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Battery Management using Secondary Loads: A Novel Integrated Approach ⋆

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Abstract: Large lithium-ion battery systems for electric vehicle and stationary storage applications use from tens to hundreds of series-connected cells. In this paper we present an advanced integrated management structure and method that uses intelligent switching to balance series-connected cells. Our analysis shows that using this approach can increase the useful system capacity by upwards of 7% compared to conventional active or passive balancing systems by fully utilising cells with different capacities. The battery system efficiency in an electric vehicle has also been shown to increase by up to 3% compared to conventional systems. Further advantages of integrated balancing include simultaneous integration of both primary and secondary power loads or sources, as well as robustness to individual cell failure. This indicates significant potential for implementation in future lithium-ion battery packs.

Keywords: Lithium-ion (Li-ion) batteries, electric vehicles, battery management, cell balancing.

1. INTRODUCTION

If charged using renewable energy generation, electric vehicles can significantly reduce the emissions caused by personal transportation. Over the past decade, electric vehicles have evolved notably and are now widely available for purchase by the general public. To store the energy required for driving extended distances, electric vehicles rely on battery packs with tens of kilowatt-hours of storage capacity. Due to their relatively high energy storage per unit volume and weight, high technological maturity and moderate cost, lithium-ion (Li-ion) is presently the chemistry of choice for electric vehicle batteries and likely to remain so for some years to come.

1.1 Battery System Configuration

Li-ion cells are chemically limited to an output voltage of between two and four volts depending on the chemistry and state of charge. However, to minimise the transmission losses between the battery pack and the power electronics that supply current to the motor, a much higher battery system voltage is required. This higher voltage is achieved by connecting a number of cells in series. Most presently available electric vehicles connect between 80 and 110 cells in series, leading to a rated battery system voltage between 300 and 400V. Depending on the size of cells available and the maximum power output and driving range required, two or more cells may also be connected in parallel blocks that are subsequently connected into the series arrangement discussed above.

While parallel connected cells automatically balance their output voltage, series connected cells do not. In an ideal system where cells are exactly alike in terms of capacity as well as state of charge at assembly, and experience exactly the same operating conditions, the sharing of currents between series connected cells means that the state of charge of all cells will remain uniform throughout their life. In practice, both certain manufacturing variability and differences in operating conditions of cells, such as the temperature, are inevitable. Series-connected cells (or blocks of parallel cells) therefore begin their life with some variations in the state of charge and if left unmanaged this difference tends to increase. Increased differences in state of charge can reduce the utilisable capacity, accelerate ageing and, if managed badly, create unsafe operating conditions for individual cells (Hung et al. [1993]).

1.2 Passive and Active Balancing

To minimise the differences in state of charge between series-connected cells so-called balancing systems are employed. Balancing systems work by drawing energy from highly charged cells and/or supplying energy to less charged cells. The simplest method, which to date remains the dominant method in industry, is passive balancing. Cells are balanced by connecting a resistor in parallel with highly charged cells to dissipate surplus energy as heat. While passive balancing has a low complexity and component cost, it is doubly inefficient as it not only wastes energy as heat, the cooling system may also require additional energy when removing this extra heat away from the battery system.

Much research in recent years has therefore been focussed on developing more efficient active balancing systems

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(Cao et al. [2008]). These systems, variations of which have recently been made available for purchase by major automotive suppliers, actively transfer energy from higher to lower charged cells using energy storage or conversion elements such as capacitors, inductors, transformers and dc-dc converters.

While active balancing systems reduce resistive losses associated with passive balancing, several issues remain. Firstly, storage and conversion elements always have a certain loss associated with them, limiting the maximum system efficiency. Secondly, cells that experience significant heating cannot be disconnected without disabling the complete battery system. And thirdly, since the balancing currents are usually notably smaller than the total currents through the cells, different capacity cells can only be utilised to a limited extent (Einhorn et al. [2011]).

1.3 Switched Balancing

One approach that has the potential to alleviate several shortfalls of active balancing is cell redundancy-based balancing, which we will refer to as switched balancing. Manenti et al. [2011] showed that placing a larger number of cells into strings than are required to support the output as well as inserting switches in series and parallel with each cell enables individual cells can be disconnected from the output and bypassed.

The advantages of this approach over active and passive balancing are that individual cells can be disconnected if required. Balancing is achieved by using the highest charged cells at a given instant to power an output load, or alternatively connecting the least charged cells to a power supply. This approach also means that to a large extent, cells with notably different capacities can be used within a single string.

2. INTEGRATED SYSTEM OVERVIEW AND FUNCTIONALITY

The approach presented in this paper uses the idea of switching but in a notably more integrated approach. The primary idea is to use switches in series and in parallel to each cell, as well as a number of additional switches, to enable cells to be connected to either a primary side, secondary side or be disconnected.

Figure 1 shows the circuit layout of a 5-cell pack using the proposed integrated system. Each switching block contains a single battery cell or interchangeably a number

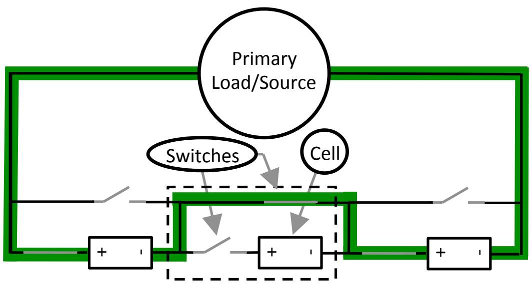

Fig. 2. Example operating state of 3-cell switched system proposed by Manenti et al. [2011]. Single switching block is indicated.

of parallel-connected cells, as well as seven switches. Of the seven switches, four (S1-S4) are principally used to carry the primary current and three (S5-S7) to carry the secondary current. However, there is an exception for S1 as discussed subsequently. Note that depending on the application either side could act either as a load that discharges cells or as a supply of energy that charges cells.

2.1 Switching Methodology

Which switches are closed and which are open depends on two factors: the state (cell connected to the primary side, the secondary side or disconnected) of a switching block itself, and the state of the subsequent block in the positive direction (in Figure 1, the block directly to the left).

Case 1: Given the primary load usually supplies/consumes the bulk of power, the most common case is for both the block and the subsequent block to be connected to the primary side. In this case the only switches conducting current are S1, which carries the main current, and S5, which carries the secondary current. This can be seen for the second and third cell from the right in Figure 1.

Case 2: If a block's cell is connected to the primary side and the subsequent cell to the secondary side, then only S3, S5 and S7 are closed (see the third and fourth cell from the right in the circuit diagram).

Case 3: Conversely, if a block's cell is connected to the secondary side and the subsequent cell to the primary side (i.e. the first and second cells from the right), then only S2, S4 and S6 are closed.

Case 4: In the rare case that both cells are connected to the secondary side, either S2, S6 and S7 are closed, or closing S1 can replace S6 and S7 by carrying the secondary current.

Case 5: If a block's cell is to be disconnected, S2 and S5 must be closed. Also either S4 or S7 or neither of the two would be closed, depending on whether the subsequent cell is connected to the primary side, secondary side or is also disconnected, respectively.

By choosing the number of series-connected cells attached to each side at any given time, the output voltage can be controlled to certain cell-voltage increments. In an EV battery system, for example, this can be used to directly supply both a high voltage for the power electronics that drive the motor, as well as a low voltage (12V) for headlights, the heating and air conditioning system, and other electrical and electronic devices. Thereby both the traditional 12V lead-acid battery and the dc-dc converter, which are required in today's electric vehicles and add cost, volume and weight, become redundant. A second application could be a domestic or industrial multiple-kilovolt stationary battery storage system, which can power a high-voltage load on the primary side and simultaneously accept low voltage solar electricity on the secondary side.

2.2 Evaluation of Cell Utilisation

In standard passive or active balancing systems that balance only during charging, a string of cells is limited by the cell with the smallest capacity and the capacity

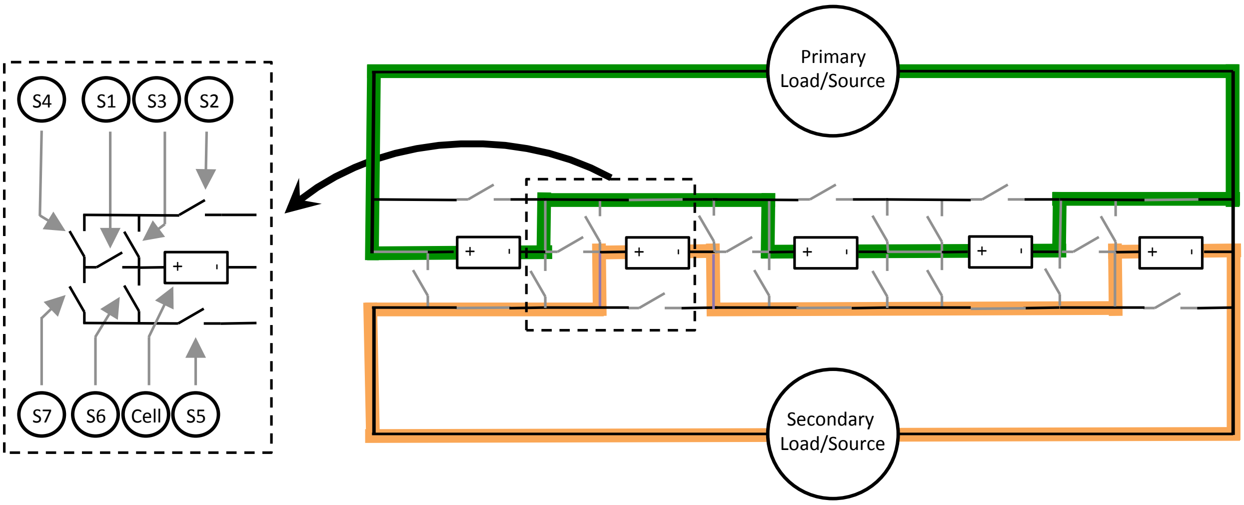

Fig. 1. Proposed integrated system. Single switching block (left) and example operating state of 5-cell system (right).

surplus of all other cells is not utilised. In advanced active systems that also balance during discharge, the utilisation is limited by the balancing currents allowed, which are usually from tens to hundreds of milliamperes. For electric vehicle systems with average discharge currents of tens of amperes, these balancing currents limit utilisation of cell capacity surplus to only 0.1-1% more than the smallest cell capacity. However, research has shown that even in mass-produced Li-ion cells, cell-to-cell capacity deviations of 1% at the beginning of life can grow to around 10% of the capacity at 1000 cycles and as much as 40% at 1500 cycles (Baumhoefer et al. [2014]). As a result, the potential gain of using advanced active balancing for increasing utilisation of different capacity cells is somewhat limited.

Conversely, the integrated balancing system proposed in this paper offers full utilisation of cell capacities under certain conditions. The conditions are found by evaluating the discharge duration for the highest capacity cell when permanently connected to the primary side. This duration needs to be shorter than the durations of discharge for each of the remaining cells, taking into account how long cells can be connected to the lower power secondary side or disconnected entirely. By rewriting the resulting analytic expression, it is found that complete utilisation of energy in all series-connected cells is possible if:

$$\frac{C_{max} - C_{av}}{C_{max}} \leq \frac{\alpha}{n-1} + \frac{\beta}{n-1}\left(1 - \frac{I_2}{I_1}\right) \tag{1}$$

where C_{max} and C_{av} are the charge capacities of the highest capacity cell and the average capacity of all other cells, respectively; α is the number of cells that can be disconnected from both the primary and secondary side simultaneously; β is the number of cells that are required by the secondary side simultaneously; n is the number of series-connected cells; and I_1 and I_2 are the average currents on the primary and secondary side, respectively.

To illustrate this on a practical example, assume a standard electric vehicle battery system with 100 cells in series of which four are used to provide a secondary voltage of 12 to 16V. Assume further that the system has seem some usage and has an 8% difference between the maximum and average cell capacity, and that the secondary current is half the level of the primary current. Based on these assumptions, Equation 1 finds that a redundancy factor α of only four blocks of cells is required to achieve full cell utilisation. Note that the cell redundancy factor has no impact on the energy storage capability and affects only the maximum instantaneous battery system power output which in fully electric vehicles is rarely if ever constrained. Therefore, in an electric vehicle battery system case as outlined above, the cell utilisation alone allows integrated balancing to unlock 7% or more additional range compared to standard active or passive balancing systems.

3. TECHNICAL FEASIBILITY

The main feasibility concern is whether switches are able to meet the required specifications of high voltage, high current capacity and low on-resistance. These requirements depend strongly on the number of cells in the system and the instantaneous power output of the system.

To simplify our analysis, for now we will evaluate only the losses over S1 switches. This should cover the majority of losses since at any given time the primary side usually has the highest currents, most cells are connected to the primary side and in primary-connected blocks S1 switches are the only ones to carry the primary current and therefore incur the most notable losses.

3.1 Output Current

The output current is the fundamental link between the power supplied by the battery system, the power output to the motor controller and the resistive loss in the switches. We can find this by evaluating the fundamental relationships between the primary output, battery and the switch resistance:

$$P_{out} = V_{out} \times I_{out} \tag{2}$$

$$V_{out} = V_{battery} - V_{res} \tag{3}$$

$$V_{res} = I_{out} \times R \tag{4}$$

where R is the cumulative resistance of S1 switches in the system.

Substitution of Equations 3 and 4 into Equation 2 gives:

$$P_{out} = (V_{battery} - I_{out} \times R) \times I_{out} \tag{5}$$

Solving this gives the output current as:

$$I_{out} = \frac{V_{battery} \pm \sqrt{V_{battery}^2 - 4RP_{out}}}{2R} \tag{6}$$

This suggests that a real solution of the system is only possible if:

$$R \leq \frac{V_{battery}^2}{4P_{out}}. \tag{7}$$

Physically this means that there is an upper limit on the total resistance the switches can have if the given output power P_{out} is to be achieved. For any resistance satisfying Equation 7, there are two solutions as given by Equation 6. In case 1 ($\pm = +$) the output current is high, leading to the majority of the energy output from the batteries being dissipated in the switches. In case 2 ($\pm = -$), the current is low and therefore the majority of the energy provided by the batteries is used to power the motor. Obviously the latter case is preferable for running the system, which is why the control system would ensure this operating condition.

We can therefore assume the following formula for the output current:

$$I_{out} = \frac{V_{battery} - \sqrt{V_{battery}^2 - 4RP_{out}}}{2R} \tag{8}$$

Analysis of this Equation 6 also finds that at the boundary case between the two solutions exactly half of the power supplied by the batteries is dissipated as resistive losses in the switches and the other half runs the motor.

3.2 System Efficiency

Having found the output current we can now define and calculate the system efficiency

$$\eta = \frac{P_{out}}{P_{battery}} \tag{9}$$

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \tag{10}$$

As we are assuming that the only losses are those due to the switch resistances, this is equal to

$$\eta = \frac{1}{1 + \frac{I_{out}^2 R}{P_{out}}} \tag{11}$$

Substituting our current from Equation 8 gives our final efficiency formula:

$$\eta = \frac{1}{1 + \frac{(V_{battery} - \sqrt{V_{battery}^2 - 4RP_{out}})^2}{4RP_{out}}} \tag{12}$$

Note that the total on-resistance of the system is linked to the on-resistance of an individual switch R_{sw} as follows:

$$R = \frac{R_{sw} n_s}{n_p} \tag{13}$$

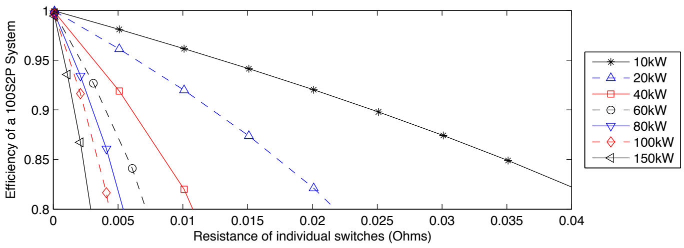

Fig. 3. Efficiency curves for different output power levels

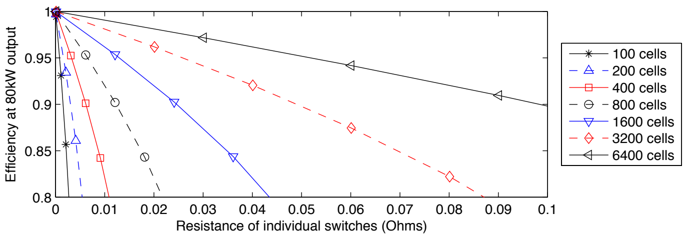

Fig. 4. Efficiency curves for different number of cell blocks

where n_s and n_p are the number of switching blocks connected in series and parallel, respectively. Also, the battery voltage $V_{battery}$ is the product of the average individual cell voltage, which we assume to be 3.7V, and n_s.

3.3 Efficiency Analysis

Figure 4 shows the relationship between the resistance of each individual S1 switch and the efficiency of integrated battery systems calculated from 13. This assumes a power output of 80kW, which is equivalent to the Nissan Leaf's peak output. Interestingly, only the total number of blocks matters, which is the product of n_p and n_s, rather than the exact configuration. It shows clearly that the more blocks are used, the larger each individual switch resistance can be to give the same efficiency. This means that a design, which uses several thousands of cells in its battery systems (such as is currently used by Tesla Motors) could use significantly lower spec switches than a design using less than 100 cells (e.g. the BMW i3).

Figure 3 show the calculated efficiency curves of a 200 block system (e.g. 100 series-connected sets of two parallel connected blocks, or 100S2P) for various output power values as a function of R_{sw}. It is found that a reduction in the output power leads to a substantial increase in efficiency given the same switch resistance. This shows that the proposed integrated systems will be much more efficient when less power is consumed than at peak power events.

3.4 Availability of Suitable Switches

To evaluate whether the proposed system is technically feasible, we need to investigate the state-of-the-art of switching technologies. We will investigate three types of switches: silicon-based semiconductors, wide band-gap semiconductors and electromechanical contactors.

Silicon-based semiconductor switches such as silicon MOSFETs and IGBTs remain the dominant switching technology. Connecting two such devices in series in opposing

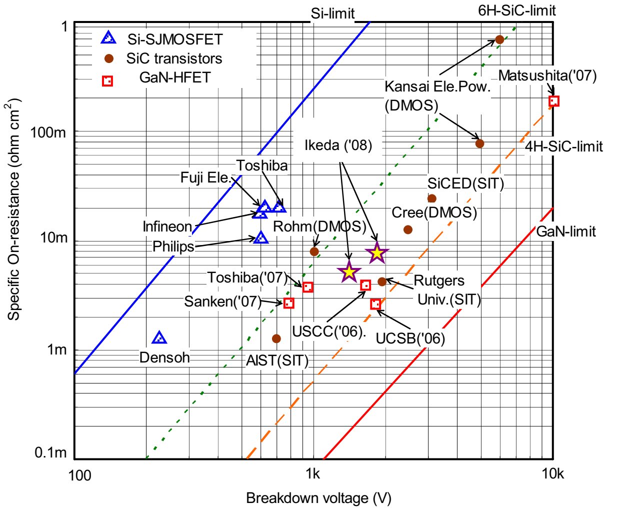

Fig. 5. A comparison between traditional silicon (Si), SiC and GaN (modified from Ikeda et al. [2008])

directions enables bidirectional switch functionality. Being both a mature technology and mass-produced, the cost of these switches is very low. However, silicon switches that are able to operate at the 400+V voltage levels required either have too high an on-resistance or too large a footprint to be feasible for the required application.

A more recent invention are wide band-gap semiconductor devices using materials such as silicon carbide (Si-C) and gallium nitride (GaN). These switches offer a much lower on-resistance per unit contact area for a given breakdown voltage. As shown in Figure 5, the theoretical minimum on-resistances of SiC and GaN materials are approximately 0.002% and 0.0003% of that of traditional silicon for the same contact area and breakdown voltage. From the 100 and 200V GaN devices already commercially available by the Efficient Power Corporation (EPC), 400V devices based on a 2-by-4mm footprint with an on-resistance of around 75mΩ seem technically feasible, which can be further decreased by enlarging the device footprint. Commercially available 400V+ devices with on-resistances in the low tens or high single digit milliohms might therefore be available within a number of years.

The third technology to be discussed here are electromechanical contactors, such as the starter solenoids in cars. These contactors are switches that isolate contacts not through polarising semiconductor layers like the technologies discussed previously, but by physically separating two contacts in a dielectric environment such as air or vacuum. While these switches can have a very low resistance in the order of single milliohms, they have the issue that when opening, their two contacts are initially separated by only a very thing layer of dielectric. If the layer is sufficiently thin and the voltage sufficiently high, the dielectric can break down and arcing occurs, which is damaging to the contractor and can be difficult to extinguish. This limitation may be overcome via intelligent timing of the switching operation. In many applications such as electric vehicles, brief periods frequently occur during which the primary load neither draws power from, nor returns energy to, the battery system. If switching is controlled to occur exactly during these periods, arcing can likely be avoided.

4. PERFORMANCE COMPARISON

To compare the efficiency between passive, active, switched and integrated management systems, we will make the following assumptions:

(1) The capacity of all cells is equal. This is reasonably accurate for battery systems using high quality cells of the same age and usage history.
(2) The maximum self-discharge of cells is $\gamma = 2\%$ of the current throughput and the average is $\delta = 1\%$.
(3) Passive balancing dissipates the energy from all cells to the level of the cell with the highest self-discharge.
(4) Active balancing is $\epsilon = 70\%$ efficient in transferring the energy from higher to lower charged cells.
(5) For integrated balancing, only the loss in the S1 switches is considered.
(6) The dc-dc converter used for all but integrated balancing is $\zeta = 90\%$ efficient and has a throughput of $\theta = 20\%$ of the total power of the system.
(7) Additional cooling consumes $\mu = 20\%$ of any generated heat, including those from active/passive balancing, switches and the dc-dc converter.

Note also that the efficiency are calculated using Equation 10, where P_{loss} for the different systems is as calculated in the following sections, respectively.

4.1 Passive Balancing

In passive balancing, we have three sources of losses: the loss due to balancing, the loss due to the dc-dc converter and the additional cooling required to remove the heat from the first two processes.

$$P_{loss,p} = (1+\mu)(P_{balance} + P_{dc}) \tag{14}$$
$$P_{loss,p} = (1+\mu)(P_{out}(\gamma-\delta) + P_{out}\theta(1-\zeta)) \tag{15}$$

4.2 Active Balancing

For systems using active balancing, the power lost is the same as for passive balancing apart from a decreased loss from balancing power due to the return of the majority of energy to lower charged cells.

$$P_{loss,a} = (1+\mu)(\epsilon P_{balance} + P_{dc}) \tag{16}$$
$$P_{loss,a} = (1+\mu)(\epsilon P_{out}(\gamma-\delta) + P_{out}\theta(1-\zeta)) \tag{17}$$

4.3 Switched Balancing

In switched balancing, the balancing loss is now replaced by the loss in the switches. The current was previously calculated in Equation 8.

$$P_{loss,s} = (1+\mu)(P_{sw} + P_{dc}) \tag{18}$$
$$P_{loss,s} = (1+\mu)(I_{out}^2 R_{total} + P_{out}\theta(1-\zeta)) \tag{19}$$

4.4 Integrated Balancing

Finally, in systems using our proposed integrated balancing, the switching loss is the same as for the switched system, but there is no dc-dc converter loss as the system itself provides the voltage step-down.

$$P_{loss,i} = (1+\mu)P_{sw} \tag{20}$$
$$P_{loss,i} = (1+\mu)I_{out}^2 R_{total} \tag{21}$$

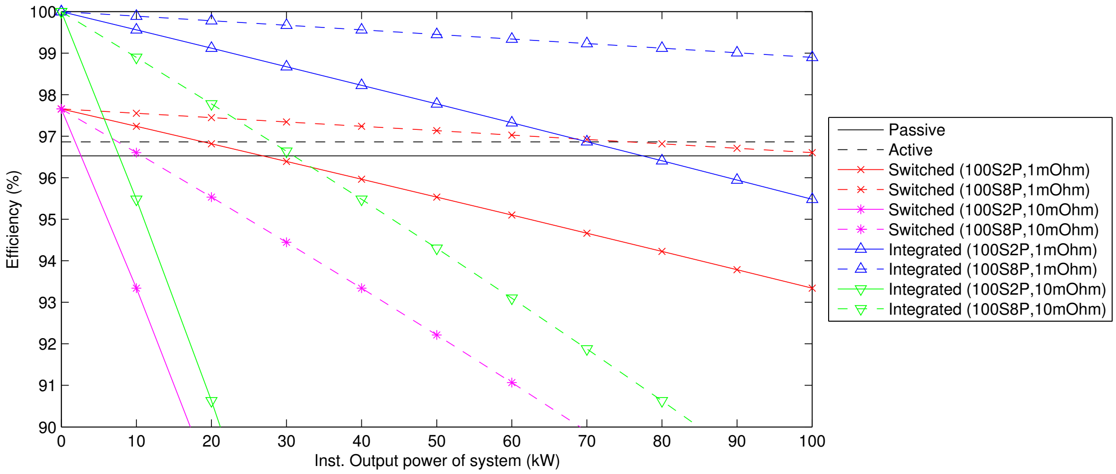

Fig. 6. Comparison of calculated efficiencies of battery systems using passive, active, switched or integrated balancing.

4.5 Results

The results of the comparative efficiency analysis are shown in Figure 6. Under the assumptions made, the efficiency of systems using passive and active balancing are independent of the instantaneous power output with values of around 96.5% and 96.8% respectively. Conversely, the switched and integrated system efficiencies decrease with power output in a way that over the range of power outputs considered is close to linear.

Unsurprisingly, the slopes of the switched and integrated system efficiencies are highly dependent on both the on-resistance of the switches and the total number of cells. For a power output close to zero, the integrated system is close to 100% efficient, whereas the switched system is only around 97.8% efficient due to the power loss in the dc-dc converter, which is magnified by the cooling. Compared to the current industry standard of passive balancing, at 20kW output power, an integrated system with 800 cells and switches with low on-resistances of 1mμ is able to increase efficiency by approximately 3%. An integrated system using the same switches with 200 cells improves efficiency by around 2.5%, whereas an 800-cell system with notably higher switch on-resistances of 10mΩ still offers an efficiency gain of around 1%.

5. CONCLUSION

In this paper we have presented a novel management approach for large lithium-ion battery packs. By intelligently controlling an arrangement made up of seven switches per cell, integrated battery systems allow both primary and secondary power sources or loads to exchange energy with the battery simultaneously. This makes both the dc-dc converter and 12V lead-acid back-up battery, which are required in present electric vehicles, redundant. Our work shows that by using wide band-gap semiconductor switches or intelligently controlled electromechanical contactors, this system is technically feasible. At an instantaneous output power of 20kW, 200-cell battery systems using this method can improve their total efficiency by up to 3% depending on the on-resistance of switches used [1].

Future work will focus on building a small system prototype, developing suitable control methods and experimentally validating the proposed integrated balancing system.

Table 1. Comparison of Further Features of Battery Management Approaches*

	PB	AB	SB	IB
Can use different capacity cells	✘	-	✔	✔
Can disconnect individual cells	✘	✘	✔	✔
Integration of multiple sources/loads	✘	✘	✘	✔

* Passive balancing (PB); active balancing (AB); switched balancing (SB); integrated balancing (IB)

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[1] This system structure and control methodology, as well as some additional features, are the subject of a patent application.