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. Voltage balance between cells is traditionally maintained using passive, resistor-based systems that dissipate surplus energy as heat. In this paper we present an advanced battery management structure and method that uses intelligent switching to balance cells. Our analysis finds that such a system provides advantages in terms of robustness to individual cell failure, flexibility regarding cell capacities and simultaneous integration of both a primary and secondary power load or source. It also can be up to 3% more efficient than the traditional system at an average electric vehicle power output level.

1. INTRODUCTION

If charged using renewable energy generation, electric vehicles have the potential to significantly reduce the emissions caused by personal transportation. Over the past decade, electric vehicles have evolved from individual tinkerers' projects to being mass-produced by major vehicle manufacturers and are now available to 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 currently the chemistry of choice for electric vehicle batteries and expected 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 a number of more efficient active balancing systems (Cao et al. [2008]). These systems, some of which have recently become available from major automotive suppliers, actively transport energy from higher charged cells to lower charged cells using energy storage or conver-

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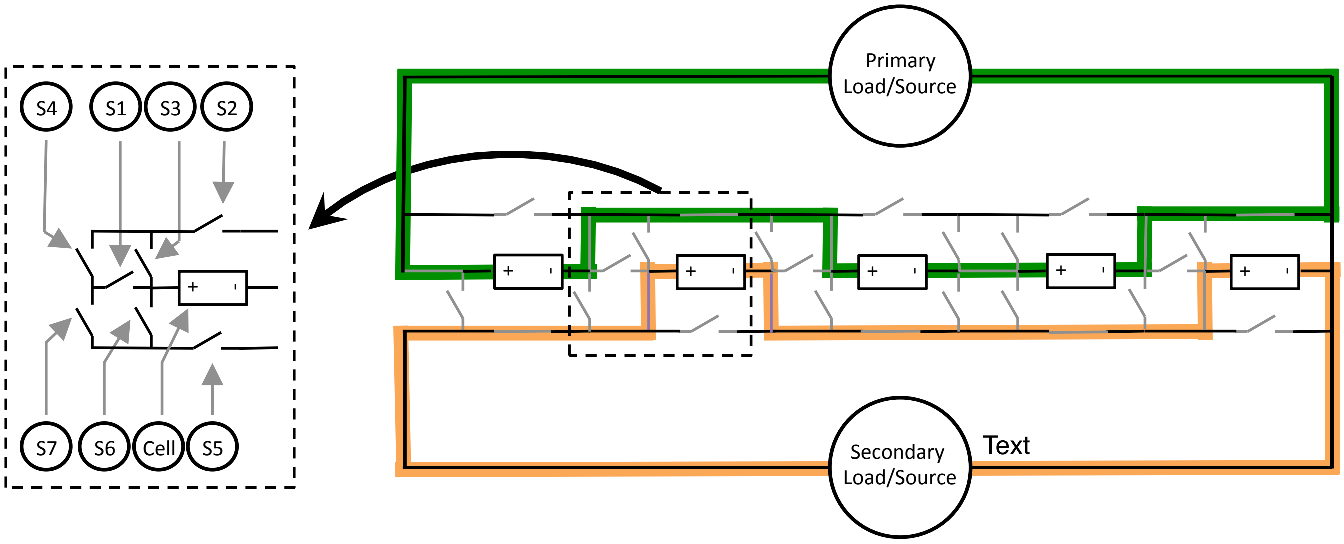

Fig. 1. Proposed integrated system. Single switching block (left) and example operating state of 5-cell system (right).

sion elements such as capacitors, inductors, transformers and dc-dc converters.

While many active balancing systems significantly reduce energy loss compared to 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 then achieved by using the highest charged cells at any given point in time 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.

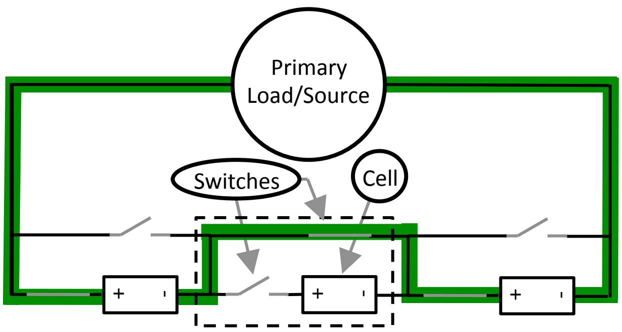

Fig. 2. Example operating state of 3-cell switched system proposed by Manenti et al. [2011]. Single switching block is indicated.

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, as well as a single switching block. Each block contains a single battery cell or interchangeably a number 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.

Which switches are closed and which are open depend 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.

3. TECHNICAL FEASIBILITY

The main concern regarding the feasibility 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:

$$P_{out} = V_{out} \times I_{out} \tag{1}$$

$$V_{out} = V_{battery} - V_{res} \tag{2}$$

$$V_{res} = I_{out} \times R \tag{3}$$

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

Substitution of Equations 2 and 3 into Equation 1 gives:

$$P_{out} = (V_{battery} - I_{out} \times R) \times I_{out} \tag{4}$$

Rewriting this gives:

$$I_{out}^2 R - I_{out} V_{battery} + P_{out} = 0 \tag{5}$$

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:

$$V_{battery}^2 \geq 4RP_{out} \tag{7}$$

and therefore

$$R \leq \frac{V_{battery}^2}{4P_{out}}. \tag{8}$$

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 8, 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:

$$I_{out} = \frac{V_{battery} - \sqrt{V_{battery}^2 - 4RP_{out}}}{2R} \tag{9}$$

At the boundary case between the two solutions, where

$$V_{battery}^2 - 4RP_{out} = 0 \tag{10}$$

the solution becomes:

$$I_{out} = \frac{V_{battery}}{2R} \tag{11}$$

Reordering and multiplying both sides with I_{out} gives:

$$I_{out}^2 R = V_{battery} I_{out} \tag{12}$$

This indicates that at the boundary case between both solutions exactly half of the power being 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

$$\eta = \frac{P_{out}}{P_{battery}} \tag{13}$$

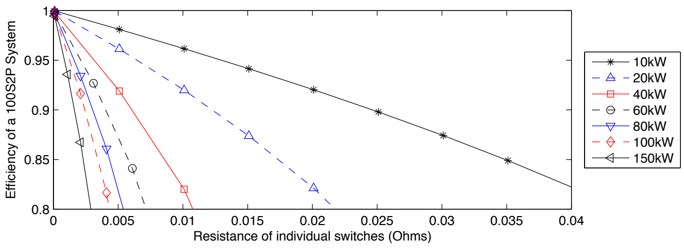

Fig. 3. Efficiency curves for different output power levels

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \quad (14)$$

$$\eta = \frac{1}{1 + \frac{P_{loss}}{P_{out}}} \quad (15)$$

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

$$\eta = \frac{1}{1 + \frac{I_{out}^2 R}{P_{out}}} \quad (16)$$

Substituting our current from Equation 9 gives our final efficiency formula:

$$\eta = \frac{1}{1 + \frac{(V_{battery} - \sqrt{V_{battery}^2 - 4RP_{out}})^2}{4RP_{out}}} \quad (17)$$

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

$$R = \frac{R_{sw} n_s}{n_p} \quad (18)$$

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 between the resistance of each individual S1 switch and the efficiency of integrated battery systems calculated from 18. This assumes a power output of 80kW, which is equivalent to the Nissan Leaf's peak output. Interestingly, only the total of 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.

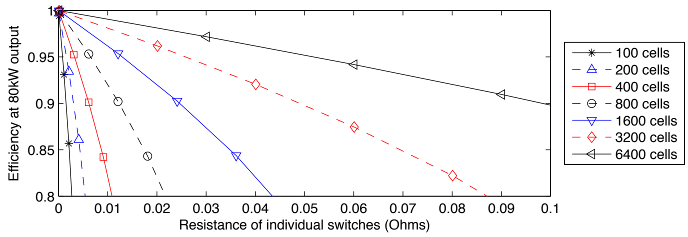

Fig. 4. Efficiency curves for different number of cell blocks

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.

Traditional silicon-based semiconductor switches such as silicon MOSFETs and IGBTs remain the dominant switching technology. 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 much more recent invention are wide band-gap switches. Currently, the leading wide band-gap semiconductor materials are silicon carbide (Si-C) and gallium nitride (GaN). Switches using these materials, which have started becoming commercially available over the past few years, offer a much lower on-resistance per unit contact area for a given breakdown voltage. As shown in Figure 5, for the same contact area and breakdown voltage, the theoretical minimum on-resistances of SiC and GaN materials are approximately 0.002% and 0.0003% of that of traditional silicon. Based on 100 and 200V GaN devices already commercially available by the Efficient Power Corporation (EPC), 400V devices based on a standard footprint of 2 by 4mm with an on-resistance of around 75mΩ seem technically feasible. By enlarging the device footprint, the on-resistance decreases further, which within a number of years could lead to commercially available 400V+ devices with on-resistances in the low tens or high single digit milliohms.

The third and final switching technology to be discussed here are electromechanical contactors, such as the starter solenoids found in conventional 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.

To overcome this limitation for electromechanical contactors, we propose using intelligent timing of the switching

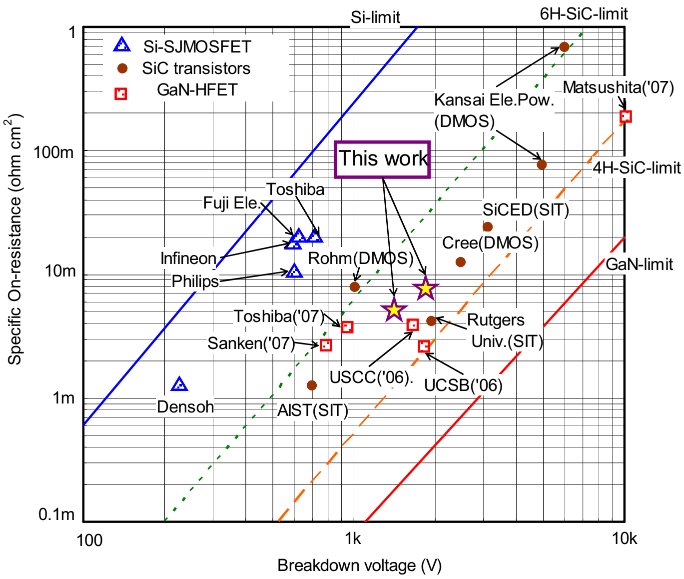

Fig. 5. A comparison of on-resistance between traditional silicon (Si), SiC and GaN (Ikeda et al. [2008])

operation. In many applications such as electric vehicles, brief periods when the primary load neither draws power from, nor returns energy to, the battery system occur relatively frequently. If switching is controlled to occur exactly during these periods, then the contactors can settle into either a fully open or closed state before the voltage is applied and arcing can 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 $\alpha = 2\%$ of the current throughput and the average is $\beta = 1\%$.
(3) Passive balancing dissipates the energy from all cells to the level of the cell with the highest self-discharge.
(4) Active balancing is $\delta = 70\%$ efficient in transferring the energy from higher charged cells 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 $\gamma = 90\%$ efficient and has a throughput of $\sigma = 20\%$ of the total power of the system.
(7) Additional cooling consumes $\omega = 20\%$ 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 15, 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.

$$P_{loss,p} = (1+\omega)(P_{balance} + P_{dc}) \tag{19}$$

$$P_{loss,p} = (1+\omega)(P_{out}(\alpha-\beta) + P_{out}\sigma(1-\gamma)) \tag{20}$$

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.

$$P_{loss,a} = (1+\omega)(\delta P_{balance} + P_{dc}) \tag{21}$$

$$P_{loss,a} = (1+\omega)(\delta P_{out}(\alpha-\beta) + P_{out}\sigma(1-\gamma)) \tag{22}$$

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 9.

$$P_{loss,s} = (1+\omega)(P_{sw} + P_{dc}) \tag{23}$$

$$P_{loss,s} = (1+\omega)(I_{out}^2 R_{total} + P_{out}\sigma(1-\gamma)) \tag{24}$$

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.

$$P_{loss,i} = (1+\omega)P_{sw} \tag{25}$$

$$P_{loss,i} = (1+\omega)I_{out}^2 R_{total} \tag{26}$$

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.

From the technical feasibility study presented previously, it comes as no surprise that 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 1mΩ is able to increase efficiency by approximately 3%. And 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%.

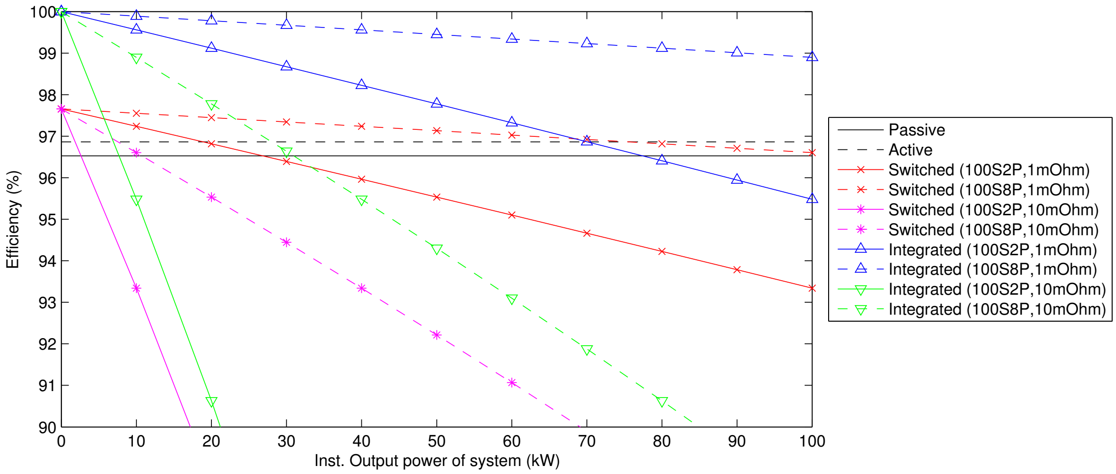

Fig. 6. Comparison of calculated efficiencies of systems using passive, active, switches or integrated balancing.

It should also be noted that in addition to the efficiency increase, there are a number of further advantages presented by integrated systems. As shown in Table 1, not only can the integrated system use strings that contain cells with notably different capacities, but individual cells that are found to overheat can be disconnected while operation is continued and multiple sources and loads can be directly integrated.

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)

5. CONCLUSION

In this paper we have presented a novel approach regarding the structure and management of 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 avoids using dc-dc converters and, in electric vehicles, makes the current use of traditional 12V lead-acid batteries redundant. Our work shows that by using wide bandgap 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 between 1 and 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.

[1] The system structure and control methodology presented here, as well as a number of additional features, are the subject of a patent application.

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