Potential evaluation of e-traction systems using active battery switching

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***Abstract*—This paper describes the research results of the use of an active battery switching to increase the efficiency of an electric vehicle drive train. The aim of this work is to quantify the improvements of the efficiency and thus the range of electric vehicles by use of a new battery switching system which allows to change the battery pack interconnections during use to adapt the battery pack to the operating point of the drive train. Therefore the intermediate circuit voltage can be changed from 60 V to 120 V and backwards by just adding an additional main contactor. Thus this system can be very cost effective.**

Keywords—electric vehicle, battery, efficiency, drive train, battery pack, switching system

I. INTRODUCTION

The range and the costs are the main problems of electric vehicles today. The electric drive train offers multiple possibilities of improvement. Possible fields of research could be the electric motor, the inverter, the battery pack or additional systems to the standard electric drive train. Efforts were already made and are still in progress to improve the battery cell technology to address those problems as the battery technology is expected to show the largest improvements compared to the other components. But there are also additional systems to face those difficulties. One could be the new battery switching system which is described in this paper. This system is nearly independent of the progress in battery cell technology and works additionally to improvements in this field. The patent about this technology was filed in 2012 [1].

Some efforts to improve the efficiency of electric vehicle drive trains by additional systems were made during the previous years. Those systems include an additional DCDC-converter in the drive train between the battery pack or single battery modules and the inverter. The main function of the additional DCDC-converter is to enlarge the battery voltage for dedicated operating points of the electric drive train [2 - 4]. In operating points with low speed of the electric motor, the DCDC-converters might be switched of and thus the intermediate circuit voltage is low [2]. This way of operating shows improved efficiency compared to a common battery pack with higher and not adjustable voltage. For higher speeds of the electric motor the DCDC-converter is switched on and increases the intermediate circuit voltage continuously to a maximum while the speed of the electric motor is increased above a threshold speed. The aim is to improve the efficiency of the inverter and the electric motor by this system to overcompensate the losses caused by the additional DCDC-converter in the drive train. While this operating strategy shows improvements of the overall efficiency to the electric drive train for operating points with low speed of the electric motor it shows disadvantages for high motor speeds. This is caused by the losses of the additional DCDC-converter which reduces the overall efficiency above a certain operating point of the electric drive train. Although these systems can show overall improvements of the efficiency of the electric drive train while regarding different drive cycles. A disadvantage are the additional costs of the DCDC-converter.

The second known system uses DCDC-converters separately for each battery module [3, 4]. The voltage of each module is limited to 60 V maximum for safety issues. The whole battery system consists at least out of two modules. The DCDC-converters transform the battery voltage to the needed intermediate circuit voltage. Advantages concerning the efficiency could only be observed in urban driving cycles. The losses could be reduced about up to 2.2 % in special cases [4]. Rural and highway driving cycles showed worse efficiencies. The losses of the highway driving cycle was increased about up to 3.6 % in special cases [4]. Another disadvantage of this system are again the high additional costs of the DCDC-converters.

Within the joint research project FORELMO funded by the Bavarian Research Foundation the new active battery switching invented at the Technische Universitaet Muenchen is analyzed besides several other aspects of research concerning the electric drive train. The battery switching system shows a simple but effective design and thus could be less cost intensive while the overall efficiency of the electric drive train could be increased. The quantification of potential efficiency improvements is focused in this paper.

II. BATTERY SWITCHING SYSTEM

A. Describtion of the System

The active battery switching system to increase the overall efficiency of electric drive trains, which is suggested in this paper, requires a battery pack which consists of several battery modules. The simplest system requires a battery pack out of two battery modules which both have the same size, thus the same amount of cells in series and in parallel. Additionally an active balancing system is suggested to be able to balance the voltages of the two modules. The active battery switching system is able to either switch the two modules in series or in parallel. Thus the voltage of the battery pack can be 100 % of a comparable battery pack of the state of the art without adjustable voltage and 50 % of that voltage. The operating strategy of the active battery switching allows to change the intermediate circuit voltage during use of the electric drive train according to the current operating point. Thus the overall efficiency can be improved as described in [2]. Besides the lower costs the advantage of this system compared to the systems of the state of the art [2 – 4] is that the losses caused by the switches (e.g. MOSFET) are insignificantly small. Thus a better performance of the active switching system is expected.

The general buildup of the system is shown in Fig. 1. It shows the considered application with two battery modules used for this research. Systems including more than 2 modules and more than two resulting voltage levels are also considerable. But for first analysis a system out of two modules and two resulting voltage levels is ideal because it has reduced complexity while showing large effects. Additionally this system shows considerably the lowest costs for later use in serial production. Battery systems which have a maximum voltage of over 60 V require two main contactors besides several additional safety systems. In our case the battery pack consists out of two modules having 60 V maximum and thus the whole battery pack can reach 120 V operating voltage. Adding one additional main contactor allows to realize a battery switching system operated by the controller of the inverter. This reduces the additional costs for serial production to a minimum.

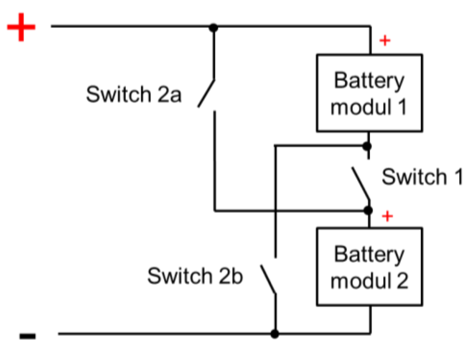

Fig. 1. General buildup of the battery switching system

As the battery modules only have 60 V maximum, it is allowed to use also MOSFET as main contactors. This allows a fast and efficient switching during use. With this battery system two intermediate circuit voltages, 60 and 120 V, can be selected depending on the operating point of the electric motor. Low motor speeds 60 V (around 50 V nominal voltage) might lead to better efficiencies while 120 V (around 100 V nominal voltage) is required for high motor speeds. Compared to systems with DCDC-converters there are no additional losses at higher motor speeds. The system should behave like a system of the state of the art in these operating points. Thus the overall efficiency of mixed driving cycles can be better compared to systems including DCDC-converters.

In case the vehicle is not used, all switches shown in Fig. 1 are switched of and thus the system voltage is set to 60 V maximum which is preferable because of safety issues. In use the vehicle battery is connected to the inverter by turning on switches 2a and 2b at first and for low motor speeds. To be able to reach higher motor speeds of rural and highway driving cycles switch 1 has to be turned on while the switches 2a and 2b have to be turned off. The behavior of the system from the driver’s point of view can be compared to the switching of the gearbox of a common car with internal combustion engine.

B. Switching strategy

The switching strategy is based on the results for the comparison of the overall efficiency between the state of the art drive train and the one using the new switched battery system. Figure 5 shows the area of expected efficiency improvement. There are operating points at higher motor speeds where the battery modules have to be connected in series to be able to reach these points. Thus in parallel mode it is not possible to reach every operating point which is a fundamental criterion and therefore has to be guaranteed at all times. In consideration of the fact to find the theoretical maximum of the efficiency improvement to examine the entire potential the switching strategy was defined as follows. A minimum motor speed was set as lower threshold speed to take care of the special shape of the cloud in Figure 5 to trigger switching into parallel mode. The upper limit looks similar to a constant power hyperbolic but in fact this line does not correspond to a constant value, so a look-up table was created to rebuild that curve. The use of a certain power level for triggering the switches is supposed to gain the maximum overall efficiency improvement. Nevertheless, there are a lot of other possible strategies, which are more likely to get into use, since they take aspects like acceptance and behavior of the driver into account. They are mentioned later in the conclusion part of this paper.

III. Simulation and Results

The analysis of the suggested active battery switching system is based on simulations using Mathworks MATLAB/Simulink and the IAV tool Velodyn. The modeling was done for a small electric vehicle having a weight of 975 kg and a continuous power of 25 kW of the electric motor. This data corresponds to the experimental vehicle built up within the FORELMO project, an electric driven Smart fortwo. The battery pack consists of cells of the standard type 18650 and is divided into two identical modules (Fig.1). The switches within the battery system are realized of MOSFET. They stand out with their low electrical resistances, thus their dissipated energy and losses are neglect ably low in every operating point.

A. Modelling

The modelling of the battery is based on Thevenin equivalent circuit models of 2nd order for the lithium-ion battery cells using parameters from [5]. In addition, the switching mechanism and an inverter model were realized this way whereat the model for the inverter was deduced by using highly detailed power loss equations given in [6]. As the software IAV Velodyn is based on MATLAB/Simulink, an easy integration of these models into the simulation environment is ensured. Figure 2 shows the highest modeling level with all components of the simulation environment.

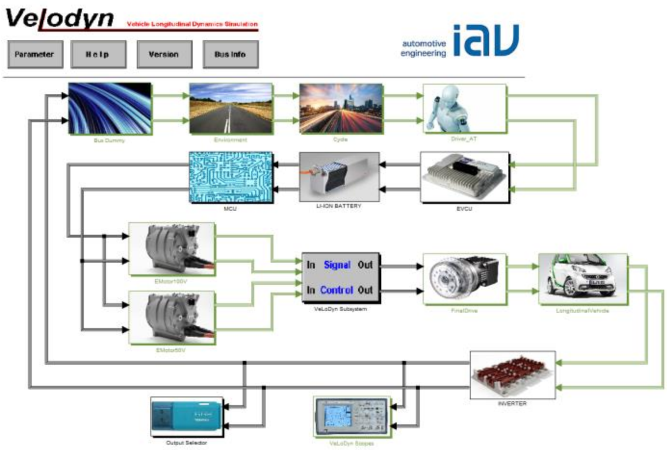

Fig. 2. Surface of Vehicle Longitudinal Dynamics Simulation

The simulated drive train in IAV Velodyn represents the main blocks namely the described battery pack with switching system, the above-mentioned inverter, an electric motor – an asynchronous machine (ASM) - and a gear box. The entire simulation is completed by models representing additional conditions like external influences of the car, the driver behavior, driving cycles and the environment itself (Fig. 2). Notice that no subsystems for additional consumer load are necessary for the performance evaluation of the drive train and therefore have not to be considered within the simulation. Taking a vast number of aspects concerning the longitudinal vehicle dynamics into account and offering a high modularity this model is tailored to tasks coming up in this research project like investigations on a special kind of drive train.

To be able to simulate the two intermediate circuit voltages in a proper way within the drive train, it was essential to use two engine characteristic maps of the electric motor controlled also by the switching system. This requirement was adjusted because the maps of the ASM where generated on the base of a real machine. There are many approaches to find the most beneficial solution for given properties between a vast number of possible electric machines. A powerful and promising approach is a so called e-motor synthesis described in [7] likewise the ASM for this application was deduced. The two characteristic maps are shown in Fig. 3 and 4 whereat Fig. 3 the efficiency map at 50 V and Fig. 4 the efficiency map at 100 V potential is shown. There are two characteristic maps of just one machine which stays electro-magnetically the same. Depending on the point of operation the switching system uses either the map with 50V or the one with 100V for simulating the electric motor model and this is why two motor-blocks are modeled (Fig. 2).

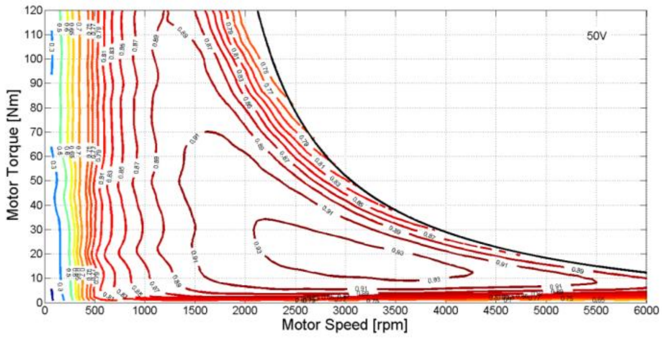

Fig. 3. Motor efficiency map at 50 V

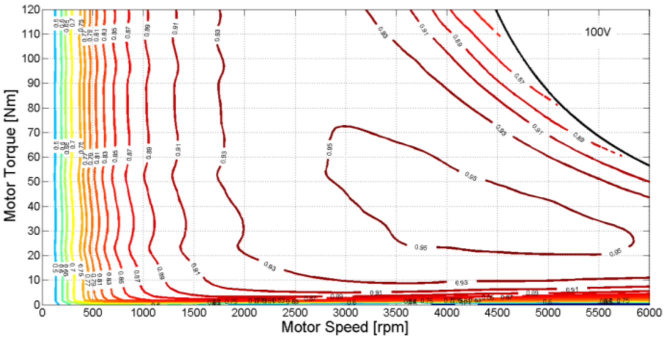

Fig. 4. Motor efficiency map at 100V

To be able to quantify the improvements of the efficiency an additional common electric drive train was modeled the same way having just one battery pack and showing only one nominal output voltage of 100V.

In consideration of comparability the simulations were conducted by using international standard driving cycles such as the New European Driving Cycle (NEDC), the US driving cycle FTP-72 and the Artemis Urban Driving Cycle (AUDC). The results were later on compared to those of the common drive train with the fixed voltage level as basis.

B. Results

The simulations revealed advantages for the active battery switching system and confirmed the theory declared at the beginning. An increase of the overall efficiency for the drive train with the new battery system to the conventional one is visible. Differences between the driving cycles can also be seen, which are caused by the nature of their velocity-time profile. Depending on the frequency distribution of the actual operating points within the cloud seen in Fig. 4, the switched battery packs become more or less useful.

As shown in Fig. 5, the efficiency is mainly improved between 500 to 1750 rpm but for low torques even up to 3000 rpm and more. For the area below 500 rpm an improvement of the efficiency is expected but not visible in the simulations. This is due to the methods which were used to create the motor efficiency maps out of simulated reengineering of a real electric motor. The data in this area unfortunately cannot be used for the analysis. Thus the increase of the overall efficiency could be even better than pointed out.

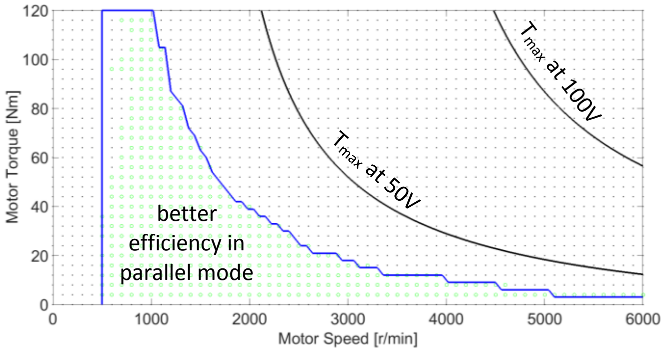

Fig. 5. Potential operating points with improvement of the overall efficiency

During the NEDC the state of the art drive train showed an average energy consumption of 14,59 $\frac{kWh}{100\ km}$ while the new switched battery system needed only 14,46 $\frac{kWh}{100\ km}$. Thus the overall efficiency in the driving cycle could be increased by nearly 1 %. Fig. 6 shows the distribution of dissipated energy and the share of each component within the drive train. As one can see the main part of about two-thirds comes along with unavoidable issues such as air drag or roll drag. For instance the NEDC speed profile requires at the end a top speed of 120 km/h and because of this combined urban and highway speed profile the loss due to mechanics is that high. Likewise only a slight improvement of 0,27% for the FTP-72 driving cycle could be determined.

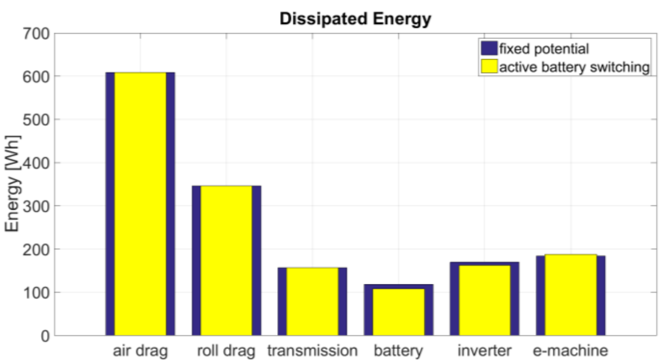

Fig. 6. Energy consumption during NEDC

The efficiency improvement using other cycles like the AUDC is supposed to be higher because their operating points are mainly within the cloud contoured in Figure 5. The simulation showed a reduction during the AUDC from a total energy loss of 639,38 Wh to 621,97 Wh which is an overall improvement of 2,7%. The positive trend is obviously strongly dependent of the speed time data provided by the various driving cycles. Following Table 1 compares the energy consumption of the new system to the standard one in above mentioned three different driving cycles. Scenario one is the common drivetrain with fixed potential whereas the second scenario represents the simulation with active battery switching.

	fixed potential	active battery switching
NEDC $[\frac{kWh}{100km}]$	14,59	14,46
Improvement	0,89%	
AUDC $[\frac{kWh}{100km}]$	13,66	13,29
Improvement	2,71%	
FTP-72 $[\frac{kWh}{100km}]$	12,78	12,14
Improvement	0,25%	

Tab. 1. Average energy consumption of the class A vehicle

Especially of interest to this project becomes the analysis of electrical losses since they are considered to be altering under the influence of the switched battery pack. Fig. 6 demonstrates the fact that mainly electrical losses change under the influence of the switching while mechanical ones are staying constant. Since the electrical mechanisms are focused in this research project, a more detailed analysis on each of the components is done. The battery as well as the inverter module are improving with the active switching strategy while the engines efficiency is deteriorating (Fig. 7).

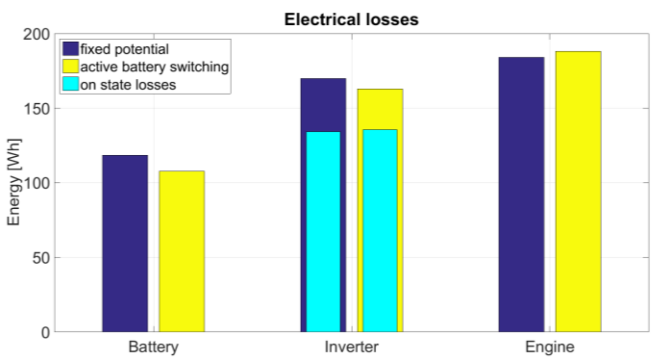

Fig. 7. Change of losses within the electric drivetrain

The strongest impact of an active battery pack was expected and also determined in the inverter module where the switching losses are considerably reduced by more than 22%

during a NEDC. The on state losses stay the same or even rise a little, because the lower voltage causes a higher current to guarantee enough power. Because of the small share of switching losses to the total amount of dissipated energy in the inverter module the benefit for the overall drivetrain is only minor. The distribution of switching and on state losses in total can be seen in Fig. 7 where again scenario 1 is the common drivetrain with fixed potential whereas scenario 2 represents the simulation with active battery switching.

As Fig. 3 and 4 already pointed out, the electric machine provides in almost all points of operation a better efficiency factor at the higher potential. Therefore the engine shows a higher energy demand of round 2%. Since the two performance maps differ only a bit the possible improvement for the total drivetrain strongly depends on the improvement in the remaining parts namely the inverter and the battery.

CONCLUSIONS

The results of the simulated drive train show that there is some potential with an active battery switching. Even without regarding the area below 500 rpm the improvement of the overall efficiency is visible and is around 0.2% and 2.7%. Since urban driving cycles typically often show phases of breaking down to low speed and acceleration afterwards the full potential of the system could not be described by simulations but the positive trend has been confirmed. Measurements on a test bench are recommended to prove the results of the simulation true.

Another interesting and supplementary aspect of this innovative concept for the drive train is the reciprocity of the components. Each single part could be designed under the same premise being used in this application to improve the total chain of effectiveness instead of independent optimizations. Collecting driver's data and creating a highly detailed job specification should support this approach.

Furthermore the simple structure consisting of only three main switches, the system can be controlled by the microcontroller of the inverter. Thus the system could be realized with less cost than systems including additional DCDC-converters. The possibility of offering e-mobility for lower costs is essential to the attractiveness of electric cars and their acceptance in general public. Notice that the less power provided by the system in parallel mode does neither handicap the driver nor prevents them of following the target course of speed. This is another interesting aspect for the acceptance of such a system for real drivers. Taking those kinds of additional criteria into account for a strategy to drive the system, on the one hand the complexity rises quickly and on the other hand the benefit of the switchable battery pack will decrease.

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REFERENCES

[1] R. Eckl, „Verfahren und Vorrichtung zur dynamischen Einstellung einer Betriebsspannung für einen Elektromotor", Applicant: Technical University of Munich, Germany, 102012214020A1, 2012.

[2] M. Hofmann, B. Eckardt, M. Maerz and L. Frey, „Effizienzoptimierung integrierter elektronischer Antriebssysteme für Hybrid- und Elektrofahrzeuge", in: Elektro Mobil Ausstellung 2010, Aschaffenburg, Germany, 8. October 2010.

[3] S. Rothgang, B. Lunz, M. Rosekeit and D. Sauer, „Modulare Batteriespeichersysteme mit dezentralen DC/DC-Wandlern für hohe Flexibilität und Zuverlässigkeit in stationären und mobilen Anwendungen", Batterietag NRW, Aachen, Germany, 2013.

[4] R. De Donker, M. Kowal and M. Biskoping, „Energieeffiziente Antriebstechnologien" in: vol. 1, ATZ/MTZ-Fachbuch, W. Siebenpfeiffer, 2013, chap. „Standardisierung von HV-Bordnetzen aus Sicht der Leistungselektronik", pp. 218-223.

[5] L. Lam, P. Bauer and E. Kelder, "A Practical Circuit-based Model for Li-ion Battery Cells in Electric Vehicle Applications", IEEE 33rd International Telecommunications Energy Conference (INTELEC) 2011, pp. 1-9.

[6] A. Wintrich, U. Nicolai, W. Tursky and T. Reimann, "Application Manual Power Semiconductors", Semikron International GmbH, ISLE Verlag, Illmenau, Germany 2011, pp. 283-285.

[7] J. Liebold, T. Schuhmann, M. Meyer, S. Paul, "Opimization of electric motors for automotive applications", 13th International CTI Symposium Berlin, 2014, Berlin, Germany, 10. December 2014.