Optimising the structure of a cascaded modular battery system for enhancing the performance of battery packs

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Abstract: The overall performance of battery packs may be affected by imbalances between the series connected cells which is more likely in packs with high number of cells needed to provide a high voltage as needed for example in electric vehicles. In this case, the overall capacity and power capability of the pack are limited by the weakest cell in the stack which results in incomplete utilisation of the pack's capabilities. In traditional centralised battery systems (TCBS), this is addressed by implementing cell active/passive balancing circuitry/techniques which restore some of the pack's energy capability. This paper proposes the use of cascaded modular battery systems (CMBS) to remove the need for extra balancing circuitry and maximises the performance and reliability of a battery system containing unequal matched/aged cells. The analysis is assessing the CMBS overall system efficiency, reliability and weight compared to the TCBS for a design of a 300 V/3.6 kW battery system as a case study.

1 Introduction

The degradation of performance of battery packs in battery-based power systems as result of mismatch of cell performance or aging can affect the overall system performance therefore battery management systems (BMS) have an important role to minimise these effects in order to improve the performance and energy utilisation of the battery pack and by reducing the stress on weaker cells, prolong its life time. The high-voltage bus required by the traction system of electric vehicles requires the use of a large number of series connected cells. Therefore, the capacity of battery packs with series connected cells may be limited by the weakest cell in the string, i.e. if one of the cells lost 10% of its capacity compared to the majority of cells, the overall capacity of the pack will lose 10% as a result as the weak cell will reach first the fully charged/discharged condition, and in order to prevent further degradation of this cell, the operation of the whole pack needs to be stopped. Although the mismatching between pack's cells can be mitigated when the pack is manufactured by selecting cells with similar performance (matched capacity), after significant utilisation of the pack, the degree of capacity mismatch between pack's cells may increase and cannot be mitigated without a corrective actions. TCBS (Fig. 1a) are implementing one of the traditional cells balancing techniques in order to achieve charge balancing to maximise the utilisation of the pack capacity. Traditional cells charge balancing techniques are classified into two categories: (i) dissipative balancing techniques that connect shunt resistors to dissipate the excess energy from cells with a too high state of charge (SoC) [1, 2] and (ii) regenerative balancing techniques that circulate the extra energy from the cells that have a higher SoC to cells with lower SoC by using an efficient converter [3–6].

The regenerative balancing techniques may have the advantages of being more efficient as there is little energy dissipation compared to the dissipative balancing techniques but this depends on how smart the energy circulation algorithm is. This is because the dissipative techniques are typically activated only when the battery pack gets closer to the fully charged conditions while the regenerative technique may require significantly longer or continuous operation [7]. However, these cannot solve the problem of internal resistance mismatch between series connected cells that results in higher losses continuing to affect weaker cells that further accelerate degradation of their performance. The mismatching of internal resistance between battery cells with very similar matched capacity may be significant and it was shown that it could reach 20% at the beginning of life (BoL) [8]; therefore, it may reach an even larger value during the lifetime of the battery.

Loading all cells with the same load current share under this mismatching condition of the internal resistances can contribute to significant differences in the cell's temperature affecting more the life time of the hotter cells. Based on this, it is important for the BMS to be able to perform a power losses balancing (PLB) strategy in addition to the charge balancing strategy in order preserve battery life time and achieve safe operation. The PLB strategy cannot be achieved in the TCBS due to the need to have the possibility to change significantly the individual currents of some cells which is impossible in a series-connected stack. To implement this, it is required to have a modular battery system (Fig. 1b) having distributed power converters to enable independent control of the current sharing of individual battery

1.!.png

Fig. 1 System architecture of (a) TCBS, (b) CMBS
cells/modules, according to each cell/module capabilities in terms of power and energy.

Recently, new research has been conducted on the modular battery system concept especially to be used with second life batteries [9]. Such configurations can implement the suggested PLB strategy, but the problem of charge imbalances between the cells of each module still exist that may require additional balancing circuits. The modular battery system concept can be implemented at cell level [10], i.e. each converter interfaces a battery cell instead of a battery module which can ensure charge balancing and also can implement the PLB at cell level, but the system will become very complex and expensive for applications where large number of series connected cells are needed as each cell requires a separate converter and control loop.

This paper proposes the use of the modular battery system and identify a design of optimised number of cells per module to maximise the utilisation of battery capabilities and overall system efficiency and reliability while minimising the size, cost, and complexity.

2 Usable capacity

The usable energy capacity of a battery pack of an \( n \)-series connected battery cells can be estimated:

\[
U_{\text{Cap}} = \sum_{i=1}^{n} \text{Cap(cell)}_i
\]  

(1)

Considering capacity mismatching between pack's cells illustrated in Fig. 2; therefore, (1) can be reconstructed as:

\[
U_{\text{cap}} = n \times \text{Cap(cell}_{\text{weak}}) + \left( \sum_{i=1}^{n-1} \text{Cap(cell)}_i \right) \times \frac{n - 1}{n - 1 - \text{Cap(cell}_{\text{weak}})}
\]  

(2)

where \( \text{Cap(cell}_{\text{weak}}) \) is the energy capacity of the weakest cell (Wh) in the pack.

Based on (2), the total usable energy capacity of the pack consists of two terms: the first term is the direct usable capacity (DUC) that can be utilised directly without any additional balancing circuitry which can facilitate fast charging/discharging. The second term is the processing needed capacity (PNC) that cannot be utilised unless a processing technique like the cell charge balancing system (CBS) is activated in the TCBS. Assuming a 10% capacity fade of the weakest cell (Cell_{weak}) compared to the average capacity fade of the other cells, this will make the PNC of the pack to become 10% of the overall usable capacity. In order to remove the need for the CBS, the PNC should be kept as minimum as possible as it will not be utilised in the absence of balancing system.

By using a CMBS topology (Fig. 3) in which the battery pack is split into \( M \)-modules each with its own converter, the weakest cell will limit only the capability of its specific module, allowing maximum utilisation of the stronger cells in the other modules.

In order to determine the optimum split of battery cells in \( M \)-modules, let us consider the need to implement a 100-series cell pack having a single cell with a capacity fade of 10%.

As shown in Fig. 4, for a TCBS \( (M = 1) \), the DUC of the pack is 90% and the PNC is 10% of the available usable capacity (U_{cap}). This means that 10% of its capacity is lost in absence of a CBS. As the number of modules increases, the PNC decreases until it reaches 0.1% when \( M = 50 \) (2 cells each module).

It can be clearly seen that the PNC reduces significantly as the number of modules increases and this reduces the penalty of not having a CBS. However, increasing the number of modules is adding other penalties on system complexity, energy efficiency, and weight which will be analysed in the following section in order to identify the optimal system configuration.

3 System design

The analysis will be performed on the CMBS based on a step-down converter topology (Fig. 5) as it is inherently fault tolerant as any module can be bypassed by just switching-off the converter switches with no need for extra switches [11].

It is also possible to implement a PLB based on cells internal resistances to ensure equal cell losses and, therefore, thermal balancing between cells based on an accurate losses observer developed in [12].

3.1 Converter design

Considering that a Li-ion cell voltage varies between 3 V and 3.6 V based on its SoC and discharging current, so the minimum converter duty-cycle \( D \) has been selected to be 80% to maintain bus voltage at 300 V when cells are fully charged and increase to 0.99 when discharged. The values of other design parameters are included in Table 1.
to maintain the overall winding resistance of the system within a core size with increasing

where $R_{\text{losses}}$ at minimum. Fig. 6 shows the required inductance and core increasing of

Based on inductor design rules considering the core geometrical constant $K_g$ for core sizing [13], the inductor core size can be estimated as:

$$K_g = L_s^2 / C' \times f(M)$$  \hspace{1cm} (4)

where $R_{\text{DC}}$ is the winding resistance, $f_1(M)$ is a function selected based on the required reduction in $R_{\text{DC}}$ with increasing $M$ in order to maintain the overall winding resistance of the system within a required value. As it can be observed in (4), the reduction of the core size with increasing $M$ is affected by $f_1(M)$, so a trade-off is required between the level of reduction in the core size with the increasing of $M$ to maintain the overall size at minimum and the reduction in the $R_{\text{DC}}$ with increasing $M$ to maintain the overall losses at minimum. Fig. 6 shows the required inductance and core size and its part numbers based on Kool M	extsuperscript{µ}T® materials for each configuration.

The overall mass of the converters inductor can be approximated by excluding the mass of the former as:

$$M_{\text{mass overall}} = M \times (m_{\text{core}} + m_{\text{copper}}), m_{\text{copper}} = d \times A_i \times MLT \times n$$  \hspace{1cm} (5)

where $m_{\text{core}}$ is the core mass, $d$ is the density of conductor material, $A_i$ is the conductor cross-section area and $n$ the number of inductor turns. As it can be observed in (5), the overall mass of the required inductors increases as $M$ increases but the core size reduces with the increase of $M$ as predicted by (4) and the reduction of the copper mass ($m_{\text{copper}}$) as a result, ramping down the increase in overall mass at high values of $M$. Similarly, the overall $R_{\text{DC}}$ can be estimated based on (6):

$$R_{\text{DC overall}} = M \times \frac{R_{\text{DC}}}{f(M)}$$  \hspace{1cm} (6)

The effect of increasing the number of modules on the CMBS overall inductors mass and overall windings DC resistance is shown in Fig. 7. It can be seen that if the increase in overall mass is somehow limited at high number of modules ($M > 20$), the increase in overall resistance is in fact increasing which means that CMBSs with too high number of modules ($M > 10$) will have significantly higher winding losses in their inductors.

The overall system losses are mainly determined by the inductor and switches losses. Inductor power losses can be approximated as:

$$P_{\text{inductor}} = M \times P_{\text{core}} + I_{\text{bus}}^2 R_{\text{DC overall}} + I_{\text{AC - RMS}}^2 R_{\text{AC overall}}$$  \hspace{1cm} (7)

where $P_{\text{core}}$ is the inductor core losses, $I_{\text{AC - RMS}}$ is the RMS value of the inductor current ripple, $R_{\text{AC}}$ are the winding’s AC resistances and can be determined as:

$$R_{\text{AC overall}} = C_r R_{\text{DC overall}}$$  \hspace{1cm} (8)

where

$$C_r = \frac{\pi \times \pi}{\pi \times \pi - \pi (r - D_{\text{penetration}})}$$  \hspace{1cm} and $D_{\text{penetration}} = \frac{\rho}{\pi \times \mu \times f_i}$  \hspace{1cm} (9)

where $D_{\text{penetration}}$ is the penetration depth, to which the current flows at a particular frequency (due to skin effect), $r$ is the conductor radius and $\mu$ is the conductor’s permeability.

The second part of the losses is the switches (MOSFETs) losses which is divided into the conduction and switching losses that can be estimated according to [14] as follows:

![Fig. 5 Step-down topology based CMBS](Image 46x552 to 283x793)

**Table 1 Converter design parameters**

| Parameter  | Description               | Value     |
|------------|---------------------------|-----------|
| $V_{\text{cell}}$   | battery cell voltage      | 3–3.6 V   |
| $N$         | total number of battery cells | 100        |
| $\Delta I$  | inductor current ripple(p-p) | 4 A        |
| $F_S$       | switching frequency       | 100 kHz   |
| $D$         | converter duty ratio      | 80–100%   |
| $I_{\text{bus}}$ | load current              | 12 A      |
| $M$         | number of modules         | 1–50      |

**Fig. 6 Required CMBS inductance and their corresponding core size**

![Fig. 7 Overall inductors mass and RDC in CMBS3.2 System efficiency](Image 323x670 to 551x793)

**Fig. 7 Overall inductors mass and RDC in CMBS3.2 System efficiency**
\[ P_{\text{MOSFETs}} = P_{\text{cond}} + P_{\text{SW}} \]  
(10)

where \( P_{\text{cond}} \) and \( P_{\text{SW}} \) are the conduction and switching losses of the MOSFETs for all modules in the CMBS and can be estimated as (11) and (13):

\[ P_{\text{cond}} = M \times (I_{D_{\text{DSonh}}}R_{D_{\text{Sonh}}}D + R_{D_{\text{Sonh}}}(1 - D)) \]  
(11)

where \( R_{D_{\text{Sonh}}} \) and \( R_{D_{\text{Sonh}}} \) are the on-resistance of the high-side and low-side MOSFETs, respectively, \( D \) is the duty-ratio and is the \( \Delta t \) the switches current and estimated as:

\[ I_{\text{rms}} = \sqrt{I_{D_{\text{bus}}}^2 + \Delta t^2} \]  
(12)

The switching losses \( P_{\text{SW}} \) is dominated by the power losses during overlap of current and voltage during the transition period that can be estimated as:

\[ P_{\text{SW}} = M \times \left( N \times V_{\text{cell}} \times I_{\text{bus}} \times t_r \times t_f \right) \]  
(13)

where \( t_r \) and \( t_f \) are the rising and fall time of the switching transition which depends on the gate capacitors and gate current.

As can be observed from (11), the conduction losses assumed to be increased linearly with \( M \), however increasing \( M \) reduces the required voltage rating of the MOSFETs and its’ \( R_{DS} \) on as a result which ramp down the increase in the overall conduction losses. Similarly, based on (13), the overall switching losses decreases as \( M \) increases due to the reduction of the MOSFETs voltage rating and the reduction of gate capacitances as a result.

MOSFETs losses (conduction and switching) as well as inductors losses are shown in Fig. 8. The switching losses are estimated based on VISHAY® MOSFETs with part numbers indicated for each design point on the graph. As it can be noticed, the losses of the TCBS (\( M = 1 \)) is dominated by the MOSFETs losses. For the CMBS topologies as \( M \) increases, the overall power losses are increasing due to increased inductors losses and MOSFETs conduction losses. The discontinuities in the increasing of the MOSFETs conduction losses at \( M = 4 \) and \( M = 20 \) are due to breaks in the \( R_{DS} \) on increasing that seems to be due to changing of the manufacturing technology in order to keep \( R_{DS} \) on at minimum similar to the semiconductor case when changing from planar to trench technology for higher voltage.

Overall, it can be noticed that the switching losses mirrors in opposition and level the inductor losses which means their sum remains roughly constant. This means that the lowest losses will be determined by the semiconductor conduction losses which seem to reach a minimum at \( M = 4 \).

3.2 Fault tolerance

The performance of the battery system under fault is very strongly defining the usability of the pack under faults, a multi-objective analysis is required in order to define the optimum configuration based on the different parameters.

The system analysis has been done based on the following parameters: (i) battery system’s DUC (in percentage of pack’s capacity); (ii) efficiency at full power (3.6 kW); (iii) UUF (in percentage of pack’s usable capacity and designed voltage) under fault in two modules of the system; (iv) system simplicity (in percentage of simplicity at \( M = 1 \)), which is inversely proportional to \( M \) as the increased number of modules means increased number of control loops and sensors; and (v) reduction in mass (in percentage of mass at \( M = 50 \)). As it can be seen in Fig. 10, although the TCBS (\( M = 1 \)) shows a reasonable efficiency, mass reduction, and simplicity, the pack’s DUC and UUF are poor. On the other hand, the CMBS (\( M > 1 \)) shows higher levels of DUC, UUF, efficiency, and simplicity based on the different values of \( M \).
shown in Fig. 11, the minimum cost function is reached at (the simplest case when all penalties coefficients are equal (1) are detailed investigations whereby the penalty coefficients can be defined mainly by the system simplicity, reduced mass, and losses.

As it can be observed in Fig. 10, it is not easy to identify an optimum solution as each configuration has pros and cons. Therefore, evaluating a multi-objective cost function is required in order to determine the optimum value for \( M \):

\[
C(M) = W_{DUC}(100 - DUC(M)) + W_{MR}(100 - m(M)) + W_{UUF}(100 - UUF(M)) + W_{eff}(100 - eff(M))
\]

where \( W_{DUC} \) is the penalty applied to the decrease in DUC, \( W_{MR} \) is the penalty applied to the increase in system mass, \( W_{UUF} \) is the penalty applied to the decrease in pack’s UUF and \( W_{eff} \) is the cost function influenced mainly by the system’s UUF and DUC, however at \( M > 10 \). The cost function is defined mainly by the system simplicity, reduced mass, and losses. Therefore, a range of \( M = 5–10 \) modules may be used for more detailed investigations whereby the penalty coefficients can be more accurately defined.

5 Conclusions

The CMBS has been proposed as a smart way to implement battery management functionality and to achieve maximum utilisation of battery capacity without the need for cell balancing techniques as used with TCBS. A system analysis have been conducted based on a battery pack of 100 series connected cells to provide a designed bus voltage of 300 V for a 3.6 kW power system. The analysis showed that a combination of better efficiency, capacity utilisation, and fault tolerance of the CMBS can be achieved over the TCBS. The methodology to determine the optimum number of modules in cascade has been detailed by means of using a multi-objective cost function evaluation based on relevant system parameters.

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7 References

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