Article

Reconfigurable Battery for Charging 48 V EVs in High-Voltage Infrastructure

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Abstract: 48 V is emerging as a safe-to-touch alternative voltage level for electric vehicles (EVs). Using a low- instead of a high-voltage drive train reduces isolation efforts, eliminates the risk of electric shock, and thus increases the system safety. In contrast, fast charging of a 48 V battery would require very high currents and is incompatible with the widely established high-voltage electric vehicle charging infrastructure. Instead of employing additional on board power converters for fast charging, the concept of a reconfigurable battery is presented. A small-scale prototype system is designed consisting of eight 48 V lithium iron phosphate battery modules. In series configuration, they can be charged at 460 V with up to 25 A. In 48 V parallel configuration, the peak discharge current is up to 800 A. The MOSFET-based reconfiguration system also operates as a module charge balancer during high-voltage charging. The cost overhead for the reconfiguration system is estimated to 3% for a scaled-up full size EV. Due to the additional reconfiguration switch resistances, the simulation of a 48 V 75 kW electric vehicle in the World harmonized Light-duty vehicles Test Procedure showed a performance reduction of 0.24%.

Keywords: 48 V; EV; charging; low-voltage; high-current; LFP; battery; reconfigurable battery system

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1. Introduction

Electric vehicles (EVs) are gaining popularity as personal transport worldwide due to their low carbon footprint during operation. Today, most commercial EVs use high-voltage battery packs in the 300 V to 500 V range, with a trend towards the 800 V class [1]. The potentially lethal high-voltage in such packs presents a safety issue from many perspectives. Even a fully discharged battery pack may administer a lethal voltage level in the system. Passengers must always be protected from such high voltage, whether at home, while driving, or at accident scenes. Service personnel must be specially certified to perform maintenance on these vehicles. In emergency situations, rescue personnel may be at risk when evacuating passengers. To manage these issues, many safety features are required in the design that contribute significantly to cost and weight in a modern EV [2]. Reducing the voltage level below 60 V, which is considered safe to touch, therefore has obvious advantages. In mild hybrid cars, with currently 10 kW to 30 kW electric motors, a 48 V system is already utilized [3,4]. For boat applications, a 80 kW 48 V Intelligent Stator Cage Drive (ISCAD) is available [5].

There are even initiatives employing safe-to-touch low-voltage 48 V systems for EVs that can realize hundreds of kW. The main concerns in high-current 48 V systems were in regards to powertrain efficiency, and the bulky cabling and connectors required that increase the overall weight and cost of the powertrain. MOLABO developed with their 3rd generation ISCAD, a 42-phase 110 kW machine [6], and demonstrated it in a fully operational car. The high copper fill-factor of these multiphase machines in combination with very low-resistance MOSFET-based power electronics allows efficient and competitive drivetrains. Compared to a high-voltage IGBT solution, a multiphase MOSFET-driven 48 V induction machine was estimated to reduce energy consumption by 20% to 25% [7].

The use of large cross-sectional conductors in high-power 48 V machines enables direct in-conductor cooling. The coolant circulates directly inside the stator winding, which is a very efficient method to extract heat from the machine's main heat source [8]. Such a design allows motors to reach higher partial load efficiency and power density with a greatly improved continuous and peak power ratio than in that of other designs.

Charging of 48 V EVs is still a major challenge as it would require very high currents that must be managed using heavy and bulky connectors and cabling. 48 V on-board chargers were developed that would suit over-night charging [9]. Fast charging at 200 kW would instead require currents more than 4 kA in the few meters of cable between a charging station and the vehicle. One approach for a flexible and lightweight interconnect is using high temperature super conductors [10]. Another fast-charging approach could be a 48 V version of a magnetic plug [11]. Nonetheless, these concepts neglect the fact that considerable investments were already made into charging infrastructure for high-voltage EVs, and it would be very challenging to introduce a vehicle that cannot utilize this existing infrastructure. A possible fast-charging solution for 48 V EVs could be a reconfigurable battery.

There is an increasing interest in reconfigurable battery systems (RBSs) as next generation battery management systems (BMSs). A large variation of RBS configurations with different levels of complexity were shown. Cell-level based RBS with two to six switches were recently reviewed and discussed by Han et al. [12].

To compensate for the charge imbalance that arise in multicell-based battery systems, RBSs can be used instead of additional cell-balancer systems in a fixed cell or module configuration. This allows reduced battery charge equalization, and thus charging time [13]. Employing RBSs also provides increased energy efficiency during charging [14,15], enhanced fault handling [16] as well as improved battery utilization [17].

This work instead focuses on the practical implementation and validation of an RBS on pack level for high-voltage charging and low-voltage discharging using 48 V modules with internal BMS. In fact, these modules use a fixed 16S8P cell configuration with a nominal voltage of 51.2 V. In this paper, a high-voltage, fast-charging solution for 48 V EVs is proposed and investigated. To reduce the charging current while maintaining power level, the battery pack's voltage is increased during charging. This is achieved by splitting the battery pack into eight 48 V modules that can be reconfigured dynamically. During charging, the modules are connected in series, while being parallel connected during normal operation of the EV. Even though the motivation for the presented design is completely different than earlier work, most of the benefits still remain but are outside the main focus of this work.

This article first presents and discusses the proposed system, in which a scaled-down prototype of the reconfigurable battery pack was designed and constructed. High-voltage charging as well as low-voltage discharging measurements are presented, and the cost of performance aspects are discussed too.

2. Battery Reconfiguration

To charge the 48 V battery pack from a high-voltage charger, the pack is divided into 8 modules. During normal operation, these are connected in parallel and only reconfigured to series connection during charging, as shown in Figure 1. For each battery module, three switches are used for reconfiguration between series and parallel mode. The reconfiguration circuit is placed on top of each module, such that all battery-to-drive interconnects maintain a low-voltage level. A main charging switch is used to connect the battery system to the charging supply. A series diode is used to avoid the body diode of the main charging switch to conduct when the input voltage is lower than the battery voltage. A previously published direct in-conductor cooling system [8], utilizing a 4.5 mm copper conductor with a 1.5 mm center-hole, can be used for the parallel battery interconnects. Running coolant with 100 kPa pressure was verified to conduct 520 A with a coolant temperature rise of just 16.6 K.

Figure 1. Schematic view of proof-of-concept battery reconfiguration system. Each module uses five N-channel MOSFETs for switch groups T_P and T_G , as well as two for T_S .

During charging, when the EV is connected to the grid at standstill, the battery-to-battery interconnects will be hazardous and must be treated as high-voltage. During this time, extra safety precautions can be applied to disconnect the high-voltage source if any malfunction is detected. During normal driving operation, the highest potential in the system will never exceed 60 V.

2.1. Prototype Design

A scaled-down version of the system, shown in Figure 2, was designed using 8 lithium iron phosphate (LFP) battery modules with a capacity of 25 Ah [18]. These battery modules use 16 series-connected cells with 3.2 V, yielding a nominal module voltage of 51.2 V. The module's internal cell balancing circuit sets a limit to the maximum permissible module voltage. Thus, the reconfiguration strategy of the proposed system prototype along with an additional over-voltage protection circuit ensures that the modules terminal voltage can not exceed approximately 60 V. The module current was sensed using an Allegro ACS770ECB-200B-PFF-T [19] current sensor, while the module voltage was measured with an isolated amplifier Analog Devices ADUM3190SRQZ [20]. Both quantities were

digitized and accessible through an I2C interface using the Microchip MCP3427 [21] 16 bit analog-to-digital convert (ADC).

Figure 2. Part of designed prototype system with 8 lithium iron phosphate (LFP) battery modules with 48 V/25 Ah each and mounted reconfiguration printed circuit boards (PCBs). Battery configuration is controlled individually, while all module voltages and currents are monitored via an I2C interface.

Ideally, the series-charging switches T_S are never subjected to more than the battery module's voltage. Thus, two parallel connected 150 V N-channel MOSFETs with an $R_{DS(on)}$ of 10 m Ω each were used.

The parallel switches T_P and T_G instead require a blocking voltage depending on their position in the module chain. The further up they are located, the greater the voltage rating has to be. Currently, five N-channel MOSFETs are connected in parallel to handle the required discharge current as shown in Table 1. All MOSFETs use a pin compatible TO247 package, such that identical PCBs could be used for all prototype modules. The bottom module in the chain does not require reconfiguration. Here, the same PCB is used without reconfiguration MOSFETs for protection and measurement only.

For this application, one of the key MOSFET properties is their $R_{DS(on)}$, besides the blocking voltage and continuous drain current. The on-resistance increases with voltage rating and operating temperature. Thus, two considerations should be mentioned here. To reach the 1.65 m Ω typical on-resistance of a single 60 V MOSFET on module #1, a parallel connection of 34 high-voltage 600 V MOSFETs of module #8 would be required. Since these high-current switches are one of the most costly parts of the design, finally a cost-to-performance trade-off is necessary. Second, to reduce the device temperature and size of the reconfiguration PCB, glycol-water cooling should finally be used for the high-current MOSFETs.

Table 1. Selection of discharging MOSFETs T_G and T_P with their adjacent typical $R_{DS(on)}$, resulting in total module switch resistance R_{sw} and cost.

Module #	Amount (T_G, T_P)	V_{DSmax} [V]	$R_{DS(on)}$ [m Ω]	R_{sw} [m Ω]	$cost_{tot}$ [\$]	MOSFET Type
1	none	-	-	-	-	-
2	5,5	60	1.65	2×0.33	16.3	IRFP7530PbF
3	5,5	200	7.9	2×1.6	22.8	SUG90090E
4	5,5	200	7.9	2×1.6	22.8	SUG90090E
5	5,5	300	35	2×7	20.6	STW75NF30
6	5,5	300	35	2×7	20.6	STW75NF30
7	5,5	600	56	2×11.2	50.6	SiHG47N60AE
8	5,5	600	56	2×11.2	50.6	SiHG47N60AE
total				80	204	

In idle state, all modules are grounded to the same potential by enabling the ground switch group T_G . Both the series and parallel switches T_S and T_P are disabled and thus open. The reconfiguration between series and parallel always transits through this idle state. The reconfiguration to series connection occurs in sequence, one battery module at a time, beginning with module #8. First, the grounding switch T_G is opened, and after a short delay the series connection switch T_S is enabled. All battery modules are shifted by 53 V in potential during each reconfiguration step. To avoid excessive ringing caused by inrush currents, the reconfiguration starts by connecting a 200 Ω balancing resistor in series with the main MOSFETs. After 20 μ s the voltage levels are balanced and the low-ohmic main switches are activated as illustrated in Figure 3.

Figure 3. Schematic of reconfiguration module. An I2C A/D converter measures battery module's voltage and current. During configuration switching, low-ohmic, high-current switches are delayed by 20 μ s to let inrush-current limiters equalize voltage levels.

The reconfiguration from series to idle mode is initialized with module #2 and continues sequentially towards module #8. First, the series switch T_S is opened, making the battery module float. After the inrush-current limiter delay, the grounding switch T_G is activated.

Both reconfiguration sequences are shown in Figure 4 where the pack voltage across all modules during the reconfiguration is measured. The inrush-current limiter ensures a smooth transition between the voltage levels and keeps the balancing current in the range of 100 mA.

Figure 4. Voltage and current waveforms during battery reconfiguration using oscilloscope's memory function. Orange curve shows battery pack voltage during transition from series to parallel configuration. Green curves show pack's voltage during transition from parallel to series configuration, both with a smooth transition and without ringing. Blue and purple curves show inrush current in lowest 48 V battery, observed to be in 100 mA range.

In the presented prototype, the modules are connected with a 1 m long 6 mm² cable that corresponds to approximately 3 mΩ per module. In the proposed full-scale implementation, water-cooled conductors would be used for interconnects to reach the required high pack current. These cooled conductors behave differently compared to that of the experimental setup, mainly due to reduced conductor temperature raise, which in turn reduces the conductor resistance. As the $R_{DS(on)}$ of the discharging MOSFETs increases with voltage rating, an imbalance in the connection resistance of each battery module is introduced. This can be ameliorated by placing the modules with the highest voltage-rated switches closest to the load connection.

A more thorough investigation of these effects on each module's lifetime would be of interest, but is outside the scope of this paper. Any battery in an EV will be subjected to rapid changes between charging and discharging during vehicle's acceleration and braking, respectively; a proper design is required to handle such changes.

2.2. Battery Pack Balancing

Balancing of the cells in a battery module as well as the pack is required to prevent overcharge and deep discharge. One of the benefits of a 48 V system is the relative simplicity of balancing cells compared to a high-voltage battery pack [22,23].

Module voltage balancing during charging is a beneficial feature of the proposed system. The specification of the battery modules used [18] allows a maximum of two

modules connected in series. This limit is set by the maximum permissible terminal voltage of each module's internal BMS. The developed reconfiguration system keeps the maximum module voltage within permissible limits and ensures charge balancing between all modules.

Currently, this paper presents just a simple charge balancing solution using the presented circuit. At regular intervals during charging, the modules are disconnected from the charger and connected in parallel, to redistribute the charge and level out the voltages between the modules. The redistribution interval could be optimized further to affect inrush current, charging duration and battery lifetime.

3. Experimental Results

The experimental verification of the design addressed both the charging and discharging phases. Rebalancing via intermediate reconfiguration to parallel module connection during charging was primarily investigated. The system was stressed to typical EV driving levels during discharging, and the arising current imbalance and following charge redistribution phase was studied. The prototype was a scaled-down version of a typical EV with a specified energy of

$$W_{Bat} = 8 \times 48 \text{ V} \times 25 \text{ Ah} = 10 \text{ kWh.} \quad (1)$$

This represents 1/7th of a typical EV battery with 70 kWh.

3.1. Charging

The charging experiments were performed using an Elektro–Automatik EA-PSB 9200-210 [24] power supply set to 440 V. To evaluate the charging behavior and module voltages in series connection, the charging current was changed step-wise. It was increased from 0 A to 10 A, as shown in Figure 5. Instead of this pattern, finally a constant current followed by constant voltage charging profile should be used as default.

Before charging, the battery pack was drained to approximately 20 % of its full capacity. While the current was equal for each module in series connection, a difference in voltage was observed. Module #1 shows the highest terminal voltage. In combination with the lowest parallel charging current of module #1, shown in Figure 6, this is an indicator for a slightly higher contact or internal resistance compared to the other modules. During charging, a balancing sequence was performed, whereby the modules were charged at rate of 5 A, with a few interruptions and reconfigurations to parallel. When the modules were connected in parallel, the voltage levels equalized, as shown in Figure 7. The rebalancing current observed was very small compared to the charging current, with a peak of 0.35 A at module #1.

To evaluate the regenerative braking capability of the purposed system in 48 V parallel configuration, the measurements shown in Figure 6 were taken. In the first phase, a constant charging current of 80 A was used. The parallel connection of the modules allows different module charging currents. It was observed that at minute 15, module #6 with the lowest voltage reaches the highest charging current, while module #2 with the highest voltage has the lowest. In the second charging phase, when the modules approach top-charge, constant voltage mode is used. Consequently, the charging current of all modules declines.

Generally, modules with lowest terminal voltage receive the highest charging current in parallel configuration. Besides the module voltage, the current share depends also on additional parameters such as the resistance of the reconfiguration PCB, cabling assembly, and the module's builtin BMS. The greatest deviation showed once more module #1 during constant current mode while charging in 48 V parallel configuration. This is assumed to be caused by a higher path resistance of the module as described before.

By the end of this sequence, the internal BMS of module #3 followed by module #4 went into trickle charging operation, indicated by the current spikes.

Figure 5. Battery pack in series configuration, charging from a 440 V DC source with a stepwise increasing current from 0 A to 10 A. Voltage at module #1 is raising most.

Figure 6. Parallel charging of battery pack in 48 V configuration, as used in regenerative braking. In first phase, total charging current is limited, while in second phase the pack's charging voltage is limited. Green peaks at right-side indicate that module #3 is close to full charge and its battery management system (BMS) went into trickle charging mode. At end of sequence, also module #4 went into trickle charging mode.

Figure 7. Battery module's voltage and current during high-voltage series charging. Modules reaching top-charge show a faster voltage rise, equalized by intermittent rebalancing of modules by parallel connection. Again, module #1 reaches highest voltage.

3.2. Discharging

The presented design is a proof-of-concept in which the balancing of wire resistances and module capacity was not specifically in focus. Some imbalance of the discharge current was expected, especially when high power was delivered from the battery. To estimate the significance of this imbalance, two sets of measurements were performed that simulated driving at 110 km/h constant speed for a duration of 60 min with 10 s peak acceleration.

The power required to cruise at $v = 110$ km/h with a car with a weight of $m = 1600$ kg, cross sectional area of $A = 3.11$ m² an air drag coefficient of $C_d = 0.31$, air density $\rho = 1.225$ kg/m³ and rolling resistance coefficient $C_{rr} = 0.02$ is calculated according to

$$\begin{aligned}
 P &= v(F_{Roll} + F_{Drag}) \\
 &= v(C_{rr}mG + \frac{\rho C_d A v}{2}) \\
 &= \frac{110}{3.6} \times (0.02 \times 1600 \times 9.82 + \frac{1.225 \times 0.31 \times 3.11 \times \frac{110}{3.6}}{2}) \\
 &= 26.5 \text{ kW}.
 \end{aligned} \tag{2}$$

As compensation for mechanical, motor, and drive losses, 30 kW is assumed. This scales down to 4 kW, or 80 A for the prototype system that is 7 times smaller. On module level, this corresponds to 10 A and is well within the modules' specified continuous discharge current of 25 A.

The battery pack voltage and current distribution is shown in Figure 8 during a 1 h discharge. The current was shared evenly with an imbalance of approximately $\pm 6\%$ from the mean value, and the voltage differed approximately 0.15 V ($\pm 0.2\%$) between the modules. This corresponds to a range of $\pm 7\%$ in utilized energy from the eight battery modules. As the load was disconnected, the modules started to redistribute the stored energy, balancing out the battery pack with a slowly decaying internal current of initially ± 0.6 A.

Figure 8. Discharging of batteries in parallel configuration during 1 h at 80 A, corresponding to highway cruising at 110 km/h.

High-speed acceleration characterization was limited by the 200 A electronic load used. With 53 V battery voltage, this corresponds to 10.6 kW power for the prototype setup. Scaled up to an EV, this corresponds to an acceleration with 75 kW for 10 s. This exceeds the maximal power required in the World harmonized Light-duty vehicles Test Procedures (WLTPs) drive cycle, which is 58 kW for an EV with the parameters listed above.

The battery pack's voltage and current distribution is shown in Figure 9. During discharging, the voltage dropped rapidly from an initial 53.5 V to a range of 51.3 V to 50.8 V. An additional drop of 0.6 V on each module was observed during the 10 s acceleration phase. The currents were quite evenly distributed between the modules and varied between 22 A to 27 A. As the load was disconnected, the voltage recovered to 52.9 V while rebalancing currents in the range of ± 1 A occurred between the cells. After 20 s, the rebalancing currents decayed to ± 0.5 A. The imbalances observed were not found to systematically associate with the additional wire and reconfiguration circuit resistances, and should thus relate to the production spread of the used cells and modules.

Figure 9. Discharging of battery pack in parallel configuration for about 10 s at 200 A and following rebalancing.

4. System Analysis

To investigate if the proposed system is suitable for a low-voltage EV, simple initial cost and performance implications were analyzed.

4.1. System Performance

Adding additional switches in series between battery and motor will obviously influence the performance, especially when using high currents as in a low-voltage EV. Ultimately, the optimal design will involve a trade-off between performance, cost, and lifetime.

During high-voltage charging, the discharging switches are subjected to different voltages. As the cost to $R_{DS(on)}$ ratio rapidly increases at high voltages, the lowest possible switch voltage rating should be used. The battery modules at the bottom of the chain can be connected with virtually no extra series resistance from the switches. The upper modules with highest switch voltage rating instead face several mΩ of additional resistance. Besides, the current sharing also depends on the interconnects between the battery modules. Thus, the modules with highest resistance should be placed closest to the drive.

As interconnect between the modules, actively cooled conductors may be used. The previously investigated in-conductor cooled wire [8] could be used to improve the current balancing and reduce conductor weight.

To estimate the losses introduced by the parallel switches, a balanced module current was assumed since the additional resistance of the MOSFETs is a fraction of the batteries internal and connection resistances. The overall battery pack current for a 48 V system was calculated from the WLTP drive cycle shown in Figure 10. The energy dissipated in the discharging switches is calculated as

$$\begin{aligned}
 W_{Diss} &= \sum_{k=1}^8 \left(\int_{cycle} (I_k(t))^2 R_{sw}^k dt \right) \\
 &= R_{sw}^{tot} \int_{cycle} \left(\frac{I(t)}{8} \right)^2 dt.
 \end{aligned} \tag{3}$$

where R_{sw}^{tot} is the sum of all MOSFET on-resistances as shown in Table 1 and $I_k(t)$ is 1/8th of the pack current. The integral part of Equation (3) can be calculated separately to a constant equal to $3.50 \times 10^6 \text{ A}^2\text{s}$. The negative portion of the current corresponds to regeneration that also contributes to losses in the switches. As the current is squared in the equation, no absolute sign is required. Scaled-up to a full-sized EV, the MOSFETs resistance is calculated to be $11 \text{ m}\Omega$, resulting in a total energy loss of $3.8 \times 10^4 \text{ Ws}$, equal to 0.0106 kWh . During the WLTP drive cycle, the overall power delivered from the batteries is calculated to be $1.6 \times 10^7 \text{ Ws}$, equal to 4.44 kWh . The additional loss of the parallel switches are thus 0.24% .

Figure 10. Velocity and calculated motor current over a World harmonized Light-duty vehicles Test Procedure (WLTP) drive cycle. Negative current corresponds to periods of regenerative braking.

4.2. Cost Estimation

The cost for the suggested approach can be split into a fixed part and a portion that scales with the power level and depends on the acceptable extent of performance loss. Allowing increased imbalance between the battery modules will reduce the system cost, as the high-voltage devices greatly contribute to the overall cost. This factor must be weighed against the potential reduction in battery lifespan.

The cost estimation below is determined by low-volume (1000 pieces) pricing from suppliers such as Farnell, Digikey, Mouser, etc., collected at the end of 2020 before the global semiconductor shortage. The fixed costs include components for voltage and current measurement, gate drivers, etc., totaling $23 \$$ per battery module for the presented prototype. At the pack level for the prototype, it totals $390 \$$ including $204 \$$ for the MOSFETs. Compared to the battery cost of $8300 \$$ for the constructed demonstrator, the component overhead is 4.7% . The MOSFETs need to be scaled-up in a full-scale system, and the cost is therefore expected to increase linearly with the battery size while the fixed cost is the same. For a 48 V , full size EV with series-charging and parallel-discharging system, the low-volume component costs are estimated to be $1660 \$$, which is about 3% of the battery cost.

5. Conclusions

A module-based reconfigurable battery system (RBS) for high-voltage charging and low-voltage driving is presented. It demonstrates a possible charging solution without additional power converters for a safe-to-touch 48 V electric vehicle (EV) that uses existing high-voltage charging infrastructure. For a scaled-up version of the designed demonstrator, the overhead cost of the reconfiguration system is about 3% for a full-size EV. The performance loss in a World harmonized Light-duty vehicles Test Procedure (WLTP) drive cycle is 0.24% due to the additional resistive losses. The cost savings achieved through the reduced isolation effort required for low-voltage EVs may compensate for the increased cost of the reconfiguration system. The interconnects between battery and drive are always kept below 60 V. During charging, however, some interconnects inside the battery pack are applied to high potential and need to be disconnected in case of a malfunction. During driving operation, the highest voltage in the vehicle and battery remains below 60 V, making the EV safe-to-touch in accident situations.

Without special effort in battery selection and connection wire matching, the module balancing was within $\pm 10\%$ and could be improved further. The module imbalances observed were not found to systematically associate with switch and wire resistances, and thus should therefore relate to the production spread of the used cells and modules.

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