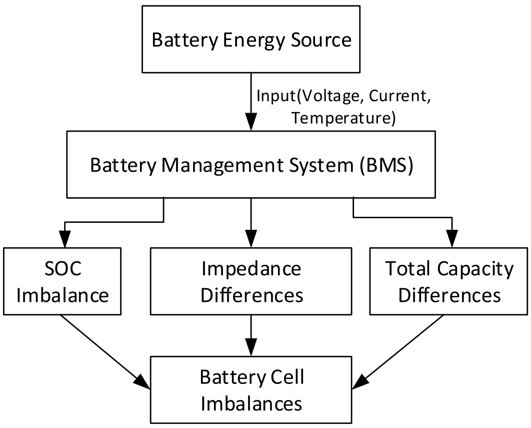


FIGURE 8. Causes of battery cell imbalances.

internal sources include manufacturing variance in charge storage value, variations in internal impedance and differences in self-discharge rate. While the external sources are caused by some multi-rank pack protection integrated circuits (ICs) which drain charge unequally from different series ranks in the pack. These protection ICs need to include a cell-balancing algorithm in-order to correct for their own unbalancing effect on the cells. Thermal differential across the pack is another external source of the imbalance, which results in differing rates of self-discharge for the cells.

1) SOC IMBALANCE

Ideally, every cell in a battery pack has the same chemical reaction but in reality, each cell has different chemical reaction due to the manufacturing process, internal resistance, self-discharge rate, degradation and temperature [7], [15], [69]. A common limitation in battery SOC estimation is ignorance of the battery parameter uncertainty if they are the same type and come from the same manufacturer. As a consequence, the accuracy of the SOC estimation may vary from cell-to-cell, and this is very critical [70]. Another important limitation is unawareness of the model uncertainty which comes from the fact that no battery model can truly represent the physical system without any error in various operating conditions. Since the SOC estimation is conducted on the basis of the assumed 'perfect' battery model, any level of model uncertainty will cause biased SOC estimation regardless of the specific numeric algorithms [71], [72].

State of charge imbalance is caused by cells being charged to different SOC levels, and also by various chemical reaction, which means that SOC imbalance can be caused by external and internal sources [50]. For example if we have 3 cells with a capacity of 2900mAh ($Qmax$), and discharge the first cell by 200mAh ($Q1$), the second cell by 100mAh and the third cell by 100mAh from a fully charged state, the first cell chemical state of charge will be $(Q1/Q_{\max})100\% = 96.55\%$, but the second and third cells will be 90.91%. So we can say the first cell is imbalanced by 5.64%. This, in turn, will result in a different open-circuit voltage (OCV) for the third cell compared to the first cell and the second cell, because the OCV is in direct correlation with the chemical state of charge. The BMS detects the rate of voltage change ($\mathrm{d}V$) with respect to SOC ($\mathrm{d}SOC$) of a battery pack based on a $\mathrm{d}V/\mathrm{d}SOC$ that represents the battery pack as a whole, without calculating $\mathrm{d}V/\mathrm{d}SOC$ of individual cells. Charging or discharging is terminated when the $\mathrm{d}V/\mathrm{d}SOC$ reaches a predetermined value. The battery OCV can be estimated based on the following equation:

$$OCV = Vd \pm Id + R \tag{11}$$

where: Vd is the value of voltage (V), Id is the value of current (A), and R is the value of resistance (Ohms). At the same time the battery SOC can be calculated using the following equation:

$$SOC = SOC0 \pm (Q/FCC) \times 100\% \tag{12}$$

where: SOC0 is the initial SOC before charging or discharging (%), Q is the current integration value (Ah), FCC is the full charge capacity, (+) means charging, while (-) means discharging. Therefore, the SOC can be computed during the charging or discharging of the battery. TABLE III represents the factors that cause the battery cell imbalances together with their probable solutions.

According to the literature [81] on SOC estimation, it was reached to the following conclusion from their simulations on SOC estimation that accuracy can be affected by the following key parameters, which in return causes the cells SOC imbalance.

1) The Ohmic resistance R_0, polarization resistance Rp, and the open-circuit voltage OCV are the key parameters affecting SOC estimation accuracy. However, the polarization capacitor Cp which is an important parameter only influences the dynamic response characteristics of SOC estimation but does not have noticeable effects on the steady-state accuracy of SOC estimation. Fig. 9 shows the estimated OCV differences versus the different SOCs.
2) Under the same SOC estimation accuracy and the robustness against modeling errors and measurement noises, the PI observer has advantages over the $H\infty$ observer and the extended Kalman filter (EKF) algorithm to be applied in BMS.
3) The relationship between SOC estimation accuracy and voltage measurement errors has been resolved, and some related guidelines on how to select a robust method which has a strong tolerance against voltage measurement errors are provided.

To solve the problem of SOC imbalances, the conventional average SOC balancing strategy is applied to compare the SOC of each cell with the average SOC of the battery pack. A positive balancing threshold and a negative value are usually applied to the average SOC to compose a balancing band [36]. If a cell's SOC is higher than the balancing band, the cell

TABLE 3. Causes and solutions battery cell imbalances.

Type of imbalance	Level	Causes	Solution	References
SOC imbalance	Cell	• Differences in electrochemical characteristics	• Capacity and resistance screening • Energy sharing control scheme	[20][36][44][45] [62][70][69][73] [74]
		• Overcharge/over-discharge • Cell inconsistency problems • Balancing current in equalization circuit	• Additional charge or discharge if there is no capacity difference • Utilize cell balancing circuits and associated controllers	
Impedance differences	Module/ pack	• Differences in coulombic efficiency caused by the energy consumed by BMS and cell balancing circuits • Battery aging	• Maximum power transfer control • Changes in voltage over current during charging/discharging • OCV pumping • Application of impedance reduction methods	[75][76][77] [39][78][79]
Total capacity differences	Module/ pack	• Different characteristics of cells within the module • Differences in initial charge capacity	• Effective balancing • Control the balance circuit on/off or/and the balance current	[20][42][80]

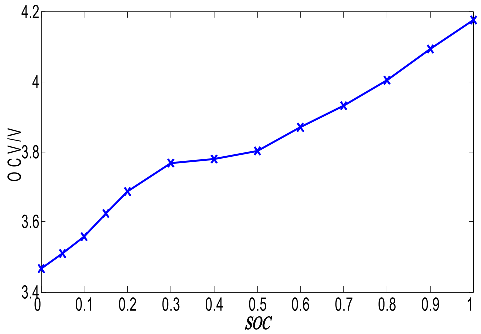


FIGURE 9. Estimated OCV differences at different SOC.

needs to be discharged until the SOC falls within the balancing band. On the contrary, if a cell's SOC is lower than the balancing band, the cell needs charging balancing until the SOC increases to the balancing band, and thus the battery pack is balanced.

An energy sharing controller and SOC balancing during the discharge-charge operation were proposed by [73] based on distributing battery energy storage system architecture where the cell balancing system and the dc bus voltage regulating system are combined together to form a single system. All battery cells in the battery pack are decoupled one from the other by ensuring that each cell is connected to a small low power dc-dc converter that stores the charge. These small dc-dc power converters are utilized to achieve both the SOC balancing between the battery cells and dc bus voltage regulation at the same time. Any form of imbalance that can arise is addressed from the root by using energy sharing concept to automatically adjust the discharge-charge rate of a cell while monitoring a regulated dc bus voltage.

2) IMPEDANCE DIFFERENCES

Impedance (Z) is the measure of the total opposition to current flow in an alternating current circuit. It is made up of the sum of two components, resistance (R) and reactance (X).

When cells have different coulombic efficiency:

$$z(t) = z(0) - \frac{1}{Q}\int_0^t \eta(\tau)\, i_{net}(\tau)\, d\tau \qquad (13)$$

there exists cell imbalance in the battery pack. This means that cells can start with the same $z(0)$, same capacity Q, and may receive the same net current $i_{\text{net}}(t)$, but because of different efficiencyη, cell SOCs diverge during charging leading to cell imbalance. Despite the coulombic charge-discharge efficiency of LIBs being close to 100%, this value changes when the battery pack is constructed as the cells are incorporated into it, due to the energy that is consumed by the BMS, and the cell balancing circuits [74], [75]. The impedance degrades as a function of cycle number when battery ages [69], [82]. In a battery pack, the individual cell impedance characteristics vary by cell compounds, differences in initial charge capacity, power losses, and differences in cell voltage due to external temperature effects [83]. Impedance can be approximated by an aggregated internal resistance, which is estimated as the ratio of the observed voltage drop and the applied load current. It is understood that as the battery degrades the internal resistance of the battery increases, and hence an estimate of this internal resistance can be used as a proxy for battery SOH [84]. The cells in the same battery stack show different electrical characteristics such as impedance and aging behavior.

The cell capacity variance becomes more and more significant over a lifetime due to internal factors (such as capacity degradation, and impedance increase) and external factors (such as operating conditions and temperature). Degradation in energy efficiency is accompanied by an increase in operating temperature which yields to an increase in cell internal impedance, where the electrolyte degrades or occurs a breakdown in the structure of the electrolyte. The cell impedance could be related to not only the electrical responses of electrochemical origins but also the Ohmic contact at each node in the circuit [19]. This cell imbalance results in two major problems: first of all, it reduces the effective discharge time. In fact, the BMS cuts off the whole battery once the first cell reaches the minimal voltage limitation even though other cells are still usable [85]. Therefore a portion of energy remains unusable in the battery pack, which is called residual energy E_{res}. At the same time, due to the voltage difference of the cells that are connected in series, the weaker cells may become undercharged or overcharged, which can lead to failure of the battery and/or reduce the battery lifetime.

Although Coulomb counting is simple and easy to implement, measurement and calculation errors may be accumulated by the integration function, thus reducing the accuracy of estimation making even the SOC estimation obtained by this technique is highly dependent on the quality of input initial conditions [86]. Coulomb counting is a relatively simple online SOH estimation method, which integrates the amount of charge flowing in and out of the battery pack. However, it does not consider the temperature effects and the self-discharge current of the battery pack and therefore does not provide accurate results.

On the other hand, electrochemical impedance spectroscopy techniques that directly measure the battery internal impedance are more accurate [65]. However, due to their requirement of high accuracy measurements and complex signal processing tasks, they are typically performed offline in a laboratory. During the estimation of battery SOH, both battery capacity fade and increase in impedance have to be taken into consideration. The battery impedance can be increased by dominant aging mechanisms on anodes are caused by Solid Electrolyte Interface (SEI) formation. This effect occurs mainly at the beginning of cycle life. Secondly, when the loss of lithium in the active carbon takes place, it leads to self-discharge and capacity fades. Also, lithium metal plating contributes to accelerated aging causing capacity fade and power fade. The lithium metal plating may occur when the batteries are charged at low temperatures (<0 °C) and/or at high current charge rates, whereby, the process of lithium-ion through the negative electrode decreases and typical metal oxide parts take place on the surface of the electrode [87]. Lithium plating results in less active material and thus the battery capacity decreases and the battery impedance increases as a consequence.

3) TOTAL CAPACITY DIFFERENCES

The battery cell capacity depends upon a good number of factors which includes: average cell discharge current, discharge time, internal cell temperature, value of end-of-discharge (EOD) voltage, self-discharge, and aging [88]. The power requirements for the BMS are a function of the capacity differences between cells and the average power drawn from the battery, whereby manufacturers typically, guarantee a maximum capacity difference of $\pm 5\%$ [89], and major discrepancies are common in cells connected in series [42], [89]. The battery pack imbalance can be caused by cells in the pack having different net current from each other. That is

$$i_{net}(t) = i_{app}(t) + i_{self-discharge}(t) + i_{leakage}(t) \quad (14)$$

need to be taken into account seriously, where $i_{app}(t)$ is the battery pack load current, $i_{self-discharge}(t)$ is the rate of cell self-discharge, and $i_{leakage}(t)$ is the current that powers attached BMS electronic circuitry. Whenever the self-discharge rates of different cells are different, different $i_{net}(t)$ is observed. When the leakage current is different for deferent cells, it also leads to different $i_{net}(t)$. All this means that when cells draw different net current, they become imbalanced [90], [91]. Unlike the series-connected cells, the current differences among the cells with the parallel combination are caused by the mismatch of the cell internal resistance. The unmatched internal resistance among the parallel-connected cells causes imbalanced discharging and aging performances. Generally, the current in each parallel-cell branch is not all monitored in the EV battery management systems [92]. Pre-assessments of imbalanced discharging and aging performances due to temperature differences among the cells are essential in the battery assembly and design of thermal management systems.

C. TYPES EFFECTS OF BATTERY CELL IMBALANCE ON PERFORMANCE

The battery cell imbalance affects the performance of the battery cells and in return, the final performance of the electric vehicles is affected greatly. The battery pack performance is affected in the following ways.

1) REDUCED CAPACITY DUE TO EARLY CHARGE TERMINATION AND OVER-DISCHARGE

The LIBs capacity can reduce due to early discharge termination, over-discharge, or even aging. This causes the consumption of active lithium accompanied by an increase in impedance and long periods of operation [93]. An imbalanced battery system can cause its cell voltages to drift apart over time and can cause over-voltage exposure (which leads to premature cells degradation), safety hazards (explosion), early charge termination and early discharge termination, which lead to capacity reduction [48], [67], [22]. Therefore this early charge termination due to safety functions against overloading may also have negative effects on the available cell capacity. The safety functions abort charging as soon as one cell reaches its over-voltage threshold [94]. The safety issues can be prevented by additional safeguards present in the BMS circuitry such as the cell overvoltage control system [91]. The charging battery with serially connected cells will be terminated if one of the cells voltages exceeds the required cell overvoltage threshold (4.35 V default). This termination of charging at this parameter means the pack will be severely undercharged, and despite the prevention of the safety hazard, the useful life of the pack is reduced. According to [95], over-discharge also causes reduced cell capacity due to irreversible chemical reactions and can cause an explosion [96].

However, LIBs have some form of limited over-discharge tolerance [23], but still, the BMS needs to monitor and control the battery based on the safety circuitry incorporated within the battery packs [41]. Whenever any abnormal conditions, such as over-voltage or overheating, are detected, the BMS should notify the user and execute the preset correction procedure. In addition to these functions, the BMS also monitors the system temperature to provide a better power consumption scheme and communicates with individual components and operators. This factor makes cell balancing one of the most critical issues related to the cycle life of a battery pack. Successful balancing can significantly increase the battery's useful cycle of life.

2) EARLY DISCHARGE TERMINATION

The BMS will terminate discharge to prevent over-discharge of cell and any resulting damage if any of the cells reached low voltage threshold [47], [48], [94], but this leads to capacity reduction. The cell-based termination voltage is usually set to the lower value than the pack-based threshold divided by the number of serial cells so that the difference can allow for a small imbalance. For LIBs it varies from 2.7 V to 2.2 V depending on the typical discharge rate. During the end of discharge phase the low cell is bypassed in order to increase the battery's useful discharge time [92], but to be effective it requires high C-rate capable bypass capability which is expensive to implement [97]. For more effective hardware utilization it is important to gradually remove any existing SOC imbalance during the entire charge/discharge period and not only when it results in acute voltage differences at the end of discharge.

3) PREMATURE CELLS DEGRADATION THROUGH EXPOSURE TO OVERCHARGE

In both cases of SOC or total capacity imbalance, the cell with higher resulting SOC is exposed to higher voltages. According to [98], the battery cells are exposed to degradation due to increased temperatures and other operating conditions and environment [99], as well as affecting aging. If one cell has less capacity than the other three serially connected cells in the pack, and if they all started in the same state of charge, then definitely that will lead to imbalance [100]. The CC/CV (constant current/constant voltage) charging will bring the pack to $4.2 \times 4 = 16.8$ V, but the individual cell voltages will not be equal.

The low capacity cell will have a much higher voltage than the remaining cells, while the normal capacity cells will have a lower voltage than what is achieved in normal charging. If the lower cell has a total capacity deficiency above 10%, its cell voltage will begin to rise into a dangerous area above 4.3 V which will result in additional degradation of this cell or even become a safety concern. To make the matters worse, the effects of cell degradation caused by imbalance is auto-accelerating, meaning that once a cell has a lower capacity it is exposed to increasingly higher voltage during charge which makes it degrade faster so its capacity becomes even less, which closes the runaway circle.

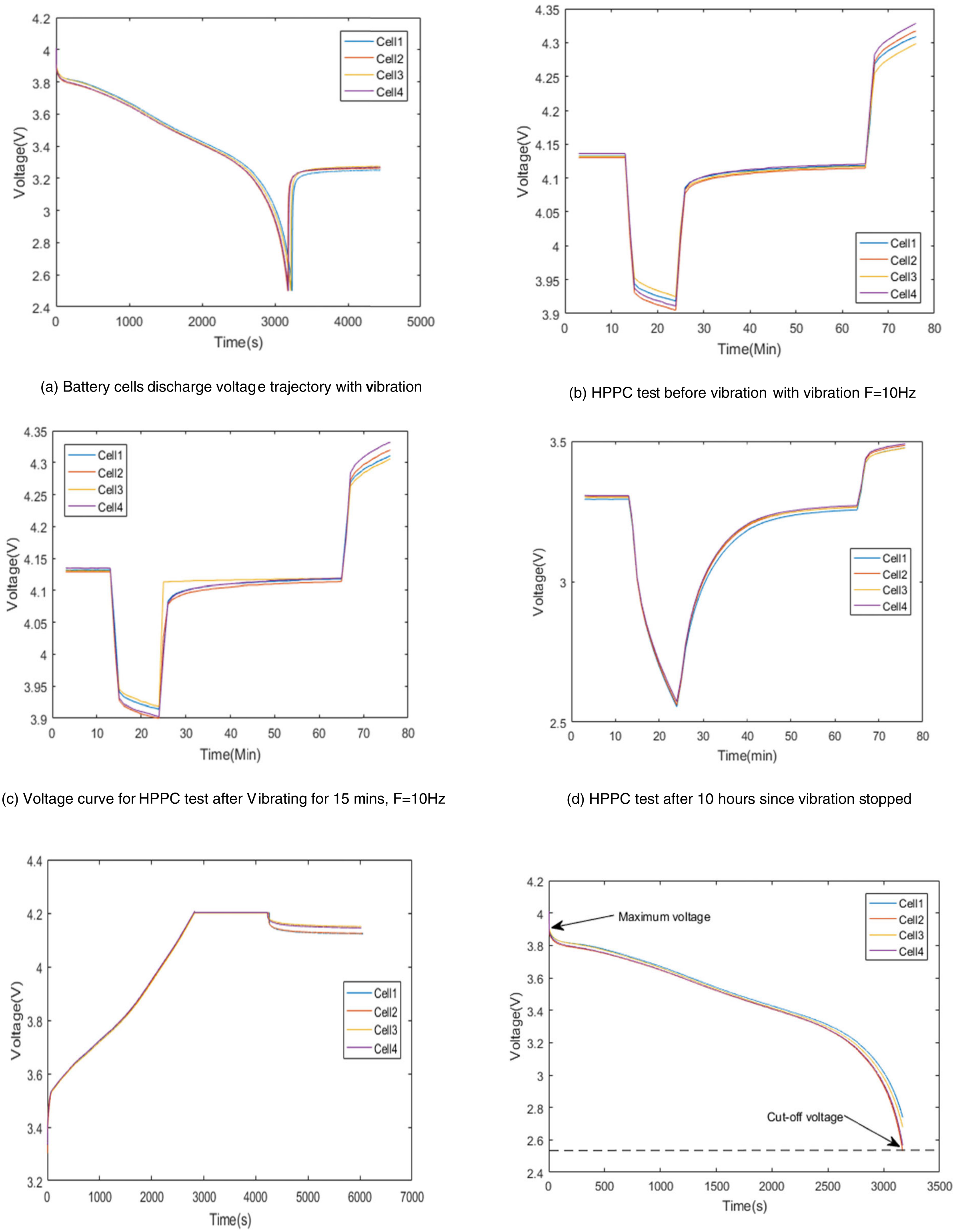
To ensure that there is uniform battery cell life, it is important to utilize each cell so that the SOC and the depth-of-discharge (DOD), remains balanced in all cells in the battery pack [58]. Even in the case that only a few cells in the battery pack that is overheated or overcharged, lifetime shortening of the battery pack may occur due to the reactions of LIBs components with electrolyte, and with each other. This means that the DOD, cell temperature should be controlled well as they are the main determinants of battery degradation. Battery degradation will lead to various uncertainties which will further affect the overall battery life.

According to [3], these uncertainties include non-linear aging, cell spreading, and exceeding critical limits. The non-linear aging leads to high uncertainty in the lifetime prediction and modeling of the LIBs and is very difficult to estimate when the turnaround and accelerated aging occurs. On the other hand, with cell spreading the cell capacities and internal resistance vary within the battery management system. This cell spreading is caused mainly by load inhomogeneity, production inhomogeneity, and battery system design (cooling system, isolation, mechanical tension, and electrical contact resistances). Finally, the critical limits can be exceeded whereby the operating parameter limits are exceeded and the consequences like dendrite growth because of the deep discharge in combination with the low temperatures. Therefore monitoring and prognosis of cell degradation in lithium-ion (Li-ion) batteries are essential for assuring the reliability and safety of electric and hybrid vehicles [77].

4) SAFETY HAZARDS FROM OVERCHARGED CELLS

LIBs have very high electric energy that is concentrated in small volumes; thus [48] states that battery equalization systems are necessary as cell imbalance can lead to poor performance and safety hazards [29]. While the possibility of their release through short-circuiting can be prevented by appropriate mechanical protections, the co-existence of highly reactive chemicals in close proximity makes this battery inherently dangerous. If the batteries are overheated and overcharged, the active components react with electrolyte and with each other which may ultimately cause an explosion and or fire [47]. If the maximum voltage is exceeded it will lead to decomposition of the cathode, which will produce high amounts of heat, as well as the deposition of metallic lithium in the surface of the anode which will increase short-circuiting risk [101]. If the voltages are extremely high, it can easily lead to decomposition of the electrolyte which is very dangerous.

The thermal run-way can be caused merely by overcharging a single cell to voltages above 4.35 V. If one cell is compromised other cells of the pack will also join the explosive chain reaction. Because of all these, cell balancing becomes handy in preventing any cells from reaching the dangerous voltage territory, since the safety protection circuit will terminate the charge if this still happens. The Li-ion battery cell is sensitive to overcharge and over-discharge which may also originate from inconsistency. Therefore, improving the consistency of the battery pack is very important and essential [102], as any form of negligence will result in an explosion.



(a) Battery cells discharge voltage trajectory with vibration

(b) HPPC test before vibration with vibration F=10Hz

(c) Voltage curve for HPPC test after Vibrating for 15 mins, F=10Hz

(d) HPPC test after 10 hours since vibration stopped

(e) Charge after vibration, f=30Hz

(f) Battery discharge trajectories with vibration F=30Hz

FIGURE 10. (a)–(f) Experimental results for battery pack health analysis at different states.

Thus the optimal equalization result is required to make the capacity of the battery pack equal to that of the cell with the minimum capacity [103]. This means that while the battery packs are cycling, this cell can be both discharged fully and charged fully, and would not be overcharged or over-discharged to ensure LIBs safety.

D. IMPORTANCE OF CELL BALANCING

Cell imbalance in battery systems is an important matter in the system life of the battery because, without the balancing system, the individual cell voltages will drift apart over time [64], [42], [104], [105], which will result to low efficiency and even hazards. There are various benefits of cell balancing namely:

- EVs range extension and increase in energy [42], [106], [89].
- To achieve LIBs cell-to-cell (C2C) voltage balance or minimized C2C SOC mismatch [63], [30].
- To account for variations in capacitance and leakage current [107], [108]. Initial charge and voltage are dependent on capacitance. Sustained voltage is dependent on leakage current.
- Battery life extension [38], [109]–[111].
- To minimize the effects of cell aging which results from lost capacity [112]–[114].
- To reduces voltage stress [45], [63] on an individual cell.
- To increase the overall reliability and safety of the individual cells [24], [105], [115], [116].

According to [19], cell balancing can aid in battery management, maintenance, and repair. Therefore, the process of cell balancing is inevitable as the results obtained are far much better than they outdo the costs that can be incurred by equalizing the battery cells. However, this process may sometimes lead to losses, whereby when a part of the battery pack is faulty, the whole battery pack can be replaced with a new one, resulting in higher costs.

IV. EXPERIMENTAL RESULTS FOR BATTERY PACK HEALTH ANALYSIS

The performance of LIB cells considered in this review is of the Panasonic 18650 battery cells, and the data was obtained from the National Center for Materials Service Safety (NCMS). The LIBs cell's test profile that incorporates both discharge and regen pulses is conducted through the Hybrid Pulse Power Characterization (HPPC) test to determine the dynamic power capability of the battery cell's usable voltage range. The results are based on the battery testing system (Neware BTS 4000) HPPC test. The following Fig. 10 and 11 in this section illustrate the concept that cells in the battery pack have dissimilarities that causes them to have variations of charge when they are subjected to various parameter changes, hence requires proper cell balancing.

When the battery cells are charging or discharging with or without vibration it is observed that the cells arrive their maximum cut-off voltage at different time. Equally, they arrive at their EOD at different intervals. When the batteries are subjected to vibration test, they yield similar results like when they are not under vibration, but with some negligible variances. For the case of (b) HPPC results before f = 10Hz, and

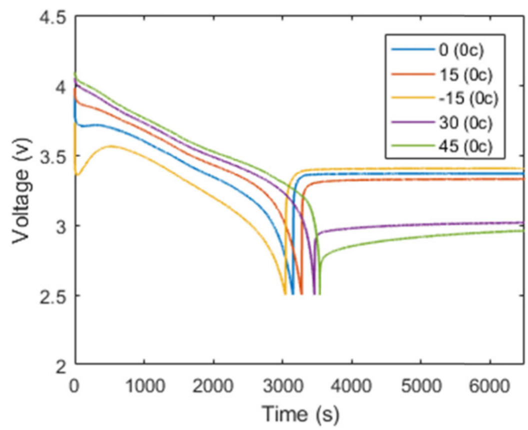


FIGURE 11. Cell voltage trajectory at different temperatures.

(d) results after 10hours since vibration stopped, the small variance is recorded, which is higher in f = 10Hz. Which means that vibration has an effect on the charging or discharging of the battery.

When the battery cells are discharging as seen in (a) or recharging as shown in they start to (e) they exhibit some slight change when they hit their cut-off voltage or EOD, which means that they undergo self-discharge/charge which occurs due to some cell chemistries. The various results of the effect of vibrations on the battery cell charge/discharge are shown in Fig. 10 (a) to (g). The performance of 18650 LIB cells is easily affected by the vibration profiles which are a representative of the typical life of the system. In Ref. [117], mechanical stress induced by vibration like the case of EV crash, is a major concern of LIBs safety in EVs response to such stress. According to the literature [18], the EVs are faced with road-induced vibrations which affect both the system's electrical performance and mechanical properties, as cell consistency deteriorates with vibration stress [8], [118]. For these reasons, various control mechanisms should be employed to eliminate noise and harshness, as well as create an equitable driving environment for EVs. Consequently, both the free and forced vibrations should be analyzed in response to prescribed disturbances, and thus employing the best control mechanisms to control any undesirable vibration levels that may arrive in the EVs driving. At the same time research should be conducted to apply the vibrational energy harvesters (VEHs) as a power source to EVs to improve efficiency and performance of EV batteries [119].

The similar results are observed when the battery cells are subjected to temperature variation either low, normal, or high, as shown in Fig. 11.

From Fig. 11, shows the results of one battery cell voltage charged and discharged at different temperatures. As shown in the Fig., if the temperature rises high, it makes the battery cell to take longer time in discharging due overheating, and when it is charging it does not reach its optimum charge value. The vice versa is true for low temperatures. If the subject temperature is very high it affects the battery life, consequently, if the temperature is too low they accelerate battery aging [2], [3], [120]. Therefore, these two parameters must be observed during battery balancing to increase battery life.

V. CONCLUSION

The battery cell balancing process is a key issue in the electric vehicular industry as it enhances the performance of the battery pack while increasing its life-cycle, reduced maintenance, and ensuring safe operation at all times. Many types of battery balancing schemes have been reviewed to underscore the types of battery imbalance, and its effect on battery performance. In nutshell the battery balancing process if properly implemented will aid in ensuring that the individual cell voltages don't drift apart over time. At the same time for the case of passive balancing, the highly charged cells can be offered more rest time as the lower charged cells attain uniform charge, and also during discharging, the lower charged cells are offered more rest time as the highly charged cells are brought down to the same charge level. Therefore the more the resting periods for highly charged and lowly charged cells the estimation of the battery SOCs improves. As the battery SOC improves, the balancing is equally fast and easy to achieve with minimal risk. From the battery experimental results analysis, it is seen that the battery balancing is very essential as there are many deviations within the battery cells parameters. Hence this requires to be monitored appropriately by the BMS and the balancing process to take place concurrently as the batteries charged, or discharged.

CONFLICT OF INTEREST

The Authors declares that there is no conflict of interest regarding the publication of this paper.

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ZACHARY BOSIRE OMARIBA was born in Kisii North, Kenya, in 1982. He received the B.S. degree in computer science from Karnatak University, Dharwad, India, in 2004, and the M.S degree in computer science from Periyar University, Salem, India, in 2006. He is currently pursuing the Ph.D. degree in materials science and engineering with the National Center for Materials Service Safety (NCMS), University of Science and Technology Beijing (USTB), China.

From 2007 to 2008, he was a Lecturer with the Information Technology Department, KCA University, Kisumu Campus. From 2008 to 2010, he was a Lecturer with the Computer Science Department, Kabarak University. Since 2010, he has been a Lecturer with the Computer Science Department, Egerton University. His research interests include big data analytics, the IoT, and prognostics, and health management (PHM) of lithium-ion batteries.

LIJUN ZHANG was born in Beipiao, Liaoning, China, in 1978. He received the B.S., M.S., and Ph.D. degrees in mechanical engineering from the University of Science and Technology Beijing (USTB), China, where he is also a Professor with the National Center for Materials Service Safety. He is the also Deputy-Secretary General of the Field Committee of Material Service Safety, Chinese Society for Testing and Materials (CSTM), the Committee Member of the Equipment and Maintenance Engineering Subcommittee, the Chinese Mechanical Engineering Society (CMES), of the Fault Diagnosis Committee, the Chinese Society for Vibration Engineering (CSVE).

He mainly engaged in research work on material damage identification, reliability design and risk assessment, big data analysis, and artificial intelligence. He has been responsible for one National Natural Science Foundation project, one national Research and Development sub-project, and five provincial and ministerial-level scientific research projects. In the past five years, he has published nearly twenty SCI/EI articles, published two monographs, and applied for four patents.

DONGBAI SUN was born in Changsha, Hunan, in 1959. He received the bachelor's degree from the Department of Chemical Engineering, Hunan University, in 1982, and the master's and Ph.D. degrees from the University of Science and Technology Beijing (USTB). He was with the Wuhan Research Institute of Materials Protection, Ministry of Machine-Building Industry, from 1982 to 1986. From 1986 to 1992, he studied in the Department of Surface Science and Corrosion Engineering, USTB, where he was from 1992 to 2017, successively as a Lecturer, an Associate Professor, and a Professor. In July 2017, he became an Executive Vice President of Sun Yat-sen University.

He current research interests include corrosion and protection of engineering materials, service performance evaluation, and forecasting for engineering materials, application of synchrotron radiation and neutron scattering in materials, hypersonic environment simulation and materials performance evaluation, electrochemical engineering, and the preparation of non-crystal and nano (crystal) materials.