Using Active Battery Switching Technology to Improve Electric Drivetrain Efficiency

CoFAT 2016

P. Wacker, J. Adermann, M. Lienkamp
Institute of Automotive Technology
Technical University of Munich
Garching, Germany
wacker@ftm.mw.tum.de

***Abstract*—this paper presents the results of research into the application of an active battery switching system in an electric vehicle's drivetrain. The system's purpose is to increase the drivetrain's electrical efficiency especially in the partial-load range. Efficiency is increased using a switching system that allows the vehicle's traction-battery circuitry to be changed during operation thereby adjusting the intermediate circuit voltage to that actually required. The system consists of three electronic switches, which allow two different voltages in the intermediate circuit. This paper presents the results of roller dynamometer test runs with this new system.**

Keywords—electric vehicle, electromobility, drivetrain, battery pack, efficiency, switching system

I. Introduction

Despite major battery-technology improvements in recent years, available traction energy in battery-powered electric vehicles is still severely limited and not comparable to that of conventional vehicle fuels. This fact results in markedly smaller vehicle ranges although the electric drivetrain's overall efficiency is significantly greater than that of conventional ones. Battery size essentially determines the amount of electrical energy available and thus the vehicle's maximum range. Since battery system's capacity is proportional to its weight and volume, a vehicle's battery cannot be enlarged arbitrarily. Furthermore, battery system costs also increase with battery size, and the battery already accounts for a large proportion of the overall costs. The better option is thus to use the available energy optimally via higher efficiency in the electric drivetrain.

Many previous research projects concentrated mainly on optimizing and improving the primary components—electric motor, inverter, and battery pack. Consequently, these have already attained very high efficiency. However, the problem is that the components' efficiency varies over the operating range but is heavily dependent upon torque and speed. Unfortunately, large values of more than 95% are only reached close to the design point due to load-independent losses in the high output-power area [3]. Vehicles are nonetheless typically not driven constantly at high power but most of the time at low and medium power. This applies even more to electric vehicles, since they are often designed for urban purposes. This fact can also be seen in the characteristic diagrams of typical driving cycles such as Artemis or NEDC [1]. The achievable overall efficiency in a realistic driving cycle is accordingly significantly lower than the optimum values. Thus it is hardly possible to further improve system effectiveness by regarding only the individual components.

One possibility for achieving this might be active battery switching technology, which the Technical University of Munich patented in 2014 [5]. The system was first described in [4] where the focus was on publication of the concept and simulation results. This paper presents measured data obtained from roller dynamometer tests, where active battery switching technology was integrated into the drivetrain of an electric vehicle.

II. State of the Art

Modern electric-vehicle drivetrains are fairly similar; only the type of battery, inverter and electric motor vary, and certain standard types exist. The components are chosen according to the vehicle manufacturer's preferences and the exigencies of the specific application. For instance, MOS-FETs as switching devices in an inverter are chosen for lower voltages and IGBTs for higher voltages. A more detailed description can be found in [6]. All series drivetrains have in common that the battery voltage is fixed at a certain level and varies only with the lithium-ion cells' state of charge.

However additional components of the drivetrain, which can help increase overall electrical efficiency by changing the intermediate circuit voltage, were presented in the field of research. Variation of the intermediate circuit voltage directly impacts the inverter's switching losses, which can be described for sinusoidal motor currents based on the following formula [7].

$$P_{sw} = \frac{f_{sw} E_{sw} \hat{I} U_{DC}}{\pi I_{c-sw} U_{DC-sw}} \quad (1)$$

where

P_{sw} = Inverter switching losses
f_{sw} = Inverter switching frequency
E_{sw} = Overall switching energy
$\hat{I}$ = Peak motor current
U_{DC} = Intermediate circuit voltage
I_{c-sw} = Reference current switching energy
U_{DC-sw} = Reference voltage switching energy

Reduced intermediate circuit voltage will clearly cause a linear decrease in the inverter's switching losses for the same operating parameters. A further advantage is that the motor's current ripple is also reduced, which minimizes eddy current and copper losses in the motor [3]. On the other hand, an intermediate circuit voltage reduction implies an offset of the motor operating map so that the maximum AC voltage is reached at a lower speed. Thus the field-weakening range must begin at lower speeds, and consequently a reduced intermediate circuit voltage leads to lower maximum motor speeds [3].

This coherence was exploited in several past research projects, for example [2] and [3]. Common to those concepts is the use of DC-DC converters between the battery and the inverter, thereby enabling a broad adjustment range of the intermediate circuit voltage. The outcomes are promising, because an overall electrical efficiency improvement of about 0.5% to 4% for typical driving cycles like the Artemis can be achieved with those systems. Nevertheless, the implementation is rather complicated and costly, since DC-DC converters are needed. Moreover, multiphase converters, which enable higher efficiency values through reduced internal converter losses, often increase the complexity. But otherwise it's difficult to obtain an efficiency improvement through intermediate circuit voltage reduction that overcompensates the DC-DC converter's losses.

Active battery switching technology might represent an alternative to existing concepts. The system is based on a simple but highly effective design, and is less cost-intensive [4]. This paper will quantify drivetrain efficiency improvements.

III. System description

Active battery switching technology involves systems that allow a battery pack's interconnection to change during operation. Thus it enables more than one intermediate circuit voltage to be supplied. The number of voltages depends on the number of battery modules that can be switched. The simplest layout requires a battery pack consisting of two modules containing the same number of cells in series and parallel. The implemented system, which is described in this paper, is a two-stage setup. It can thus supply 100% and 200% of the single-module voltage. MOS-FETs are used as switching devices, since they are very efficient, low priced and easy to apply. An optimized implementation for possible use in serial production could use the two mandatory main contactors adding an additional one. This would minimize overall system costs [4].

Several optimization measures were implemented to further improve the prototype of the active battery switching system (cf. fig. 1).

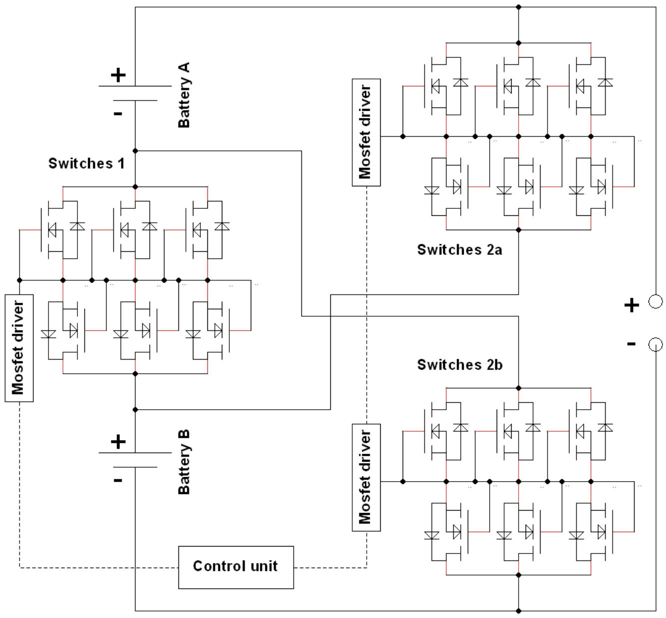

Figure 1: Active battery switching system

The major amendment is the switches' multiphase approach. MOS-FETs are still used as switching devices; however, every switching channel consists of three parallel MOS-FET pairs so that internal system losses are significantly reduced. Furthermore, the larger heat transition area facilitates thermal management. Moreover, the MOS-FET gate drive is fully galvanically isolated, which enhances the system's safety features. A dedicated control unit, which implements the operating strategy and communicates with the test vehicle's other ECUs, was also developed.

IV. Roller dynamometer tests

A. Test vehicle

Test runs were conducted in the test center for electric vehicles at the Fraunhofer Institute for Integrated Systems and Device Technology (IISB) in Erlangen. The fully air-conditioned all-wheel roller dynamometer was available for the tests. The active battery switching system was integrated into an electric Smart 451 for the experiments. The vehicle was first converted to electric drive and then prepared for roller bench testing. The battery and its management system as well as the main electronic control unit are proprietary developments. The inverter and the motor are purchased parts, which were selected to meet the requirements of the active battery switching system tests. Table 1 shows the specifications of the test vehicle and its drivetrain.

Table 1: Specification of the testing system

Vehicle	
Type	Smart 451 (converted to electric drive)
Range	about 180 km
Mass	about 950 kg
Battery	
Cells	Panasonic NCR18650PF
Quantity	Two modules each 1008 pcs.
Circuitry	14S 72P per module
Voltage	51.8 V nominal
Capacity	2x 10.82 kWh
Energy density	132 kWh/kg
Inverter	
Type	DMC superSigma2 QRM
Power	50 kW
Voltage	24 V to 120 V
Switches	MOSFETs
Frequency	16 kHz
Motor	
Type	Schwarz Elektromotoren AKOE 132
Technology	Asynchronous
Power	S1 25 kW/S2 35 kW
Torque	S1 55 Nm/S2 110 Nm
Gear ratio	1:5.7

B. Test procedure

The objective of the test runs was to obtain information about the overall efficiency of vehicle's drivetrain with and without use of the active battery switching system. In the interest of testing the system under realistic circumstances, it was decided to perform full vehicle tests on a roller dynamometer. Therefore, several sensor systems were needed to measure electrical and mechanical energy flow (see table 2).

Table 2: Measurement system of test rig

Voltage/Current	
Type	ISAscale IVT-MOD
Accuracy	±0.1%
Sampling rate	100 Hz
Position	Battery module 1+2, DC side of inverter
Torque	
Type	Roller bench measurement system
Accuracy	±0.1%
Position	Wheels, rear axle
Speed	
Type	Roller bench measurement system
Accuracy	±0.1%
Position	Wheels, rear axle

Particular emphasis was placed on the comparability of single test runs to obtain valuable results. Environmental influence was first minimized through constant temperature in the testing room. Moreover, the vehicle and the roller dynamometer were warmed up for a specific time before each test series until all components reached temperature equilibrium, which was constantly supervised and tracked by temperature sensors. To improve the accuracy even more, each test series was conducted several times in exactly the same sequence. To keep the results simple and easily interpretable, only torque-speed characteristic maps of the overall drivetrain with and without the active battery switching system were measured. Hence, a valuable database for analyzing the performance and characteristics of the new system was acquired. A further advantage of the drivetrain maps is the possibility of optimizing the operation strategy for the greatest achievable efficiency. Driving-cycle tests will follow in future research activities.

C. Results

Test-run results are presented below. Fig. 2 provides an initial overview of the active battery switching (ABS) system's benefits.

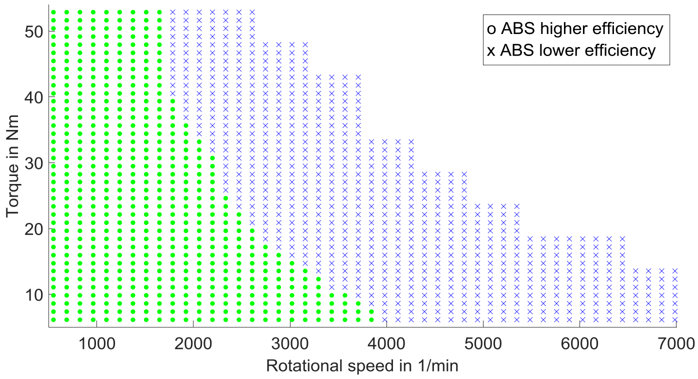

Figure 2: Overview of the efficiency of active battery switching

In Fig. 2, the active battery switching system's efficiency is compared to that of the conventional drivetrain in a torque-speed characteristic map, where the overall efficiency of the drivetrain from the battery to the wheels is considered. The circles represent the areas within the characteristics map where activation of the active battery switching system increases overall efficiency. At which activation means that the voltage is reduced to the low-voltage state through switching the two battery modules in parallel. In contrast, the crosses show the part of the map in which the conventional drivetrain without the active battery switching is more efficient.

It's apparent that the active battery switching system increases the drivetrain's efficiency across a great part of the operating range. Losses are reduced particularly in the area of low to partial loads. It also appears that the limits of the system are directly proportional neither to the torque nor rotational speed but are described in higher-order terms. More importantly, the results conform to previous simulations presented in [4]. However, this illustration only shows a qualitative analysis of the new system. Efficiency maps will be further considered below (cf. figs.3 and 4).

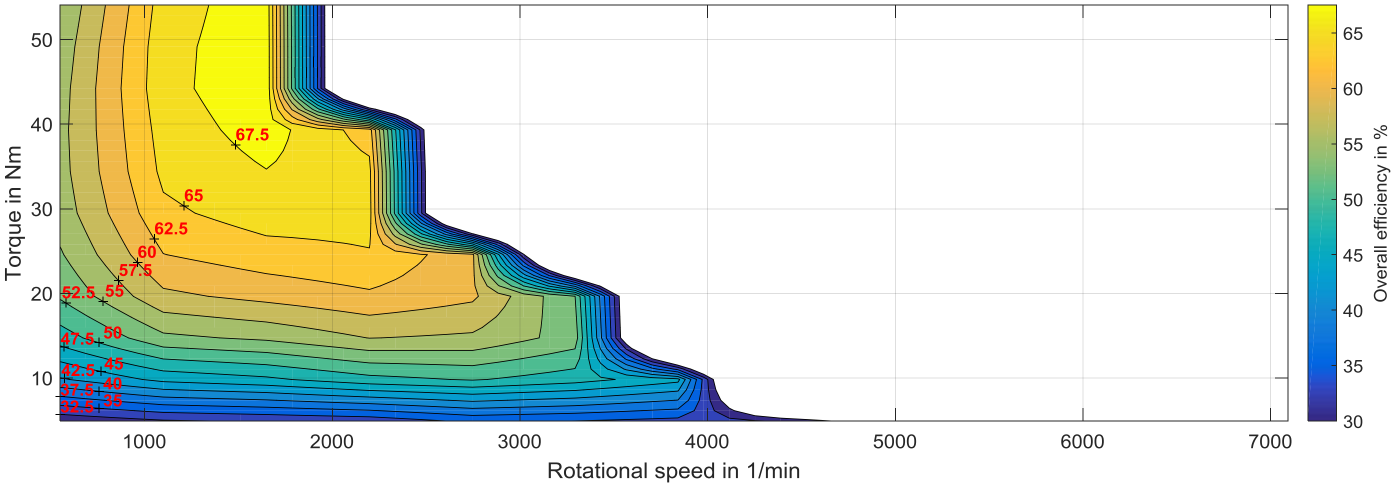

Figure 3: Overall efficiency map with the active battery switching system in the low-voltage state in %

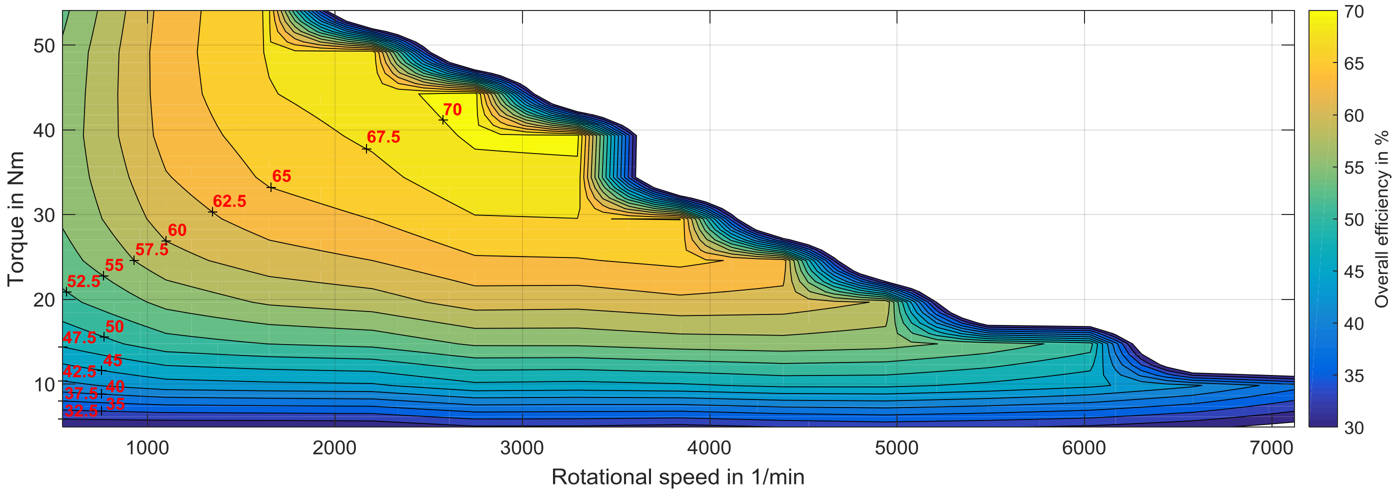

Figure 4: Overall efficiency map with the active battery switching system in the high-voltage state in %

The efficiency maps where obtained through stationary recording of operating points. For this purpose, the operating range of the drivetrain was split up into discrete measurement points of fixed torque and speed values. Those points were then driven on the roller dynamometer and the efficiency was measured after the system was fully stationary. This was done in several test series both in the high-voltage state of the active battery switching system and the low-voltage state. The results were then interpolated and ploted in figs. 3 and 4.

First of all it can be seen that the obtained efficiency maps meet expections for electrical drivetrains regarding the location of areas with higher and lower efficiency [3], [4]. The overall rather low values are due to the efficiency measurement over the entire drivetrain including transmission and tire losses. The influence of the active battery switching system is manifested by a displacement of the diagram in low and partial load towards the left bottom. Consequently, efficiency increases in this area in contrast to that in the high-voltage state. As expected, it also shows that the entire operating range is unobtainable in the low-voltage state. This is due to dislocation of the limiting speed causing the field-weakening area to be reached earlier, which limits the maximum rotational speed.

However, this is not a disadvantage of the new system, since the high-voltage state will become active in this operating area, which is then also more efficient. It therefore appears that the operating strategy is an important aspect that will be researched in further tests.

Efficiency maps give a good overview of the influence of the active battery switching system on the drivetrain. However, the quantitative benefits of the new system are difficult to recognize. The achievable efficiency improvements for several representative operating points are therefore presented in table 3. The percentages quoted represent the efficiency improvements of the low-voltage state compared with those of the high-voltage state. Empty fields mean that the high-voltage state is more beneficial. The active battery switching system's internal loses are not considered, but they are low and almost negligible due to the highly efficent MOS-FETs.

Table 3: Overview of efficiency improvement

Torque in Nm ↑ / Rotational speed in 1/min →	550	1100	1650	2200	2750	3300
54	0.8%	2.5%	1.5%	-	-	-
49	0.6%	2.7%	1.7%	-	-	-
44	0.7%	2.9%	2.1%	-	-	-
39	0.7%	2.6%	2.4%	-	-	-
34	0.8%	3.2%	2.0%	-	-	-
29	0.8%	3.4%	2.5%	0.9%	-	-
25	0.7%	3.4%	2.6%	2.3%	-	-
20	1.0%	3.7%	2.9%	3.2%	-	-
15	0.8%	3.0%	3.0%	4.4%	1.7%	-
10	0.4%	1.9%	2.7%	4.6%	3.3%	2.0%
5	0.4%	2.0%	2.5%	3.0%	3.4%	2.8%

Table 3 shows the quantified values of the efficiency improvements due to the active battery switching system under low and partial load. It can be seen that the gain depends on the operating point and peaks at 4.6%. The average efficiency increase is 2.2%, which is the arithmetic mean of all measuring points. But it appears that in realistic driving cycles, the average increase could be even higher since the lowest values are in the area of very low speeds of around 10 km/h. But the average speed is significantly higher even in city driving cycles, which means that the vehicle is traveling more extensively in areas of the operating range where the active battery switching system is more beneficial.

V. CONCLUSION

The technology researched in this paper shows a promising possibility for enhancing the efficiency of electric drivetrains and thus for increasing the range of electric vehicles. Especially less efficient low and partial loads are improved, which accounts for a great portion of typical use cases. It was demonstrated that the new technology can be realized and incorporated into the drivetrain of an electric vehicle, where the developed system is rather simple and low prized especially compared to DC-DC converters. This is due to the simple architecture and limited control systems needed. However, a detailed cost estimate for the active battery switching system and a cost comparison to available DC-DC converters is pending. This will be calculated in cooperation with industry partners in future research activities.

Roller dynamometer tests were performed that showed the benefits of the active battery switching technology. Depending on the operating point, the efficiency improvement can be up to 4.6%, which is comparable to the possibilities for DC-DC converters [3]. A direct comparison, especially regarding the possible efficiency benefit in driving cycle scenarios and usability issues, shall be performed in future research activities. The active battery switching system is unable to improve efficiency during high-performance operation, but the internal losses are very low so that only very small additional losses accrue. It was furthermore shown that the system is able to change voltage during normal vehicle operation. A detailed study of how the vehicle's occupants perceive the switching process and whether the dead time is noticeable will be performed in a subsequent research project.

Future investigations will also concentrate especially on driving-cycle analyses of the new technology. This will determine how much efficiency increase is possible in real driving cycles. The data obtained will furthermore help to implement an optimized operating strategy providing greatest possible efficiency and most improved driving characteristics. The number of switching stages is another important aspect that future research activities will address. At present, the easiest system architecture has been implemented; however, a system with more than two stages might be even more efficient. This nonetheless entails increased hardware complexity and costs.

Using the two mandatory main contactors plus an additional contactor could even further simplify the system for possible use in serial production. This would minimize overall system costs. A possible system architecture will be developed and analyzed in cooperation with industry partners.

In summary, the active battery switching system is a promising possibility for improving the characteristics and performance of drivetrains in electric vehicles. The unresolved problems and questions mentioned above will therefore be investigated in a new research project.

ACKNOWLEDGMENT

This work was supported by the Bavarian Research Foundation within the joint research project FORELMO.

CONTRIBUTIONS

P.W. developed the active battery switching concept further and designed its prototype. P.W. and J.A. built up the electric vehicle, defined the test procedure and conducted the roller dynamometer test runs. P.W. developed the operation strategy and J.A. implemented it on the control unit. P.W. evaluated the test results. M.L. made an essential contribution to the conception of the research project and revised the paper critically for important intellectual content. M.L. gave final approval of the version to be published and agrees to all aspects of the work. As a guarantor, M.L. accepts responsibility for the overall integrity of the paper.

REFERENCES

[1] E. Knischourek, K. Mühlbauer, D. Gerling, “Reduktion der Batteriekapazität in Elektrofahrzeugen durch Wirkungsgradsteigerung des elektrischen Antriebstranges,” in Tagung / Technische Weiterbildung - Haus der Technik, April 2012.

[2] T. Schoenen, M. Kunter, M. Hennen, R. Doncker, “Advantages of a variable dc-link voltage by using a dc-dc converter in hybrid-electric vehicles,” IEEE Vehicle Power and Propulsion Converence (VPPC), September 2010.

[3] M. Hofmann, B. Eckardt, M. März, L. Frey, “Efficiency optimization of integrated electrical drives for hybrid and electric vehicles,” Elektro Mobil Ausstellung (EMA), October 2010.

[4] R. Eckl, P. Wacker, A. Bullejos, M. Lienkamp, “Potential evaluation of e-traction systems using an active battery switching,” Conference on Future Automotive Technology (CoFAT), April 2015.

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

[6] H. Tschöke, “Die Elektrifizierung des Antriebsstrangs,” S.35-41, Springer Vieweg, Wiesbaden 2015.

[7] B. Eckardt, M. März, A. Schletz, “Application-specific design of power electronics for electric powertrains,” Elektrik/Elektronik in Hybrid- und Elektrofahrzeugen, November 2008