A Novel Energy Management System for Full Electric Vehicles.

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Abstract

Full Electric Vehicles (FEVs) is a type of Electric Vehicle (EV) in which all power is derived from electrical sources. Main disadvantages of FEVs are short driving range and low performance in demanding conditions. In this paper a novel battery-battery hybrid system is proposed. The system has a cell-scale energy management strategy in order to maintain modularity and compatibility. Also the system has ability of active battery voltage balancing without any extra effort. Additionally a semi-active hybridization strategy with a simple control scheme is introduced. Both system and the control strategy is introduced with details. Simulations are performed with different scenarios in order to demonstrate both voltage balancing and energy management capabilities of the system.

1. Introduction

Electric vehicles (EVs) can be classified as Hybrid Electric Vehicles (HEVs) in which an electric motor is used alongside an internal combustion engine, Plug-in Hybrid Electric Vehicles (PHEVs) which can be charged externally and Full Electric Vehicles (FEVs) in which only propulsion mechanism is an electric motor. Main deficiencies of FEVs are short driving range with single charge, low life span of battery stacks and low performance.

A common strategy to overcome these disadvantages is using supercapacitors (SCs) with batteries [1], but when compared to batteries SCs are more prone to voltage imbalances and they have lower energy densities and higher self-discharge rates [2]. Lithium-Ion batteries are lighter than other battery types with relatively higher energy and power densities, higher open circuit voltages and lower self-discharge rates then other battery types [3,4]. Moreover recent developments in lithium battery technology show that these batteries would be alternatives for SCs in EV applications in near future.

In this study a battery-battery hybrid energy system is proposed instead of a battery-SC hybrid. First battery type is a power dense, lithium-titanate (LTO) battery with power density of 1675 W/kg and a lifespan of 16000 cycles [5]. Second type battery is an energy dense, lithium-nickel-manganese-cobalt-oxide (NMC) battery with energy density of 160 Wh/kg and lifespan of 1400 cycles [6]. LTO battery is being operated in demanding conditions meanwhile duty of NMC battery to support LTO without exceeding a current limit.

Energy management is an important issue for EVs. In HEVs energy management is mostly based on fuel saving. Also in most of energy management approaches whole route information is assumed to be known. [7-12] To overcome this situation advanced optimization techniques are used [13-17] These approaches have heavy computational work as a result of advanced control techniques.

Main motivations of energy management in battery-SC are extending driving range and increasing performance. Energy management strategies for FEVs can be categorized under three headlines: passive, semi-active and active hybrids [18]. In passive hybridization both battery and the SC are connected in parallel with load [18-22]. Semi-active hybrids include a DC/DC converter in order to adjust voltage of a source with respect to other. There are three different configurations for semi-active hybrids. In battery semi-active hybrid battery and SCs are cascaded where the converter is placed between the battery and the load. The purpose of this configuration is to control battery current [23-25]. In capacitor semi-active hybridization DC/DC converter is placed between SC and the load to improve usage of SC energy [26-28]. The third configuration is called parallel or load semi-active hybridization. In this topology battery and the SC are connected in parallel where the DC/DC converter is placed between this parallel block and the load. This structure enables to satisfy high load demands with limited energy sources [28, 29]. Active hybridization topologies can also be categorized as series or parallel active hybrids. Series active hybrid topology can be achieved by adding another DC/DC converter to a semi-active hybrid where in parallel active hybrids all sources and the load are connected in parallel with DC/DC converters between each connection [28, 30-34]. For the energy management of LTO-NMC battery hybrid system, passive hybridization was studied and applied earlier [35]. It is shown that unlike battery-SC hybrids, huge Choke inductances should be used in order to achieve a successful hybridization.

The proposed system has a cell-scale hybridization in order to maintain modularity and compatibility with battery management and monitoring systems. Thus a semi-active hybridization strategy with a simple control scheme is introduced. Furthermore the system has ability of active battery voltage balancing without any extra effort.

2. Proposed system

Proposed system can be designed in different number of levels. Block diagram of a five level of the system is shown in Fig. 1. As seen from the figure LTO batteries are connected in series and directly connected to the load. Every level of the system includes a DC/DC converter. NMC batteries are placed in the other side of the converters. Cathodes of the batteries are connected to a common node where anodes are connected through a resistor. This part is called Share Bus and the resistors are called bus resistors. Battery voltage balancing is performed by the share bus. The left side of the system including LTO batteries and load are named as primary side meanwhile the right side is named as secondary side owing to the transformer in converter circuit.

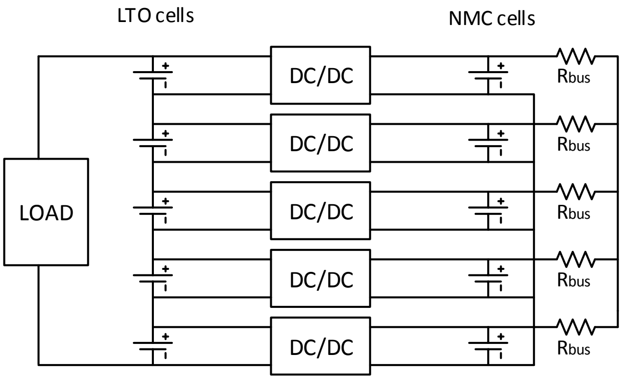


Fig. 1. Block diagram of the proposed system.

The circuit diagram for DC/DC converter is shown in Fig. 2.

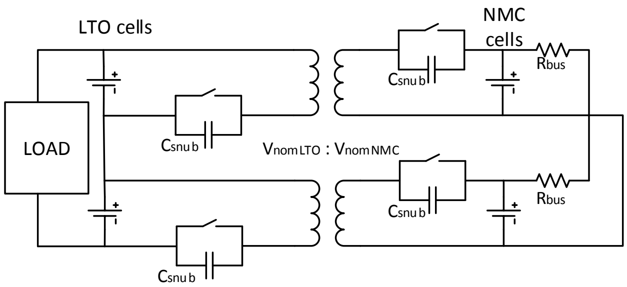


Fig. 2. Circuit diagram of the converter.

The circuit is basically an isolated bidirectional DC/DC converter where the voltage ratio of transformer is chosen as 2.8 to 4.2 which were the nominal voltages in room temperature of LTO and NMC batteries respectively [5, 6]. Switching elements of the converter is bidirectional and operated with 0.5 duty cycle. There are snubber capacitors connected parallel to switches. The values of capacitors are determined by using inductance of transformer and operating frequency. Thus a resonance circuit is formed when the switches are off.

Excitation current of transformer increases when the switch is on. When switch is off, the switch current decreases to zero and the excitation current redirects to capacitor. By this way the energy stored in transformer inductance is transferred to capacitor. Because of the operating frequency of the system is equal to resonance frequency, energy in capacitor will be transferred back to inductance precisely at the time of commutation. The switch will be on again when capacitor voltage is zero providing almost lossless switching.

The system is established and simulated in Simulink environments for different scenarios. The simulation setup can be seen in Fig. 3.

Simulation circuit consists of ideal switches, which were connected parallel with a series RC block. The turn ratio of transformer is 2.8 V to 4.2 V. Both LTO and NMC batteries are modeled by using template (battery block) in Simulink.

3. Modes of Operation

There are three modes of operation for proposed system: idle, charge and discharge modes.

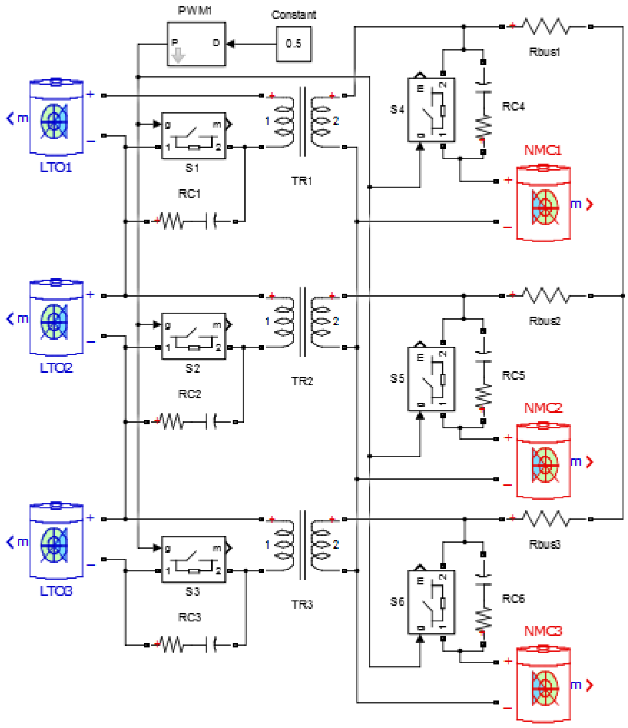


Fig. 3. Simulation circuit of the proposed system

3.1. Idle Mode

In this mode system works as an active voltage balancing circuit. System stays idle unless there is an unbalancing condition.

Secondary side of the system including five batteries is shown in Fig. 4. Cathodes of NMC batteries are connected to a share bus through bus resistors where anodes of batteries are connected to a common node. This concept is called balancing through a share bus [36].

If voltage level of some cells in the stack is lower than others, current will flow from high cells to the low ones. All cell voltages will be balanced at the average voltage level (V_{ave}). The balancing current for each cell can be calculated as given in (1).

$$I_{cell} = \frac{V_{cell} - V_{average}}{R_{bus}} \tag{1}$$

Where V_{cell} is the actual cell voltage and V_{ave} is the average voltage level of the stack.

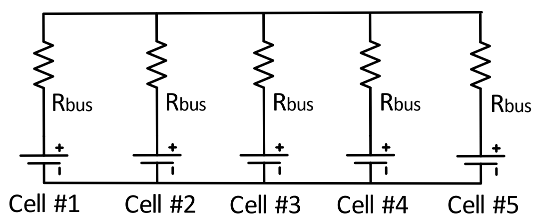


Fig. 4. Secondary side of the system

There is a relation between two cells of the same level as in (2) because of maximum charge voltages of the batteries.

$$\frac{V_{LTO}}{V_{NMC}} = \frac{2}{3} \quad (2)$$

If an unbalancing condition occurs in primary side of the system it will be reflected to the secondary side through the transformer. The balancing operation will continue until all the cell voltages in secondary side (then primary side) is leveled. Let $V_{LTO_1}, V_{LTO_2} \dots V_{LTO_n}$ be the voltages of the batteries of the primary side, $V_{NMC_1}, V_{NMC_2} \dots V_{NMC_3}$ be the voltages of secondary side and N_1/N_2 be the transformation ratio in the system. Average cell voltages can be calculated by using (3) and (4) respectively for primary and secondary sides.

$$V_{LTO_{ave}} = \frac{V_{LTO_1} + V_{LTO_2} + \cdots + V_{LTO_n}}{n} \quad (3)$$

$$V_{NMC_{ave}} = \frac{V_{NMC_1} + V_{NMC_2} + \cdots + V_{NMC_n}}{n} \quad (4)$$

Total voltage in the system will be sum of $V_{LTO_{ave}}$ and $V_{NMC_{ave}}$. After balancing operation cell voltages for each LTO and NMC cell will be equal. New cell voltages for LTO and NMC cells can be found by using equations (5) and (6).

$$V_{LTO_{bal}} = \left(V_{LTO_{ave}} + V_{NMC_{ave}}\right) \frac{N_1}{N_1 + N_2} \quad (5)$$

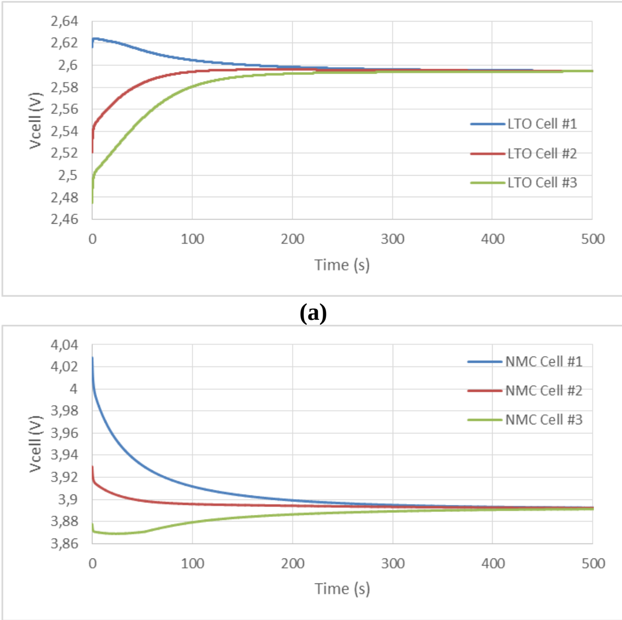
$$V_{NMC_{bal}} = \left(V_{LTO_{ave}} + V_{NMC_{ave}}\right) \frac{N_2}{N_1 + N_2} \quad (6)$$

Balancing process is simulated in a 3 level system as shown in Fig. 3. State of Charge (SoC) for each cell is set to 95%, 90% and 85% for both LTO and NMC cells. Corresponding voltages for this charge states are $V_{LTO_1} = 2.6166$ V, $V_{LTO_2} = 2.5209\,V$ and $V_{LTO_3} = 2.4754\,V$. Average voltage level in primary side of the system can be found $V_{LTO_{ave}} = 2.5376\,V$ by using (3). Similarly voltage values for NMC batteries are $V_{NMC_1} = 4.0283\,V, V_{NMC_2} = 3.9297\,V$ and $V_{NMC_3} = 3.8776\,V$ and average voltage in secondary side can be found $V_{NMC_{ave}} = 3.9452\,V$ by using (4). Considering the turn ratio of transformer as 2/3, from (5) and (6), voltage levels after balancing are 2.5931 V and 3.9452 V respectively for LTO and NMC cells. Results of this simulation is given in Fig. 5.

3.2. Discharge Mode

In discharge mode load is directly applied to LTO cells in primary side. During this operation NMC cells continues balancing duty if there is an unbalancing situation. Otherwise NMC cells support LTO cells by maintaining voltage ratio of the transformer.

Several simulations are performed in order to observe this mode. At first fully charged three LTO batteries connected in series, are discharged by using a load of 80 A in order to observe the response of batteries without proposed system. The simulation is repeated by using the system with fully charged NMC cells in the secondary side. Results can be seen in Fig. 6.



(a) **(b)**

Fig. 5. Simulation results for **(a)** LTO **(b)** NMC cells.

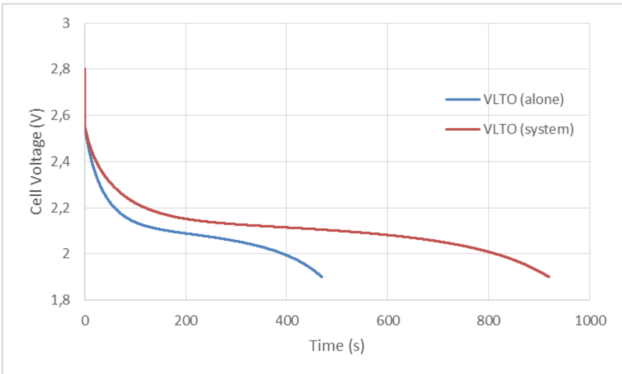


Fig. 6. Comparison of voltage signals of LTO cells under 80 A load.

It can be seen from the figure series LTO cells totally discharged in 469 s. With proposed system this duration increases to 919 s.

Another simulation with same conditions but different cell voltages for is done with LTO and NMC cells with different voltage levels. SoCs of cells are set to 100%, 90%, 80% for both cells. Where the cell voltages are $V_{NMC_1} = 4.21\,V, V_{NMC_2} = 3.9297$ and $V_{NMC_3} = 3.8494\,V$ for NMC cells and $V_{LTO_1} = 2.5547, V_{LTO_2} = 2.2569$ and $V_{LTO_3} = 2.1895\,V$ for LTO cells. The purpose of this simulation is to show that balancing operation can continue during discharge. Results are given in Fig. 7.

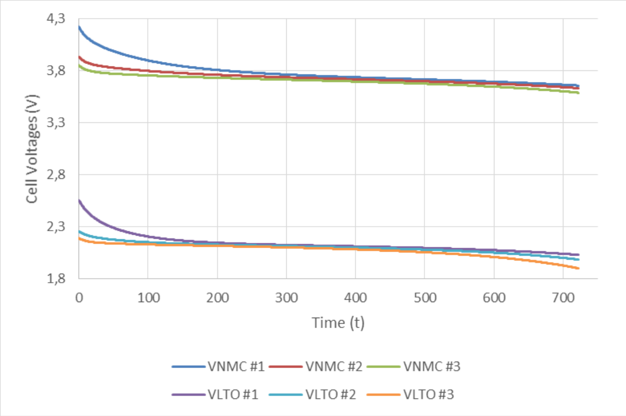


Fig. 7. Balancing during discharge.

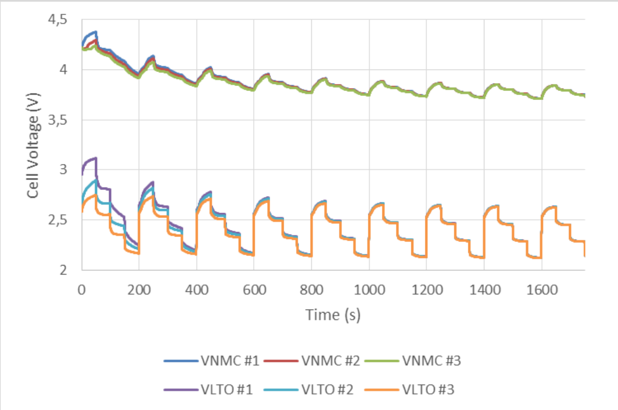


Fig. 8. Balancing under variable load profile.

3.3. Charge Mode

Operation in charge mode is almost same with discharge.

Another simulation is done under variable load conditions. The load profile consists of 50 seconds parts of 40 A charge, idle mode, 40 A discharge and 80 A discharge repeatedly. SoCs of LTO cells are 100%, 90% and 80% where all NMC cells are fully charged. Cell voltages are, $V_{LTO_1} = 2.9506\,V, V_{LTO_2} = 2.6529, V_{LTO_3} = 2.5854$ where $V_{NMC} = 4.218\,V$.

4. Conclusions

The novel energy management system which is proposed in this study provides a successful solution for both short driving range and low performance issues of FEVs. The most important feature of the system is simplicity of control. Energy management approach is based on using power dense LTO cells as main energy sources while supporting them with energy dense NMC cells. The simulation results show that battery runtime is extended almost 2 times with the system. An effortless solution to battery voltage imbalances is also obtained by zero voltage switching DC/DC converter circuit, The validity of balancing scheme during both in no-load and in charge or discharge operations is shown with simulations either. Studies on implementation of the system is still ongoing.

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