Comparison and Evaluation of Modular Multilevel Converter topologies for Li-Ion Battery Systems

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Abstract

The need for inexpensive high performance battery systems for stationary and automotive applications stimulates the investigation of Modular Multilevel Converters (MMCs) with integrated battery cells – herein referred to as Modular Multilevel Battery Systems (MMBS). MMBS offer considerable advantages in designing flexible and highly efficient Li-Ion battery systems. This paper compares different MMBS topologies for 3-phase applications and presents their simulation results as well as a prototype design. Suggestions for the design of a MMBS are provided.

1. Introduction

Battery powered AC motors and low-voltage electrical grids are typically driven by a DC link with two-level 3-phase voltage-source inverters equipped with six IGBTs. However, due to the large voltage steps between the switching states, high switching losses occur. Moreover, the generated AC voltage contains unwanted harmonics which produce significant iron losses in the motor and reduce its lifetime and efficiency [1]. Some drawbacks of standard 3-phase inverters can be overcome by MMCs (Fig. 1). MMCs can produce multiple output voltage levels by dividing the DC voltage source into several individually controllable sub-modules (SM) with smaller voltages sources (Fig. 2, Fig. 3). As multiple SMs can be switched independently, the effective switching frequency may be increased. Due to the smaller voltage steps, switching losses and total harmonic distortion (THD) of the output voltage are reduced as well as EMI, noise problems and iron losses [1]. In conventional MMCs, the SM use capacitors to buffer energy.

MMCs can also yield benefits in battery systems for electric motors of electrical vehicles (EVs) [2], [3], [4] or in stationary Battery Energy Storage Systems (BESS). BESS utilized as operating energy reserve for the grid are reported to deploy MMC technology [5].

Instead of connecting the battery to the DC side of the MMC (DC+/- in Fig. 1), the individual cells are separated to replace the sub-module capacitors (Fig. 2, Fig. 3). This concept is herein referred to as a Modular Multilevel Battery System (MMBS, see Fig. 1). In the following sections different MMBS topologies and their pros and cons are discussed. Furthermore a specific implementation of a MMBS is proposed and simulation results are presented.

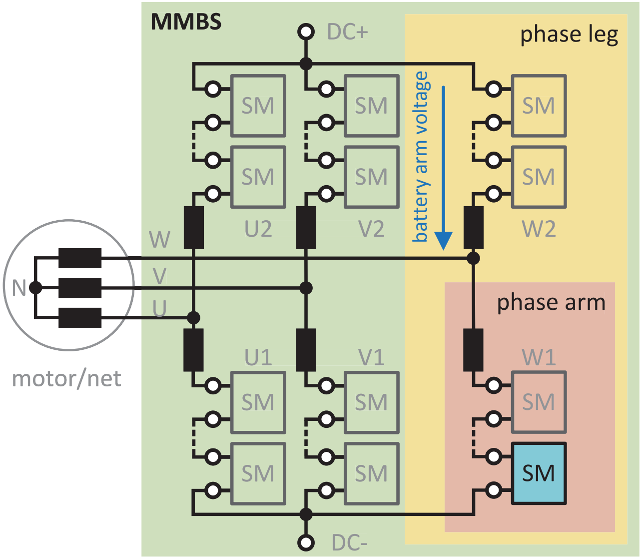

Fig. 1. Typical system topology of a Modular Multilevel Battery System (MMBS) with double star (DS) topology driving a motor.

2. MMCs in battery systems

If each sub-module contains only one battery cell, a smart selection of sub-modules based on the State of Charge (SoC) may act as an active charge balancer. Active balancing redistributes energy instead of dissipating it when equalizing the SoC, thus speeding up charging and maximizing efficiency and the usable battery charge. Cells can be bypassed permanently, so the MMBS allows an emergency operation in drivable state even if some cells are overheated, deteriorated or defective.

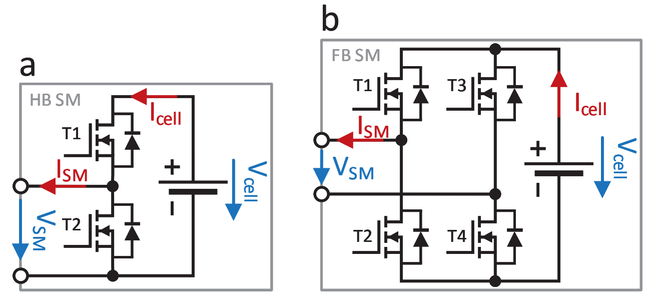

Fig. 2. Sub-module topologies used in MMBS: capacitor connected with (a) half-bridge (HB) using two transistors or (b) full-bridge (FB) with four transistors

Hence, the MMBS can replace a separate Battery Management System (BMS) and provides improved functionality.

A Modular Multilevel Battery System for motor drive or grid applications consists of one to three phase legs, each of which may include one or two phase arms (Fig. 1). Every arm has a number of sub-modules that contain one or more battery cells connected with a full-bridge (FB), a half-bridge (HB) or a DC/DC converter in combination with either of those (FBDCDC/HBDCDC).

2.1. Comparison of sub-modules

Half-bridge (HB) sub-module

Transistors T1 and T2 in Fig. 2a are used to control the output voltage V_{SM} between the terminals of the SM - either T1 or T2 are active.

Activating both T1 and T2 would result in a short circuit and therefore is not allowed. If both transistors are switched off, only the body diodes conduct current. Hence, the polarity of the SM voltage V_{SM} is determined by the polarity of the SM current I_{SM}. Due to the ambiguous behavior, this state is only used as a transition between the two valid states to realize break-before-make (BBM) behavior. Tab. 1 summarizes all possible states.

The switching states of all sub-modules of the MMBS determine the overall voltage between the terminals U, V and W (Fig. 1). An application of a half-bridge SM in MMBS is described in [6].

Tab. 1. Half-bridge sub-module: Switching states of the two transistors and resulting output voltage and battery cell current

T1	T2	V_{SM}	I_{Cell}
off	off	(during transitions)	
off	on	0	0
on	off	V_{Cell}	I_{SM}
~~on~~	~~on~~	(forbidden)	

Full-bridge (FB) sub-module

The full-bridge (Fig. 2b) uses four transistors and can generate positive, negative or zero output voltages V_{SM} (Tab. 2).

Tab. 2. Full-bridge: Switching states of transistors T1 - T4; resulting SM voltage, battery cell current.

T1	T2	T3	T4	V_{SM}	I_{Cell}
on	off	on	off	0	0
off	on	off	on	0	0
on	off	off	on	$+ V_{Cell}$	$+ I_{SM}$
off	on	on	off	$- V_{Cell}$	$- I_{SM}$
~~on~~	~~on~~	-	-	(forbidden)	
-	-	~~on~~	~~on~~		
off	off	-	-	(during transitions)	
-	-	off	off		

The polarity of the sub-module and the cell current may differ depending on the switching state. Neither T1 and T2, nor T3 and T4 are allowed to be active as a pair at once.

An application of a MMBS using full-bridges is described in [7]. A variation of a FB that also allows parallelization of adjacent sub-modules is explained in detail in [8] (English summary: [4]).

DC/DC converter sub-modules (HB/FBDCDC)

In SM topologies described above, the capacitor was replaced by a battery cell (Fig. 2). However, the capacitor can also be used in combination with a one or more battery cells connected through a DC/DC converter that represents an interface between MMC and battery [9] (Fig. 3).

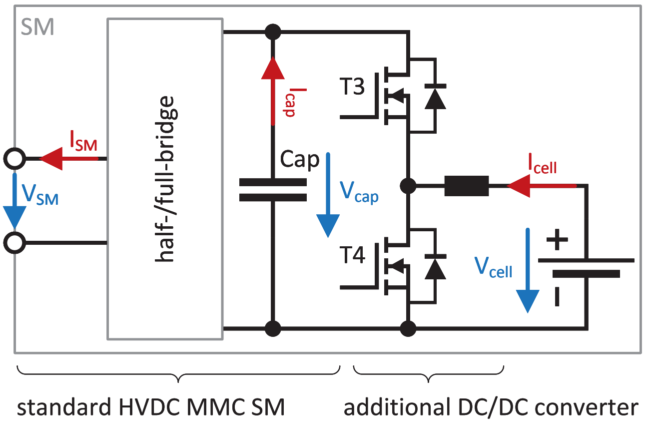

Fig. 3. Using a DC/DC converter to charge a SM capacitor from a battery cell

In this example, the DC/DC converter comprises of the half-bridge transistors T3, T4 and an inductor. Sub-module voltages are higher than cell voltages $|V_{SM}| \geq V_{cell}$ and the average current of the cell is larger than the sub-module current:

$|\bar{I}_{SM}| \leq |\bar{I}_{cell}|$. When the MMBS is powered down and the capacitor voltage drops, the body diode of T3 will discharge the cell. The usage of a low leakage current capacitor is recommended. Also, without further safeguards, a broken capacitor would lead to a short circuit of the battery cell.

Other DC/DC converters may be used. For example, the half-bridge in Fig. 3 can be connected the other way round: T3 is connected to the cell and the inductor to the capacitor, resulting in $|V_{SM}| \leq V_{cell}$ and $|\bar{I}_{SM}| \geq |\bar{I}_{cell}|$. Like this, the cell is not discharged while the MMBS is powered down. However, more sub-modules are required to achieve the same system voltage.

Instead of using a single cell per SM, a stack of multiple cells can be connected to the DC/DC converter. Especially for large MMBS applications in the BESS proposed in [5] and [10], the use of higher system voltages is possible without increasing the number of SMs excessively. However, the MMBS cannot balance individual cells anymore; hence, a separate battery management system has to be utilized.

2.2. Comparison of system topologies

In high voltage DC (HVDC) MMCs, a double star configuration is used since the sub-modules are powered by a single constant voltage DC source (DC+/- in Fig. 1) – the same configuration can be used in MMBS (Fig. 1). As the sub-modules are not powered by a single DC source but by the battery cells included in the SMs, the DC link is not required any more. However, the DC terminals can be used to charge the battery with DC current, which is especially interesting to quickly charge batteries in EVs. Without the DC terminals alternative configurations can be realized, as shown in Fig. 1 and Fig. 4. The topologies displayed in Fig. 1, Fig. 4a and b are compared in detail in [11], Fig. 4c in [3].

Single star (SS) topology

Single star (SS) topology [5] offers a simple BMMS realization (Fig. 4a). Existing motor windings are utilized for filtering and only one arm per phase leg is used, which makes the system easy to handle with a standard motor controller and an overlain balancing controller.

In single star half-bridge (SSHB) configuration, positive and negative output voltages are generated by differences of positive arm voltages.

An additional zero-sequence voltage can be used to balance different arms. Battery ("0") and motor star point ("N") must not be connected.

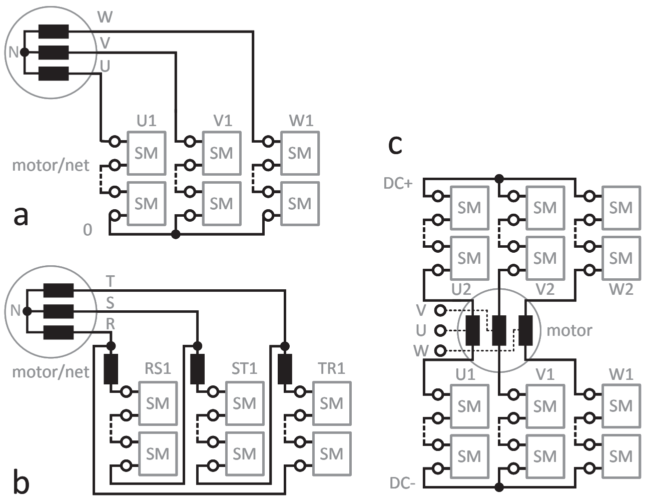

Fig. 4. (a) Single star (SS) and (b) single delta (SD) system topology, as well as (c) double star topology with motor winding filtering

The maximum charge rate of the battery cells determines the maximum applicable motor current.

The battery can be charged with DC-current via N/0 terminals using the motor inductivity. No motor torque is generated if the arm currents are equal. When charging with AC current via U/V/W terminals, additional inductors are required and the motor is disconnected to avoid motor rotation.

Single delta (SD) topology

In contrast to SS, single delta (SD) connection requires additional inductors to avoid short circuits and to filter currents (Fig. 4b). The motor controller needs to be adapted: Instead of controlling the motor currents with motor voltages as control variables, it is easier to control the phase arm currents with arm voltages as control variables. The desired motor currents are controlled by the sum of the currents of two adjacent arms connected to each winding. An additional circulating current may be overlain to balance charge between different arms. However, this may cause additional conduction losses. Half bridge sub-modules cannot be used in a SD topology as both positive and negative voltages are required to drive the motor.

Choosing smaller delta inductors requires higher switching frequencies to avoid high ring current ripples. If the inductors are too large (i.e. in the range of the motor inductivity) the motor current controller is significantly slower compared to other topologies as the optimal time constant of the PI current controller depends on the size of both motor and arm inductors.

If the motor is disconnected, the battery can be charged with AC current via R/S/T terminals or with DC current, e.g. via R/T if the connection between terminal R and arm TR1 is opened.

Double star (DS) topology

Double star (DS) topology uses two phase arms per leg, which require separate inductors as well (Fig. 1). To control the MMBS, a standard motor controller is overlain by a balancing controller. Control algorithms known from HVDC MMCs may be used as a basis. DS topology supports DC charging (via DC+/- terminals, Fig. 1) and AC charging comparable to an application in HVDC MMCs (via U/V/W when disconnecting the motor).

Double star topology with motor winding filtering (DSM)

As proposed in [3], the filter inductors can be replaced with a six or nine terminal motor as well to save space, weight and cost (Fig. 4c). Like in regular DS topologies, DC charging via DC+/- is possible. AC charging via U/V/W is possible without removing the motor and the windings are used for filtering. If the currents in opposite arms are equal, no torque is generated.

2.3. Strengths and weaknesses of MMBS

Half-bridge sub-modules

Fig. 2a indicates that a half-bridge is the simplest realization of a SM containing a lithium-ion cell. In HB SMs, exactly one transistor per SM lies within the current path. Compared to other SM topologies, a half-bridge has minimal conduction losses and needs the least amount of components per SM.

As seen in Tab. 1, no negative voltages $\mathrm{V_{SM}}$ can be generated with a half-bridge. However, the MMBS terminals voltages are negative if the positive phase arm voltages differ.

Tab. 1 also shows that a cell current $\mathrm{I_{Cell}}$ is either zero or equals the sub-module current $\mathrm{I_{SM}}$. Therefore, negative currents (which are required in AC applications) are limited to the maximum charge current of the used battery cells. Charge rates of lithium-ion cells are usually much smaller than the maximum discharge rates, effectively limiting the AC power of the MMBS.

Full-bridge sub-modules

The conduction losses per SM are doubled compared to a HB since two transistors are active at a time. However, the obtainable voltage range is also doubled due to the ability to generate negative voltages. Therefore, only half the amount of SMs is required to obtain equal output characteristics. Thus, conduction losses for FB and HB systems are roughly the same.

The current in a FB SM is not necessarily limited to the charge current of a cell, as the polarity between cell and SM current may differ.

Moreover, the ability to generate negative voltages offers more degrees of freedom. For example, two cells in an arm can be used in opposite directions to transfer charge between them without changing the output voltage. All in all, full-bridges are preferred over half-bridges.

HB/FB sub-modules with DC/DC converters

The capacitor in a DC/DC SM may decrease cell current ripples – the converter can charge or discharge the cells with a constant rate depending on the required sub-module current $\mathrm{I_{SM}}$ and the available capacitor and cell SoC. Hence, dynamic cell peak currents are much smaller compared to other SM topologies and no alternating current is present in the cells any longer.

When using the DC/DC converter sub-module in Fig. 3, the achievable output voltage is higher than the cell voltage. However, the converter causes additional losses.

On the other side, compared to a simple HB/FB, complexity and cost rise. Not only the cell voltages, but also the capacitor voltages have to be monitored and eligible capacitors, additional transistor drivers, controllers are required for the DC/DC converter.

Pros and cons of system topologies

Double star topology with motor windings (DSM) is the most flexible and cost efficient solution. It requires no additional inductors for DC or AC charging with various voltages. However, only a 9 terminal motor can make use of all benefits.

DSM and single star topology require the least amount of transistors and serial battery cells to realize a desired output voltage. SS only needs additional inductors when charging with AC.

Arm currents in single delta topology are decreased by a factor of $\sqrt{3}$ compared to other topologies because two arms per motor phase generate the motor current. However, twice as many SMs per arm are required to obtain a desired voltage. Therefore, the power loss is approximately $2/3$ of other topologies. As proposed in [4], all three phases of a SD topology could be interconnected in series to enable charging with high DC currents. However, separate inductors are required in every arm during motoring. Higher requirements on the switching frequency and a more complex motor controller are adverse.

General pros and cons of MMBS

In EVs, additional bidirectional DC/DC converters are often used in order to keep the DC link voltage for the motor inverter at a desired level despite of the variable battery voltage [12]. Charging the battery requires another AC/DC or DC/DC converter, each of which can decrease the overall efficiency of the car and increase cost. In contrast, Modular Multilevel Battery Systems can produce both alternating and direct current with variable voltage levels and they can flexibly change their functionality. Therefore, they replace several AC/DC, DC/DC or DC/AC converters in EVs or in BESS that are used to charge or discharge the battery or to adapt the voltage level (Fig. 5).

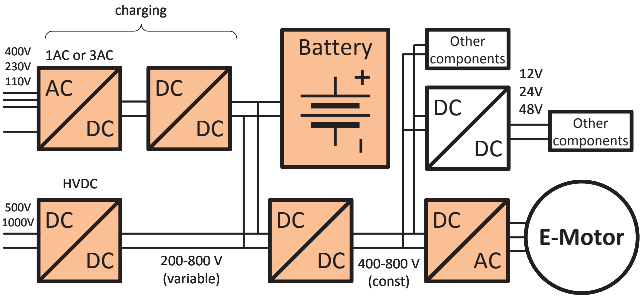

Fig. 5. Typical topology of an electrical vehicle with used converters and voltage levels. Orange parts could be united into a single MMBS.

If a SM contains only one battery cell, the MMBS can also take over the functionality of a battery management system without additional hardware.

Overall, an MMBS can be realized with almost the same space and weight of a classic BMS. Additional converters used for charging and motoring in EVs including transformers, inductors and IGBTs are not required anymore. As the power dissipation is spread over several transistors and therefore a larger area, passive or air cooling of the MMBS power electronics might be sufficient.

Ideally, only single transistors in a phase arm have to be switched per control cycle (Fig. 7). Due to lower voltage steps of the transistors, switching losses and total harmonic distortion (THD) are significantly reduced in comparison to standard two-level inverters with IGBT six-packs.

MMBS may also increase reliability. In a classic battery system, the weakest cell limits the functionality of the complete battery. In contrast, the MMBS can simply bypass deteriorated, broken or temporarily unavailable cells without or only with little limitations.

No balancing method can achieve higher balancing rates than the MMBS. In an extreme case, whenever charging and discharging the MMBS battery, selected cells can be permanently bypassed as well as used whenever possible, so balancing may take place at maximum rate all of the time instead of only during the last phase of a charging process. This decreases charging time and enables the efficient use of significantly aged cells or even completely different types of cells. For example, BESS could be equipped with various worn-out EV battery cells which could offer a cheap yet efficient alternative to new cells.

Despite of numerous advantages, many new challenges occur. First and foremost, battery cells cannot be connected directly with each other but need MOSFETs in between (compare Fig. 2 and Fig. 3). As a consequence, battery voltages cannot be measured easily with available *multicell battery monitors* (e.g. Linear Technology LTC6811) but have to be measured with individual ADCs or need special operational amplifiers (op-amps) to use one ADC for multiple cells.

Almost all reasonably priced transistors for this application (MOSFETs) with low $R_{\mathrm{DS(on)}}$ are SMD parts that need to be soldered to a PCB and cannot be directly connected to the cells. Even with thicker copper layers, we found that PCB layout and the connection of cells to the PCB plays a significant role and may be one of the limiting factors regarding dense high power MMBS applications. Even without regarding the PCB, the sum of conduction losses of suitable MOSFETs is higher compared to standard IGBT two-level inverters.

Furthermore, a MMBS is very complex compared to a classic separate BMS and two-level inverter architecture. The amount of gate drivers to be controlled with several kHz is many times higher – around $n_{FET} = n_{arm} \cdot n_{cells\ per\ arm} \cdot n_{FET\ per\ SM} = 3 \cdot 80 \cdot 4 = 960$ FETs for a typical MMBS in EVs are required. Fast communication with the SMs plays an important role. Every sub-module needs separate isolated drivers and associated signal and power supply isolators as well as separate ADCs or high common-mode voltage op-amps to connect multiple cells (that dynamically change their potentials) to the same ADC. The resulting costs have to be carefully traded off against alternatives to the MMBS and are heavily dependent on the application. The additional cost of these components may be justified if the MMBS replaces other power electronics like DC/DC charging converters or if the efficiency is significantly increased (for example if aged cells are used in BESS). Application specific integrated circuits (ASIC) may reduce cost and complexity.

A MMBS is only capable of driving one motor or net. Driving multiple loads is not easily realizable.

3. Simulation

3.1. Simulation Setup

Various combinations of SMs and system topologies of a MMBS driving a permanent synchronous motor were simulated in a Simulink model (Fig. 6). Acceleration, steady-state and deceleration of the motor were simulated to analyze both charging and discharging of the battery and validate different BMMS concepts.

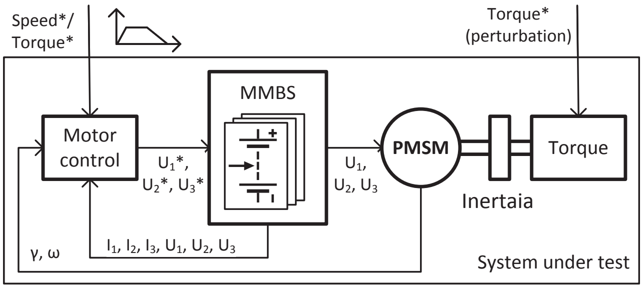

Fig. 6. Simplified block diagram of a MMBS simulation

In the first step, switches with constant conduction losses were used to simulate MOSFETs in the SM. The focus of the simulation was to compare the ability to drive a motor and the current stress on the cells. The ability to quickly balance cell charges was already proven in an earlier prototype (chapter 4.1) and was not simulated to reduce complexity.

3.2. Results

Fig. 7 and Fig. 8 show the simulation output of a single star full-bridge (SSFB) model with 12 SMs per phase arm. In comparison to two-level inverters, the MMBS has lower switching voltage steps (Fig. 7).

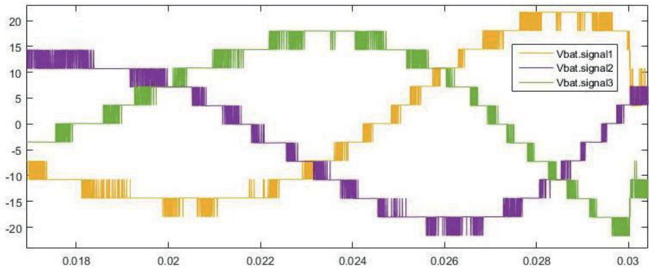

Fig. 7. Output voltage (in volts) of a SSFB MMBS during acceleration (time in seconds)

Fig. 8 shows that even when using full-bridges, comparatively high charge rates can occur (positive currents in the upper plot). The effects of square wave current ripple loads like at $t = 0.017\,s$ and $t = 0.075\,s$ on battery cell lifetime and usable charge will be analyzed in the prototype.

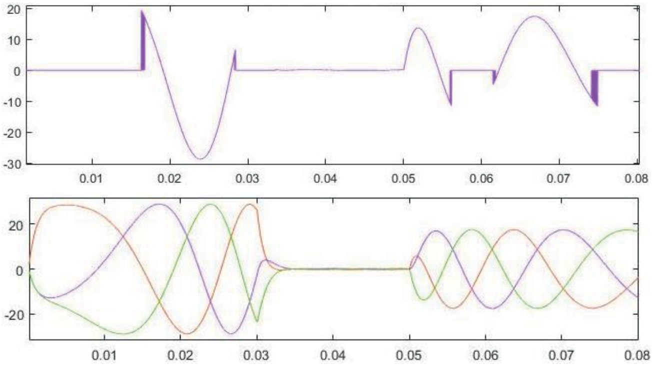

Fig. 8. Top: current (in A) of a cell in a SSFB during acceleration (0.01 to 0.03 s), steady-state (0.03 to 0.05 s) and deceleration (0.05 to 0.08 s). Positive current is charging the cell. Bottom: corresponding motor current (in A)

4. Prototype

4.1. Proof of concept of a single HB arm

A prototype of a single star half bridge (SSHB) arm with 12 cells was developed. The goal was to analyze and optimize the switching behavior of sub-module MOSFETs, as well as the effects on battery cells and to find a suitable balancing algorithm. Unlike in normal batteries, the cells are not connected directly with each other but on a PCB. This revealed several challenges in low-resistive/-inductive and dense integration of cells.

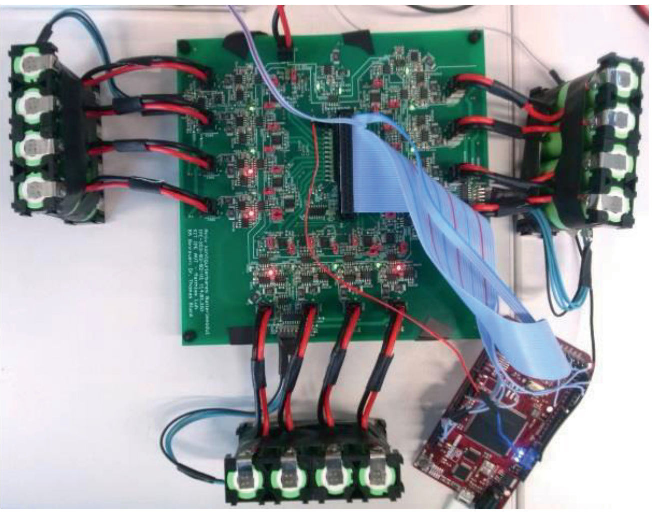

Fig. 9. Early prototype of a single HB arm with 12 lithium-ion battery cells (type 18650)

Fig. 10 shows the depth of discharge curve of 4 battery cells that initially had a different state of charge (SoC). While powering a load, they were balanced by selecting or bypassing individual cells based on a suitable algorithm.

Difficulties arise when estimating the state of charge. Alternating current stress caused by different cell selections results in changes of the cell voltage due to the cell impedance (Fig. 11). These dynamic effects dominate the cell voltage curve; no simple and reliable conclusions from voltage about the SoC of the cell can be made.

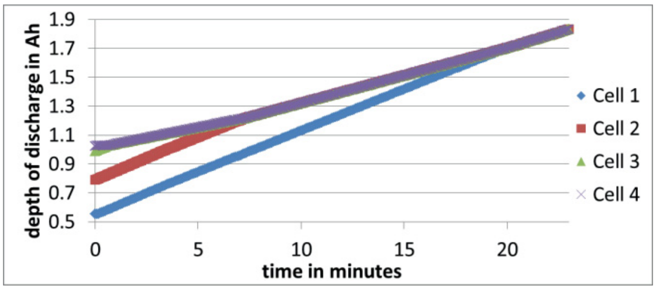

Fig. 10. Balancing of four initially unevenly charged cells while discharging the battery

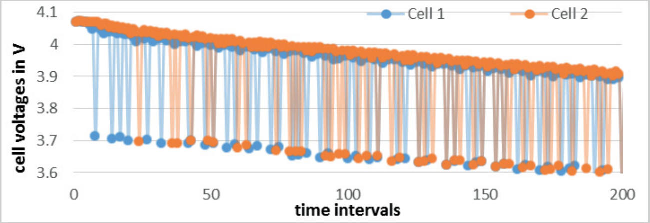

Fig. 11. Measured voltages of two li-ion cells during discharge operation (1 interval = 5 seconds). Lower points measured when cell is active, upper points when cell is not used

It is therefore recommended to track the individual depth of discharge (DoD) of every cell by accumulating the present current over time with high sampling rate whenever the cell is active.

A live estimation of the cell impedance can support the SoC estimation by estimating the open circuit voltage (OCV) of every cell, for example using Kalman filters as described in [13]. Alternatively, a single cell could be disabled for a few seconds or minutes to let its voltage relax for an OCV measurement.

4.2. Implementation of a SSFB MMBS

A fully functional single star full-bridge (SSFB) MMBS prototype with 36 pouch cells for up to 100V and 30A is in development (Fig. 12). A master board is connected to three slave boards that control one arm consisting of 12 sub-modules each. Each SM consists of a lithium-ion battery cell, a full-bridge (comprising IRL6283 MOSFETs) and a high common-mode voltage op-amp to enable cell voltage measurement of all 12 cells of a slave with a single ADC. Two MOSFETs at a time share a dual unipolar gate driver and a dedicated digital signal isolator as well as an isolated voltage supply. Every cell is thermally monitored by an NTC. The slave boards also have an additional MOSFET switch which can either activate or disable the arm or completely bypass all SMs. Break-before-make (BBM) switching is realized by hardware logic to enhance safety during tests and to reduce the number of signals to the microprocessor and the number of software operations. Only two digital signals control a FB.

In the prototype, motor current and voltage measurements are realized on the slave board and two port expanders per slave are used to control all 24 SM signal with an SPI bus.

The master board uses an Infineon TriCore processor that implements both BMS and motor control. A ranking of the strongest (weakest) cells which are preferably used to discharge (charge) the cell is determined.

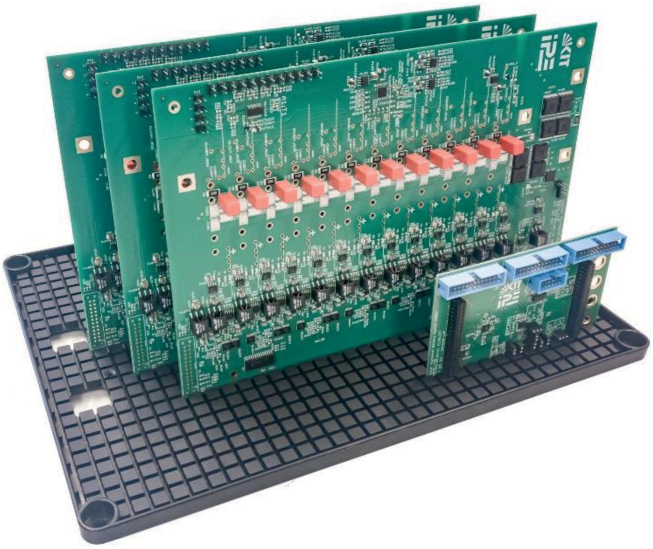

Fig. 12. Slave and master boards of the new MMBS

Further advice on MMBS design

Several challenges arose during development. First, for a typical 400V motor voltage, an MMBS comprises about 1000 MOSFETs. They have to be controlled with a switching frequency of approximately 10-50 kHz. The control of these MOSFETs and the measurement of cell voltages requires about 200-300 signal lines for typical EV. Thus, a master-slave topology is the preferred system configuration. Latency between master and slave has to be kept extremely low and it is recommended to use a high speed bus that can meet real-time requirements. However, bus speed may be limited by the physical distance between the slaves.

In general, all hardware-related operations should be handled by slave controllers. High-level functionality like balancing, safety monitoring and motor control could be implemented in the master.

Cell voltage measurements, PWM duty cycles and break-before-make could be realized on the slave controllers. Basic BMS functionality, for example regarding the operation within a safe operation area of temperature and voltage, could be implemented on the slave as well. Periodically but with low priority (e.g. once per second), the slaves can send all cell measurements to the master which then generates a ranking of the strongest and weakest cells as described above. Field oriented motor control and selection of active cells can be handled by the master as well.

High common-mode voltage op-amps may be used to measure all cell voltages of a slave with a single ADC, which decreases cost a lot.

5. Perspective

The prototype will be used to proof the functionality of a SSFB MMBS and to compare its performance and efficiency to a standard inverter. The effects on the usable capacity and state of health of li-ion cells is about to be analyzed.

A new communication concept with focus on high data rate and low latency has to be developed.

In contrast to the MMBS prototype, in a mature version motor current and voltage measurement are only required once per phase leg. Each slave could have its own microcontroller that conditions all measurements, processes PWM control with BBM and therefore relieves the master processor.

A compact MOSFET module with integrated cell contacts, a driver/sensor/isolation ASIC and enhanced cooling could further improve the performance of MMBS. Improved MOSFET technology will further reduce conduction losses.

A long term effect of high-frequent current ripples on li-ion cells has to be investigated, although some tests show that there is no significant difference to a constant current loads [14].

6. Conclusion

MMBS can reduce power losses, THD and EMI in battery systems of EVs and stationary battery storages. Especially double star full-bridge MMBS that use motor windings for filtering (DSMFB) can flexibly replace multiple converters in EVs and hence enhance compatibility of charging modes. Depending on the situation, they can be more complex and expensive, but may significantly improve battery lifetime and reliability.

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