Integration of non-isolated DC–DC converters in battery storage systems – a topological exploration

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Abstract: This paper presents a topological exploration and evaluation of modularised battery systems with integrated non-isolated DC–DC converters (battery-integrated-converters). Converter requirements for battery operation in charging/discharging, charge balance, bypass, and pass-through modes have been considered. Topological variations have been derived to permit all battery operation modes. Design considerations and equations for each topology have been presented. The topological requirements have been summarised in tabular form with a 380 V bus storage system case study presented to demonstrate application of the design consideration discusses to a typical battery system specification. The comparison shows the buck, boost, and non-inverting buck-boost-based converters are all similarly suitable, and other performance metrics are likely to determine the best choice for a given set of circumstances.

1 Introduction

Battery energy storage systems are widely used in high-voltage and high-power applications, such as aerospace, electric and hybrid vehicles, energy storage devices for renewable energy systems; and energy storage for power networks, micro-grids, and smart grids in power systems. In these applications, cells are usually connected in series and assembled into batteries to provide a higher output voltage. Multiple batteries are then typically required to be connected in series to fulfil higher voltage requirements [1–4].

In practice, due to manufacturing tolerances and environmental variances battery cells have intrinsic mismatches in their characteristics [4]. Series connected battery cells are forced to charge or discharge with the same current. However, the energy stored in different cells is not equal, due to inherent variations between cells and/or different initial states of charge (SOC), and over-charging/discharging may occur for some cells [2, 4, 5].

To solve the problem of SOC imbalance among series connected battery cells, different battery management systems (BMS) with charge balancing controllers have been proposed. In conventional BMSs (see Fig. 1a), a charge balancing system using a passive or active charge balancing controller is applied to solve the problem of charge imbalance within a string of battery cells during charge and discharge processes [6]. In the passive approach, the excess energy of different cells is dissipated through resistors connected in parallel with each cell. Although this method is simple and cost-effective, some energy is wasted as heat. In the active method, the charge balance is achieved by transferring the extra energy from cells with higher SOC to cells with lower SOC. This method is able to utilise the whole energy from all cells, however, the charge balancing circuitry becomes complex when high numbers of cells are connected in series [3, 5, 6].

Recently, modularised charge equalisation based on cascaded converters has been proposed as an alternative to passive and active charge equalisation in series connected batteries (see Fig. 1b). In this configuration, each battery source is provided with a bidirectional DC–DC converter to control the charge and discharge current of each individual battery source via manipulating the duty cycle of its dedicated DC–DC converter [3, 7, 8].

The modular battery system provides several performance advantages [6]:

- Active charge balancing among the different battery sources is ensured by controlling each battery source separately based on its SOC.
- High reliability is achieved through fault tolerance and redundancy. Faulty batteries can be bypassed via their dedicated converters. The remaining healthy modules compensate to meet the required output voltage and power.

Different battery-integrated-converter systems have been proposed, mostly with a focus on charging and/or discharge balancing control methods [7–11]. However, implications of different topologies on design parameters required for charge and discharge balancing and to fulfil different application requirements have not been investigated, which will be discussed here. The discussion will provide a roadmap for design considerations of battery-integrated-converter system for different applications.
Balancing can be achieved by applying a proper control method to different SOC or intrinsic mismatches can reach the same SOC at the end of the charging process [1, 9].

2 Battery-integrated-converter systems

The battery-integrated-converter system was first proposed to solve the problem of current mismatch of series-connected PV modules arising from partial shading conditions [12]. When applied to a battery-integrated-converter system, each battery source is equipped with its associated bidirectional DC–DC converter, as shown in Fig. 1b. Battery sources can be a single battery cell or several cells connected in series.

During the discharging mode, the converters draw current from batteries to power the load. The current flow from each battery source is controlled by the duty cycle of its dedicated converter. Thus, by applying a proper control method, battery sources with different SOC or intrinsic mismatches can reach the same SOC during the discharging process. The sum of the output voltages of the converters is controlled to meet the required load voltage. Similarly, all battery sources can be charged in series from a common DC source. The charging currents can be individually controlled through the duty cycle of DC–DC converters to reach the same SOC at the end of the charging process [1, 9].

3 Operating mode requirements for battery-integrated-converter modules

Each battery power module should be capable of four operational modes of charge, discharge, bypass, and pass-through.

The charging and discharging modes are normal operational modes of a battery module. As previously mentioned, charge balancing can be achieved by applying a proper control method to control the duty cycle of different modules [8] and is one of the main purposes behind the idea of integrating converters in battery systems.

Bypass mode allows for the disconnection of a faulty battery source from the rest of the system such that the overall system performance is not affected. Pass-through mode should provide a low loss, high power direct connection of the battery source to the system. Some converter topologies inherently are capable of providing bypass and/or pass-through mode without requiring extra switches; however, other topologies require extra switches for disconnecting the battery source and/or for short-circuiting (bypassing) the converter output [7].

Provision of redundancy is one of the key advantages of a battery-integrated-converter system. Considering a k of M module redundancy capability in the system design, the system performance can be assured as long as K out of M modules are operational. The bypass mode capability discussed above is one of the requirements for redundancy to be achieved.

However, the system reliability is highly dependent on the number of series-connected battery cells per module (N) and the number of modules (M), which must be considered when designing for different applications [13].

4 Topological variations for non-isolated DC–DC converters applied to battery-integrated-converter systems

Non-isolated DC–DC converters can be categorised into three different groups, based on their conversion ratio: buck, boost, and buck-boost (which include inverting buck-boost, non-inverting buck-boost, Cuk, SEPIC). These six basic topologies are summarised in Fig. 2. Different DC–DC converters have been derived from these basic converters, typically with extra circuitry to improve certain performance metrics or fulfil different application requirements.

Here, we focus on deriving topological variations from the basic converters to fulfil the specific requirements of battery-integrated-converter systems. The buck, boost, and four-switch non-inverting buck-boost converter only are considered here. The inverting buck-boost converter has poor switch utilisation and discontinuous current flow to and from the battery source which is not preferred for this application [14]. Fig. 3 shows these converters in three different modes: discharge/charge, bypass, and pass-through modes.

Other buck-boost topological variations can be derived to improve the performance metrics of module integrated battery systems, but are outside the scope of this paper.

5 Analysis of characteristics and design considerations

5.1 Battery-integrated-converter system with buck converters

In the buck converter topology (see Fig. 3a), the battery source is placed on the high-voltage side of the buck converter. The low-voltage side of the buck converter is connected in series with other modules to build the required output voltage.

One advantage of the buck topology is that if there is a fault or weak cell in one of the battery sources which makes it unable to handle the output current, the dedicated converter can protect the battery source by decreasing its current to a safe level. However, this protection can be also achieved by bypass mode without extra switches.

One potential drawback of this topology is that the output voltage of each module is always less than the battery source voltage. Consequently, more battery cells/modules are required for a given output voltage, compared to the boost converter [6].

In a battery-integrated-converter system where all battery sources are modularised with the buck converter, the number of series-connected battery cells per module (N) is restricted by the maximum voltage of the battery cell as per (1):

\[
V_{cell} < rac{V_{output}}{N}
\]
In this equation, \( V_{\text{module,max}} \) is the maximum voltage rating of power electronic switches.

The minimum number of modules (K) to prevent the output voltage dropping below the required bus voltage is dependent on the minimum voltage provided by each battery source. Accordingly, in a battery-integrated-converter system composed of \( N \) cells per battery source (per module), \( K \) can be selected based on (2):

\[
k = \frac{V_{\text{BUS}}}{N \times V_{\text{cell,min}}} \quad (2)
\]

However, in order to provide module redundancy, it is necessary to increase the number of modules to \( M_{\text{(R)}} = K + X \) where \( X \) is the maximum number of modules that can be bypassed in case of failure, without affecting the performance of the system.

### 5.2 Battery-integrated-converter system with boost converter

In the boost converter topology (see Fig. 3b), battery sources are connected on the low-voltage side of the converter. The high-voltage side of the boost converter is connected in series with other modules to build the required output voltage.

One advantage of the boost topology is that the voltage that each module contributes to the output voltage is always higher than the battery source voltage. Thus, fewer battery cells/sources are required to reach a given output voltage, compared to the buck converter [6].

One drawback of this topology is that the battery source current of individual modules cannot be reduced to a safe level in the case of a cell failure. This problem can be solved by bypassing the faulty battery module; however, as Fig. 3b shows, this requires one extra switch per module in series with the battery source. In normal operation, the SOC balancing of individual batteries via their integrated converters during charge and discharge should be a continuous operation, which eliminates the requirement of battery source disconnection. In this circumstance, the only time disconnection of the battery source is required is when the battery source fails. In this condition, the faulty battery source can be disconnected by blowing a series connected fuse instead of adding one extra switch per module.

In a battery-integrated-converter system where all battery sources are modularised with the boost converter, the minimum number of modules is dependent on the maximum voltage of each battery source (module), as per (3):

\[
K = \frac{V_{\text{BUS}}}{V_{\text{module,max}}} \quad (3)
\]

where \( V_{\text{module,max}} \) is the maximum voltage rating of power electronic switches.

Consequently, by calculating the total number of modules based on the required redundancy level \( M_{\text{(R)}} = K + X \), the maximum number of cells per battery source with \( M_{\text{(R)}} \) modules can be calculated using (4):

\[
N_{\text{(max)}} = \frac{V_{\text{BUS}}}{M_{\text{(R)}} \times V_{\text{cell,max}}} \quad (4)
\]

### 5.3 Battery-integrated-converter system with non-inverting buck-boost converter

The buck-boost topology provides more flexible charge/discharge balancing as the output voltage of each module can be smaller or larger than the battery source voltage. In other words, the battery sources with voltages lower than the nominal voltage can be boosted, while those with voltages greater than nominal voltage can be bucked to provide a fast charge/discharge balance among different modules. For battery chemistries such as the Lithium Iron-Phosphate which have a relatively flat voltage profile across the majority of their SOC curve, the buck-boost topology may advantageously operate in bypass mode or at an efficient operating point for most of the batteries SOC range.

Considering the same logic as buck and boost topologies, (5) and (6) can be used to decide the number of modules and number of cells per module for designing a battery-integrated-converter system with buck-boost topology.

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**Fig. 3** Basic types of single-phase non-isolated bidirectional DC-DC converters with bypass and pass through switches

(a) Buck, (b) Boost, (c) Non-inverting buck-boost
\[
N_{\text{max}} = \frac{V_{\text{module, max}}}{V_{\text{cell, max}}} \\
K = \frac{V_{\text{BUS}}}{V_{\text{cell, nom}} \times N}
\]

6 Topological comparison of battery-integrated-converter systems

As previously discussed, different converter topologies impose different limitations on the number of modules and number of cells per module for battery-integrated-converter system. Table 1 provides a comparison of the characteristics and design constraints for battery-integrated-converter systems constructed using the three different converter topologies investigated. The application of these formulae for a specific design example is given in the next section.

7 Case study discussion

In this section, to provide an explicit comparison, an example design for each converter topology is presented using an example, representative system specification. The design assumptions are summarised in Table 2, and the results are tabulated in Table 3.

The 60 V MOSFET specification chosen for the battery-integrated-converters will keep these modules ELV rated. For a buck-based solution, 13 fully charged (3.65 V) cells = 47.5 V, which allows an acceptable margin of safety for the MOSFETs. At minimum cell voltage and a duty cycle \(D = 1\), the modules can produce 32.5 V, so a minimum of 12 series modules is required to achieve the nominated 380 V bus voltage. Allowing for six additional modules for redundancy, the duty cycle \(D = 0.445\) at maximum voltage. The total number of cells in this solution is 234 (18 modules \(\times\) 13 cells per module).

### Table 1 Characteristic comparison of battery-integrated-converter systems with different topologies

| Type | Buck- discharging | Boost- discharging | Non-inverting buck-boost |
|------|-------------------|-------------------|-------------------------|
| maximum number of cells \((N_{\text{max}})\) | \(\frac{V_{\text{module, max}}}{V_{\text{cell, max}}}\) | \(\frac{V_{\text{module, max}}}{V_{\text{cell, max}}}\times M(R)\) | \(\frac{V_{\text{module, max}}}{V_{\text{cell, max}}}\) |
| number of modules without redundancy \((K)\) | \(\frac{V_{\text{BUS}}}{V_{\text{cell, min}} \times N} + K\) | \(\frac{V_{\text{BUS}}}{V_{\text{cell, max}} \times N} + K\) | \(\frac{V_{\text{BUS}}}{V_{\text{cell, nom}} \times N} + K\) |
| conversion rate \((Vo/Vin)\) | \(D\) | \(D = 1 - \left(1 - \frac{V_{\text{cell, min}}}{V_{\text{cell, max}} \times M(R)}\right)\) | \(D = 1 - \left(1 - \frac{V_{\text{cell, min}}}{V_{\text{cell, max}} \times M(R)}\right)\) |
| maximum switch voltage \(Q\) | \(Q1, 2: V_{\text{cell, max}} \times N\) | \(Q1, 2: V_{\text{cell, max}} \times N\times M(R)\) | \(Q1, 2: V_{\text{cell, max}} \times N\times M(R)\) |
| number of switches \(2 M(R)\) | \(3 M(R)\) | \(4 M(R)\) |
| number of passive elements | \(M(R) \times (2C + 1L)\) | \(24C, 12L\) | \(30C, 15L\) |

### Table 2 Assumptions for designing a module-integrated battery system for a 380 VDC BUS

| Cell type | Li-Fe-PO4 |
|-----------|-----------|
| \(V_{\text{cell, max}}\) | 3.65 V |
| \(V_{\text{cell, nom}}\) | 3.20 V |
| \(V_{\text{cell, min}}\) | 2.50 V |
| \(V_{\text{BUS}}\) | 380 VDC |
| switches | 60V MOSFETs |
| redundancy | \(K = \frac{2}{3} \times M(R)\) |

### Table 3 Example of characteristic comparison of battery-integrated-converter systems with different topologies with Li-Fe-PO4 battery when modularising with \(K = 2/3 \times M(R)\) redundancy

| Type | Buck- discharging | Boost- discharging | Non-inverting Buck-Boost |
|------|-------------------|-------------------|-------------------------|
| number of cells per module \((N)\) | 13 | 8 | 12 |
| number of modules without redundancy \((K)\) | 12 | 8 | 10 |
| number of modules with redundancy \(M(R)\) | 18 | 12 | 15 |
| total number of cells | 234 | 96 | 180 |
| duty cycle | 0.445 < \(D < 1\) | 0 < \(D < 0.543\) | Buck: 0.498 < \(D < 1\) |
| Boost: 0 < \(D < 0.625\) |
| maximum switch voltage | \(Q1, 2: 47.45\) V | \(Q1, 2: 47.5\) V | \(Q1, 2: 43.8\) V |
| | \(Q3: 29.2\) V | \(Q3: 29.2\) V | \(Q3: 38\) V |
| number of switches | 36 | 36 | 60 |
| number of passive elements | 36C, 18L | 24C, 12L | 30C, 15L |
For a boost-based system, the 60 V MOSFET specification sets the minimum number of series modules to achieve a 380 V bus at seven (380/7 = 54 V), however eight is chosen as a more conservative and realistic choice (380/8 = 47.5 V). This allows the DC bus voltage to rise (e.g. for control via droop), and also unequal voltages for the individual modules, a necessity for balancing. For redundancy, four additional series modules are added for 12 modules in total. The maximum module voltage is then 380/12 = 31.6 V, and this sets the maximum cell count per module with fully charged cells at eight cells (as 8 × 3.65 V = 29.2 V < 31.6 V). Again this choice allows some small margin for the difference in module voltage and movement in bus voltage. Total cell count is only 96 cells. These two example systems have very different cells counts; 234 vs 96 cells. However, since the total installed capacity (kWh) and power rating (kW) are usually the important system parameters, the number of cells merely alters the choice and configuration of the cells which are specified and used.

As an example, consider 3.2 V 2.5 Ah 8.0 Wh capacity cells which can be discharged at a maximum rate of 2C (5 A). With single-cell strings, the buck battery-integrated-converter with 13 cells has a capacity of 104 Wh, so an 18 module system would have a ratings of 1.87 kWh and 3.75 kW. A boost-based battery-integrated-converter with eight cells would have a capacity of 64 Wh per module, so the 12 module system would be rated at just 0.768 kWh and 1.54 kW. To achieve a similar capacity and power rating to the buck system, either two parallel strings of modules, or two parallel cell strings within each module (2P8S) would double the capacity to 1.54 kWh and 3.07 Wh.

The buck system could be expanded from a minimum of 12 modules (but with no redundancy) to a system of for example 23 modules. For 24 or more modules, two series strings of 12 could be paralleled. The boost-based system cannot exceed 12 series modules, but for larger systems could be formed from parallel strings of six or more modules. In this way, either system can be seen to be flexible, expandable, and reliable.

The non-inverting buck-boost battery-integrated-converter has the greatest flexibility in configuration. With 12 series cells, the nominal module voltage is 12 × 3.2 V = 38.4 V. Ten series connected modules can then achieve a system bus voltage of 380 V with high efficiency by operating a near unity duty cycle. By operating some converters in bypass or pass through modes, perhaps in a round-robin fashion, even lower losses might be achieved, even when additional modules are added for extra capacity and redundancy.

This discussion has not considered the many other factors which may lead to an optimal solution. Factors which should be considered are reliability and redundancy, efficiency, effective balancing, safety and of course cost.

8 Conclusion

Here, the three major topological variations of non-isolated DC–DC converters – buck, boost, and non-inverting buck-boost – have been considered for a battery-integrated-converter system. The equations for estimating the number of modules and number of cells per module for these battery-integrated-converters are derived and tabulated along with the other topological variables.

A specific example has been provided for each converter topology which shows the impact of converter topology on the application requirements of a battery-integrated-converter system. No one topology shows a distinct advantage. The preference is likely to depend on other performance metrics such as reliability, efficiency, density, charge/discharge balancing capability; and cost considerations based on the priority of metrics. The discussion here provides a roadmap for designers which along with appropriate controller can be used to evaluate each topology with different performance metrics.

9 References

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