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Máthé, László; Schaltz, Erik; Teodorescu, Remus; Haddioui, Marcos Rejas

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Multi-functional Converter with Integrated Motor Control, Battery Charging and Active Module Balancing for Electric Vehicular Application

Laszlo Mathe
Dep. of Energy Technology
Aalborg University
Aalborg, Denmark
lam@et.aau.dk

Erik Schaltz
Dep. of Energy Technology
Aalborg University
Aalborg, Denmark
esc@et.aau.dk

Remus Teodorescu
Dep. of Energy Technology
Aalborg University
Aalborg, Denmark
ret@et.aau.dk

Marcos Rejas Haddioui
Dep. of Energy Technology
Aalborg University
Aalborg, Denmark
mrejas13@student.aau.dk

Abstract— In order to reduce the fuel consumption and the acoustical noise generated by refuse lorries, electrification of the waste compactor unit is a very promising solution. For the electrical energy storage Lithium-Sulfur (Li-S) battery technology has been selected with potential for reducing the cost, weight and volume in comparison with other Li-Ion based chemistries. The control of the energy flow has been done through a Modular Multilevel Converter (MMC), which has demonstrated advantages over 2 level converters in terms of efficiency, fault tolerant operation, flexible operation modes. It has been used successfully in HVDC/FACTS and large drive applications. In this paper the use of MMC for a battery driven waste compactor unit addressed with integrated functionality including: motor driver, battery charge and active balancing is presented. The challenges addressed here are related to the design of control strategy and current ripple reduction through the battery for life time extension.

Keywords—Li-Ion batteries, Li-S, MMC, motor control, battery charger, active balancing

I. INTRODUCTION

A traditional refuse lorry is noisy and therefore annoys the refuse collectors and citizens and in the same time is a source of pollution. Electrification is a means of these issues. However, in order to reduce the fuel consumption and thereby lowering the CO₂ emissions and to improve the working environment of the refuse collectors it is not necessary to electrify all processes of a refuse lorry. The lift and compactor of a refuse lorry is traditionally driven by a diesel engine, but in this work an electric system of the same is used as application. By electrifying the lift and compactor and maintaining the internal combustion engine only for propulsion purpose a cost effective solution of a green refuse lorry can be obtained. Commercial Electronic Power Takeoffs (EPTOs) for refuse lorries already exist [1]. However, these EPTOs are based on a traditional electrical power system, i.e. a battery pack connected to a two-level inverter which then controls the motor for the lift and compaction. For charging purpose a separately onboard three phase charger is connected

to the battery pack. A Battery Management System (BMS) is monitoring, protecting and balancing the cells. The system diagram can be seen in Fig. 1.

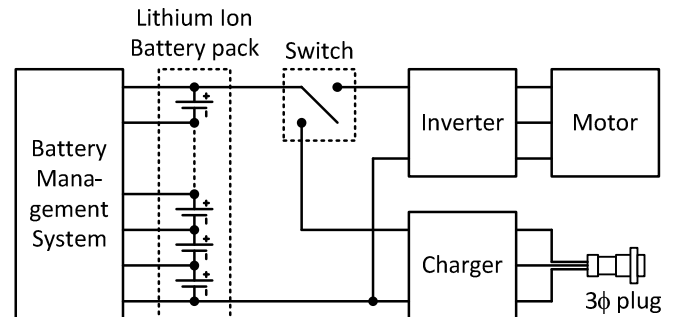


Fig. 1. Diagram of commercial available Electronic Power Takeoff for lift, compaction and charging of a refuse lorry.

The system shown in Fig. 1 is relatively simple and well known. However, for vehicle applications it's important to have a light system which doesn't require too much space. Research has shown that Modular Multilevel Converters (MMC) provides some interesting features for battery applications [2],[3],[4]. MMC switches with the fundamental frequency and the switching losses and electromagnetic radiation is therefore very low. Due to the near-sinusoidal voltage generation it is obvious to use the MMC for charging purpose also, because only a very small grid-filter is necessary. The MMC also has the capability to control the energy flow of each module individually. Thereby BMS functionalities can also be applied in the MMC. All-in-all the MMC provides a very compact alternative to the traditionally power system as the motor control, charging and module balancing can be integrated in the same device. In this work the three modes of operation of a MMC: motor control, charging control and module balancing during idling, for a refuse lorry application will be presented.

II. LI-S BATTERY

The type of battery cells used for the MMC are Lithium-Sulfur (Li-S). Cells based on Li-S chemistry are the latest

generation of lithium cells is on the edge of market introduction. Li-S cells have a higher specific energy than other Lithium-Ion (Li-Ion) chemistries on the market. A specific energy at 200 - 350 Wh/kg on cell level have already been demonstrated and 400 - 600 Wh/kg is soon expected [5], [6]. Another big advantage of Li-S cells over the conventional Li-Ion chemistries is the inherent safety which is very important for vehicular applications. Due to cheap raw materials it is also expected that Li-S cells will be less expensive than competitive Li-Ion chemistries. Li-S cells are still operational during and after iron nail (see Fig. 2) or bullet penetration. They can also be short circuit, over charged or crushed without catching fire.



Fig. 2: Iron nail penetration of Li-S cell [5].

Disadvantages of Li-S cells are lower cell voltage (2.1 V nominal) and shorter life cycle. However, soon 2000 cycles are expected before the capacity has reached the end-of-life, i.e. 80 % of the initial capacity [5].

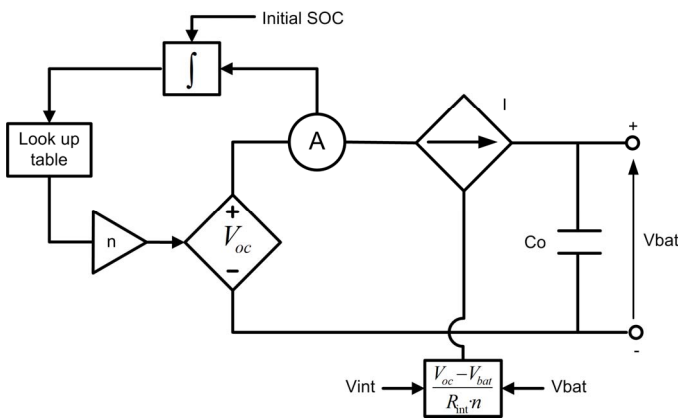


Fig. 3. Li-S battery model.

The LiS battery model consists in controllable voltage source, a controllable current source that models the internal resistance of the battery and an output capacitance in order to model the dynamic response.

Three assumptions have been made in the model: constant cell temperature, constant internal resistance and a current rate (c-rate) less than 1.

By integrating the current and considering the initial State of Charge (SOC), it can be calculated the actual SOC in the battery. This value is introduced in a 1-dimension look up table, that contains the internal voltage versus the SOC, both in vector form with the data extracted from the battery datasheet. This model can be used for any number of cells in series by adjusting the parameter n .

III. MODULAR MULTILEVEL CONVERTER INTRODUCTION

The main idea behind modular multilevel converters (MMC) is to increase the number of discrete voltage levels at the output of the converter. In this way the current ripple is reduced, which results in smaller sizes for the filters in grid connected application, or higher efficiency in motor drive application. The MMC topology for multilevel inverters presented in Fig. 4 (a), has the advantage of easy manufacturing, because similar smaller size modules has to be built. By adding redundant modules the reliability of the converter can be increased [7]. Each sub-module works at a fraction of the full DC voltage, so the components used in the converter does not have to block the full DC-link voltage. In order to achieve high dynamics, the full bridge topology has been used, as it is shown in Fig. 4 (b).

A challenge for the battery driven motor drive is that it cannot be ensured all the battery cells are discharged in the same manner. Thus, a BMS is needed in order to ensure the balancing of SOC for the battery cells. With the MMC concept it can be controlled how much energy is taken out or charged in a sub-module, therefore the balancing can be done by proper control without additional hardware.

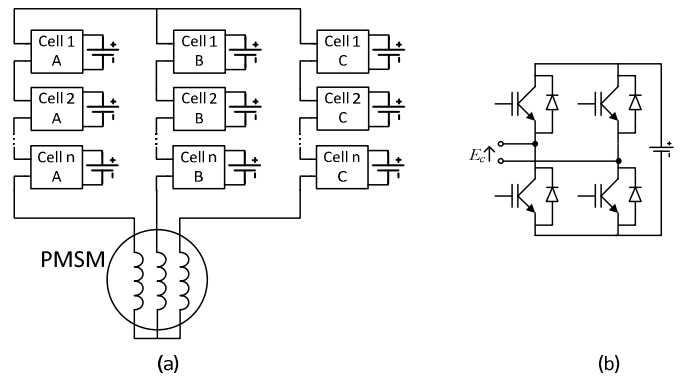


Fig. 4. Modular converter using battery as storage, a) the Motor control using MMC, b) topology used in one module.

IV. CONTROL STRATEGY

Three independent control schemes have to be used in order to operate the electrically driven compactor. In Fig. 5 a block scheme of the control process is presented, with the motor control and the battery charging.

The motor control algorithm is based on vector control principle which consist a closed loop current regulator which ensures constant torque for the compactor. The measured motor currents and the rotor position is the feedback signal for the control block. In many applications the rotor position is estimated based on the motor current measurement. This technique is called sensorless control [8]. Its main disadvantages are the low performance at close to zero rotor speed and the need for higher calculation power. As an advantage it has to be mentioned the cost effectiveness due to avoiding the use of an expensive mechanical position sensor.

The battery charging is done through the MMC, by disconnecting the motor and connecting the grid instead through an inductance. The motor winding can be also used as inductors [9]. The batteries have to be charged with a constant current, this is why the input for the control block is the reference battery charging current i_{ref} .

The control is very similar to the motor control algorithm; here instead of the synchronization with the rotor position the synchronization has to be made with the grid voltage. Several Phase Lock Loop (PLL) algorithms have been developed recently for synchronization with the grid for renewable energy generation [10].

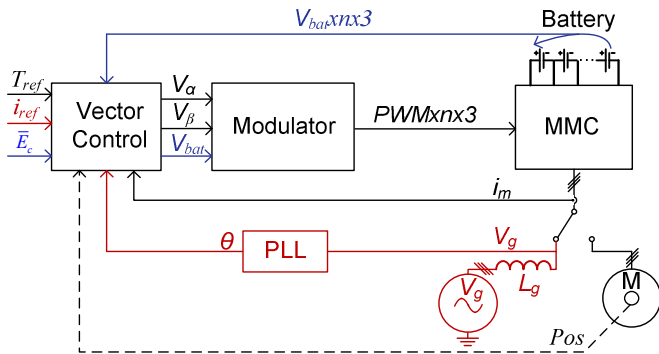


Fig. 5. Block scheme of the motor control and charging,

The above presented two control algorithms are totally independent; they cannot run in the same time.

V. BALANCING CONTROL

The balancing control should ensure the SOC balancing at two levels: cell-level and stack level.

A. Cell-level balancing

In this work the battery modules are composed of groups of 32 individual cells, where flying capacitors are responsible to balance the voltage of each cell as is shown in Fig. 6 by connecting a capacitor in parallel to the first cell from the battery stack it will charge up to the voltage of the battery.

In case the second cell from the battery pack has lower voltage than the first, by connecting this capacitor charged to a higher voltage, this cell it will discharge the capacitor till it reach the

same voltage as the second battery cell. In this way, the amount of energy the first cell charged in the capacitor is pumped in the second cell. By switching this bank of flying capacitors in parallel the bank of battery cells, as shown in Fig. 6, it can be ensured to have balance between the cells. This balancing method can be done in open loop by applying a rectangular signal to the gate of the switches as it is shown in Fig. 6.

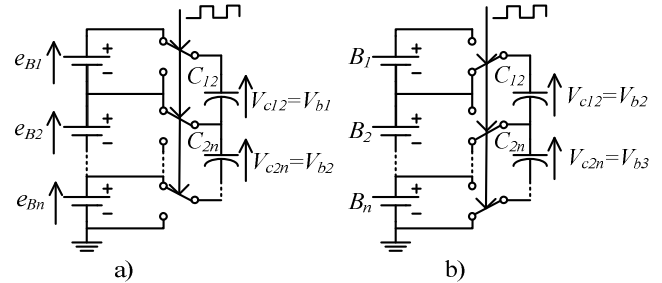


Fig. 6. Battery balancing at cell level by employing flying capacitors.

B. Module level balancing

The balancing between a stack of cells which are connected to one MMC sub-module can be done through the control of the MMC converter when in stand-by mode.

One strategy to ensure the module-level balance between the sub-modules is a sort and select algorithm, where two sub-modules with the highest difference in the state of charge are connected in parallel through the motor windings as it can be seen in (a). By switching on T_{2j} , T_{3j} from module j and T_{1k} , T_{4k} from module k , the batteries plus terminals are connected through the inductance and resistance while the negative terminals are connected directly forming a circuit sketched in (b). Similar circuit can be obtained by switching on T_{1j} , T_{4j} , T_{2k} , and T_{3k} with the difference the inductor with the resistance is connected between the negative terminals.

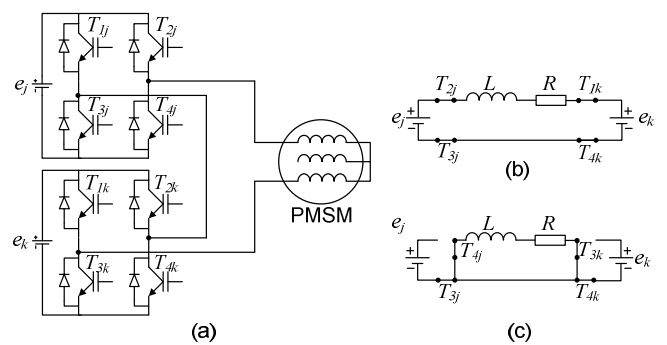


Fig. 7. Balancing of two battery modules connected to each sub-module.

The L and R are equal with the sum of the inductance and resistance of the two motor windings. The current will flow from the cell with the highest SOC to the one with the lowest

and it will become zero when they have equal charge. In case of the voltage difference between the cells is large the current which transfers the energy between the cells becomes also high. This high current can damage the motor or the cells. In order to reduce the current both modules can be bypassed by switching on T_{3j} , T_{4j} , T_{3k} , and T_{4k} forming a circuit shown in (c). Due to the high inductance of the motor, the dynamics of the system are low; with a simple hysteresis control it can be maintained the current in the safety region.

VI. SIMULATION RESULTS

A simulation model, presented in Fig. 8, is set up in order to test the performance of the balancing strategy when 4 modules are used per phase. A worst case scenario is selected when one of the four modules is replaced, three are fully charged while one is charged at storing SOC. This charge balancing is usually done over the night when normal charging is performed.

An additional case is simulated, where the modules have a SOC difference between them of less than 5%. Simulation results for both cases can be found in Fig. 9 and Fig. 10 respectively. The resistances R1 and R2 are set to 0.1Ω while the inductances L1 and L2 are set to 3 mH, both corresponding to a 27 kW PMSM parameters. The control algorithm is running with a fixed frequency of 100 Hz

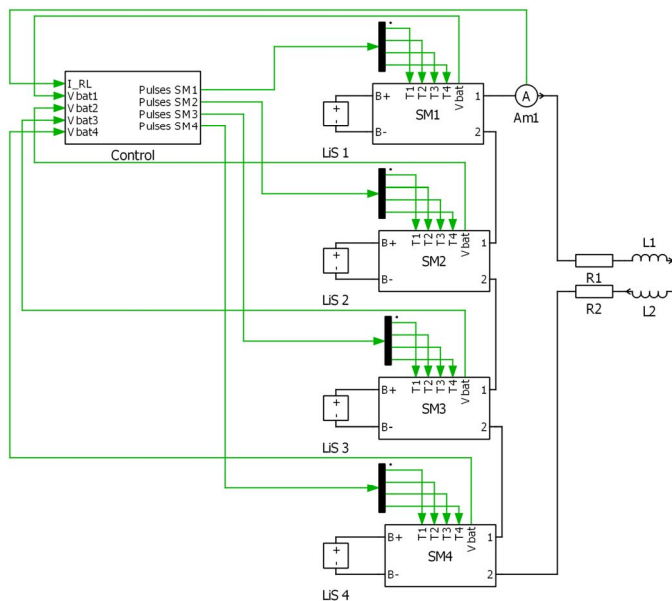


Fig. 8. Simulation model for balancing algorithm testing.

The inputs for the control block are the battery module voltages and the measured current through the RL circuit. At the first stage the SM with the largest battery pack voltage and the SM with the lowest voltage are selected. The other two SMs are bypassed by switching on T_{1x} and T_{2x} or T_{3x} and T_{4x} . By turning on T_{2j} , T_{3j} from the SM which has the higher voltage and T_{1k} , T_{4k} from the SM with lowest voltage the

circuit from (b) is realized. The voltages of the two battery modules start to equalize as it can be seen in Fig. 9.

The current through the RL has to be controlled in order to not damage the motor windings and cells. The current limit was set to $\pm 30A$ (limitation of the MMC-SM). When the current exceeds the limits, all the SMs are disconnected (all the 4 modules are bypassed as shown in (c)).

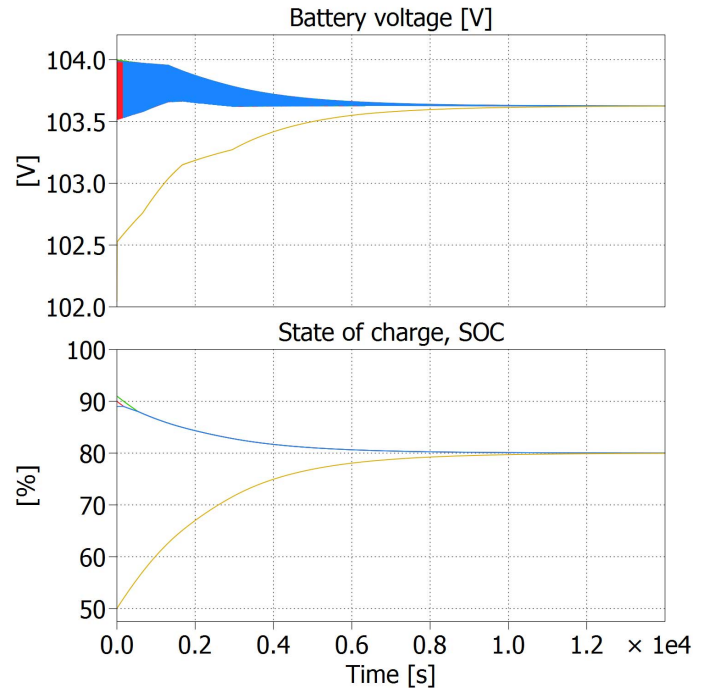


Fig. 9. Simulation results: three modules with around 90% SOC and one with 50% SOC.

In this first case, at the starting point, the three modules SOC are 91, 90 and 89% and the replaced module SOC is 50%. The control algorithm selects the module with the highest voltage and the module with the lowest. As the voltage difference between the three modules with higher SOC is small, in the next iteration of the control algorithm there is another module with higher voltage.

The control algorithm selects alternatively one module, therefore the SOC of the three modules with higher value are maintained almost equal. It can be noticed that after one hour the SOC difference is 9% approximately and after one and a half hours the SOC difference has been reduced to around 3%.

In this second case the SOC of the 4 stacks are: 78, 80, 82 and 83% that is close to normal operation. It can be noticed that the dynamic of the system is slower, due to the lower voltage difference between modules. This is not an important issue because during normal operation the waste compactor unit is working intermittently, where the balancing is performed during the standby period and thus the unbalance will be maintained low.

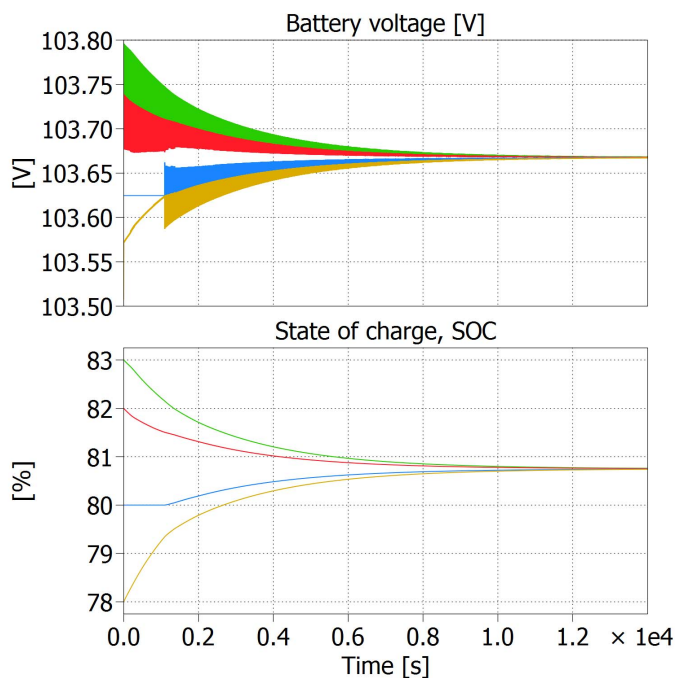


Fig. 10. Simulation results: unbalanced case with 83, 82, 80 and 78% SOC in each module.

VII. CONCLUSIONS

The electrification of the waste compactor from a refuse lorry by using MMC has been analyzed in this digest. The main purpose was to reduce the fuel consumption and the acoustic noise. Li-S batteries were selected to be used for electric energy storage, due to their high specific energy, high safety, and low costs. Due to the need of a balancing circuit which ensures the same state of charge for each battery cell, the MMC converter topology is proposed. Each sub-module of the MMC is connected to a battery pack. With this topology the motor control, battery charging and active module balancing

can be integrated in one converter unit. A balancing method has been presented and analyzed through simulations.

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