Modern High Voltage Drive Train Architecture to Accommodate the Needs for a Variety of Components for Future Automotive Applications
Conference on Future Automotive Technology: Focus Electromobility

Karsten Mueller[1] and Rico Heinrich[2]
[1] *Systems E-Traction Division, IAV GmbH, Gifhorn, Germany*
[2] *Transmission, Hybrid and Electrification, IAV Inc., Northville 48167, USA*
E-mail: karsten.mueller@iav.de, rico.heinrich@iav-usa.com

ABSTRACT: We can see a variety of different concepts in prototypes and series programs. In HEV drivetrains with power-split architecture, the use of a DC to DC boost converter between the high voltage battery and the voltage source inverter is widely spread for years. Though often discussed, a boost converter in a parallel hybrid (HEV) or pure electric vehicle (EV) drivetrain architecture has no break-through yet. By introducing a high voltage DC to DC converter to the (H)EV architecture, an additional degree of freedom is added to the system design. That can be used to develop new drivetrain concepts to improve efficiency of components, energy management strategy, system costs and add additional benefits for customers. The presentation will take a closer look at the effects and opportunities of a high voltage DC/DC converter for the overall drivetrain architecture.

Keywords: electrical drive train, DC boost converter, DC buck converter, MTPA, optimal DC-link voltage, high voltage drivetrain

1. INTRODUCTION

Currently we see an increasing number of different types of vehicles, which are already in production or just on tiheir way into dealer showrooms, equipped with components freshly developed to electrify our modern driving experience. One of the most sold and well known representative of its kind is the Toyota Prius in its third generation and a plug-in version since 2009.

Forced by politics, customer expectations, increasing oil prices, environmental responsibilities and the attraction of cutting edge technologies all major automotive OEMs are developing high voltage drivetrain architectures and their Tier 1 suppliers are following suit. This expansion leads to a huge variety of different types of architectures like pure electric vehicles (pure EV), Plug-in Hybrids, parallel Hybrids, serial Hybrids, EV with range extender devices, power splits and axle splits and many more. These varied types are equipped with an even greater assortment of unique high voltage components like (see Figure 1):

- Electrical Motors (EM)
    - Interior permanent magnet motors (IPMSM)
    - Induction motors (IM)
    - Switched reluctance motors (SRM)
    - Brushless DC motors (BLDC)
- Energy storage systems (ESS)
    - Lithium-Ion battery
    - Nickel-metal-hydride battery
    - Fuel cell system
    - Super capacitors (Super-caps)
    - Lithium-air battery
- Energy transfer and modulation devices
    - Voltage source inverter (VSI)
    - Low voltage DC to DC converter
    - High voltage DC to DC converter
    - AC to DC converter as charging devices
    - Inductive charging devices
- Auxiliary devices
    - High voltage climate compressor
    - PTC heating

One particular parameter drives the design for those components, listed above. The DC-link voltage is the key design parameter for all the different drivetrain architectures. The voltage level for the DC-link vehicle bus is commanded by the main source of electrical energy in the system (the high voltage battery, and for most systems). This dependency leads to severe limitations for the drivetrain architecture design, the component layout (especially the EM) as well as the energy management and control strategy.

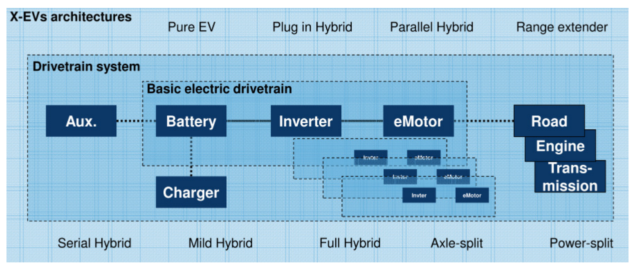

Figure 1: x-EV architectures

To overcome this limitation, a high voltage DC to DC converter could be used to decouple the ESS voltage level from the vehicle DC-bus voltage level and gain an extra degree of freedom to be leverage for system design, control and energy management.

A well-known example for such a kind of separation between ESS voltage level and vehicle DC-bus in certain drive situation is the Toyota Prius since its second generation. As described in [1] and [2], the changes resulted in system improvements for design, control and energy management.

This paper gives a more detailed insight of the effects of a high voltage DC to DC converter induced to pure electric vehicle architecture. It outlines different opportunities for the overall system design, which the automotive industry is presently facing. Aspects of potential energy savings, reduction of components variety and an increasing fulfilment of customer expectations are discussed. As summarized in this paper, there is a path outlined for future drivetrain architecture and set of components to reduce costs, increase efficiency and increase performance and customer expectations satisfaction.

2. SYSTEM ARCHITECTURE WITH HIGH VOLTAGE DC TO DC CONVERTER

2.1. Current DC-link bus design

When we look at the current DC-link bus design in common electrical drive trains, we see the situation outlined in Figure 2. We see a varying Lithium-Ion battery voltage, which is varying by the current State of Charge (SoC) and the current battery current I_{Bat}. Typical values for the lowest and highest allowed cell voltage are shown in Figure 2. At a cell voltage of 3.2 V the cell is considered as “fully” discharged and at a cell voltage of 4.2 V as “fully” charged.

Between those boundaries the typical cell voltage for a Lithium-Ion cell is about 3.7 V. For a battery pack with 100 cells in series connection that results in an operational battery pack voltage between 320 V and 420 V. Those boundaries are not fixed. They vary with the current operational temperature and the aging of the battery, too. To summarize, the battery pack output voltage depends on SoC, aging of the battery, temperature, current load, number of cells connected in series and the type of cells and so does the vehicle DC-link voltage too. The vehicle DC-link voltage also changes, when we change the ESS (battery, fuel cell, etc.).

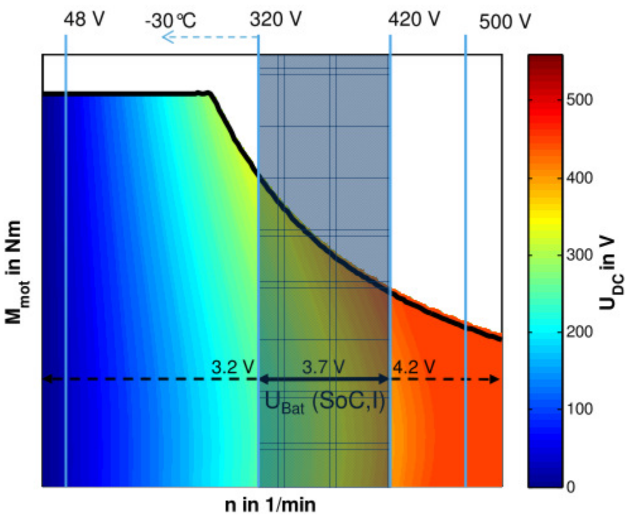

Figure 2: Current DC-link voltage situation for xEVs

This fact states a major problem in designing a high voltage vehicle drivetrain. There are two more obstacles, which will only be named at this point but not be discussed further in this article.

The currently used semiconductors for devices like VSI are usually rated only for a maximum input DC-link voltages up to 450 V, as well as other components like EM. At higher DC-link voltages components like EM need to be double checked and re-designed if necessary to achieve sufficient insulation requirements.

By introducing a bi-directional DC to DC converter in the high voltage electrical architecture we would be able to overcome the fact of a varying DC-link bus voltage corresponding to the varying battery output voltage.

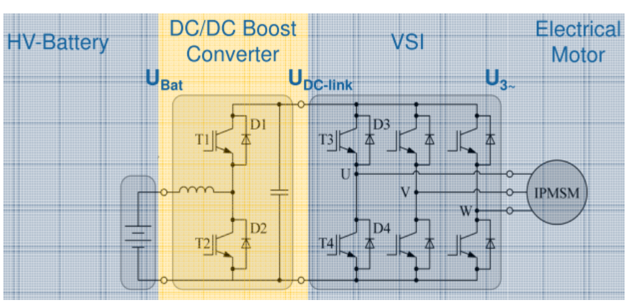

Figure 3: Suggested high voltage architecture with a DC to DC converter [3]

2.2 Proposed system architecture with DC to DC converter

The further discussed system architecture is shown in Figure 3. The DC to DC converter is directly linked to the high voltage battery and capable of controlling the vehicle DC-link bus. The shown type of DC to DC converter in Figure 3 is a so called bi-directional boost converter topology. In further discussions the DC to DC converter device assumes a bi-directional Buck/Boost topology. That comes with the capability to adjust the DC-link voltage to values below and above the current battery voltage.

The capability of adjusting the vehicle DC-link bus voltage independently comes with a variety of benefits. This paper discusses the impact on the drivetrain efficiency and a variety of system aspects, which come with that additional degree of freedom.

3. EFFICENCY IMPACT TO THE DRIVETRAIN

The basic ideas of the efficiency impact by adjusting the vehicle DC-link voltage to an optimal value has already been discussed in papers like [3] and [4]. The strategy on how to optimize the DC-link voltage is described in [5] by using a so called MTPA strategy. The idea of that strategy is to optimize the phase current in such a way, that the torque output can be maximized and the efficiency is increased by reducing the phase current related copper losses.

Especially for IPMSM in high speed regions an additional amount of phase current is needed to reduce the flux (the so-called flux weakening current). Flux weakening is needed to reduce the induced back EMF. If the DC-link voltage could be aligned with the increasing back-EMF no flux weakening current would be required.

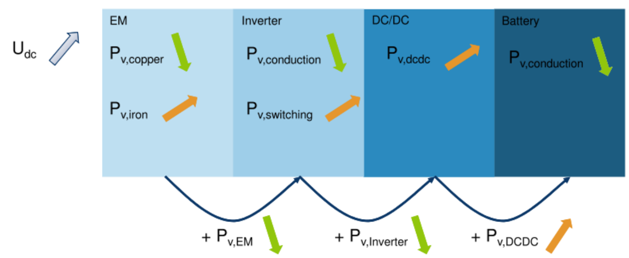

Figure 4: The idea of efficiency improvement

In areas below the so-called base speed point, the DC-link voltage is higher when the induced back-EMF would require. In that region, active decrease of the DC-link voltage could lead to efficiency advantages. This is basically related to the fact that the VSI switching losses decreases with a decreasing input voltage for the switching device [6].

The described simulation results in this article address both topics. The discussed variants are shown in Figure 5. All the variants use the same type of machine (IPMSM) and VSI. The drivetrain is assumed to be designed to propel a vehicle segment B. The first variant is a battery with 200 V compared to a battery with also 200 V and a DC to DC converter adjusting the DC-link bus voltage between 200 V and 450 V. The second variant is a battery with 150 V compared to a battery with 150 V and a DC to DC converter adjusting the DC-link bus voltage between 150 V and 450 V. The third variant is a battery with 200 V compared to a battery with 450 V and a DC to DC converter adjusting the DC-link bus voltage between 0 V and 450 V.

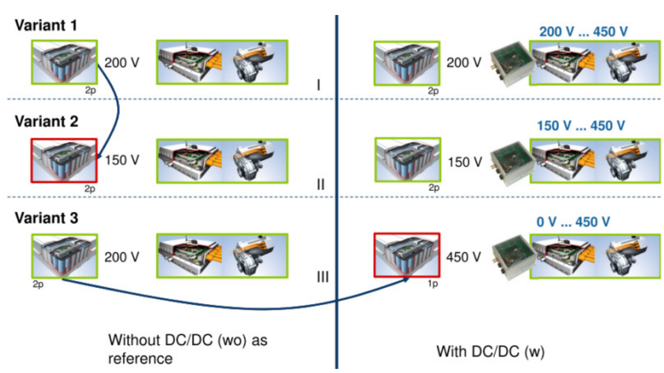

Figure 5: Overview of the discussed variants with and without DC to DC converter

3.1. System loss simulation in Matlab/Simulink

Matlab/Simulink was used to calculate the overall system losses. The discussed system consists of a lithium-ion battery pack, a voltage source inverter, an interior permanent magnet synchronous machine (IPMSM) and a bi-directional high voltage buck/boost converter.

3.1.1 IPMSM loss calculation

The lion share of losses in an IPMSM is caused by copper losses and iron losses (hysteresis and eddy current losses). At low/mid speed regions (below the rated speed) the copper losses are dominant compared to the iron losses. At mid/high-speed regions the iron losses have overcome the copper losses and become dominant. Besides the copper and iron losses also eddy current losses in the magnets and friction losses need to be taken into account.

The iron losses can either be calculated by using the Steinmetz equation [9] or by numerical calculations (FEM). For this paper the IPMSM was designed for a rated voltage of 200 V and the calculations were executed with Opera FEM. As result of the FEM analysis the iron losses, magnetic losses, copper losses and drag losses were separated. By post-processing the FEM results maps for each loss share were created reflecting the dependencies on phase current, voltage and rotational speed [8]:

$$P_{v,cu} \sim I_{Phase}^2 \quad (1)$$

$$P_{v,Fe,hys} \sim \omega \quad (2)$$

$$P_{v,Fe,eddy} \sim \omega^2 \quad (3)$$

$$P_{v,PM} \sim \omega^2 \quad (4)$$

The total IPMSM machine losses result in:

$$P_{v,EM} = P_{v,cu} + P_{v,Fe} + P_{v,PM} + P_{v,drag} \quad (5)$$

3.1.2. Power electronic loss calculation

For the targeted application the losses for the voltage source inverter and the DC to DC converter need to be calculated. The overall losses for both components consist of switching and conduction losses of the IGBTs. Conduction losses of interconnections or the power consumption of the the device itself are neglected.

The IGBT losses of the voltage source inverter and DC to DC converter were calculated according to [3], [6]. The conduction losses consist of the conduction losses of each IGBT and the corresponding freewheeling diode in the half bridge. The switching losses are derived from the datasheet of the estimated IGBTs.

The current conduction losses of the DC to DC converter depend on the current battery current. The battery current is not constant and varies with the efficiency of the overall system. During the calculation of the conduction losses a starting value for the battery current has to be assumed. With the updated value for the conduction losses of the DC to DC converter the battery current will get updated and the conduction losses need to be updated too. After multiple iterations the calculation of the conduction losses for the dc/dc converter settles and the calculation can move on.

The sum of all conduction losses and switching losses results in the overall power electronics losses

$$P_{v,PE} = P_{v,VSI} + P_{v,DC2DC} \quad (6)$$

3.1.2. Battery loss calculation

Also the battery losses within the system are taken into account for the overall system losses with and without a DC to DC converter. Only conduction losses of the battery are calculated and a varying internal battery resistance by temperature and state of charge are neglected.

$$P_{v,Bat} = R_{Bat} * I_{Bat}^2 \quad (7)$$

3.1.3 Overall system loss calculation

In order to calculate the overall system losses the sub-system losses for power electronics, electrical machine and battery are summed up for each operation point:

$$P_v = P_{v,PE} + P_{v,EM} + P_{v,Bat} \quad (8)$$

A Matlab script is used to calculate the optimal phase current and angle by using a MTPA strategy. The Matlab script allows you to either calculate the MTPA trajectories for a fixed battery voltage or for a DC-link voltage within certain boundaries. Within the boundaries the DC-link voltage is optimized by the script to minimize the DC-link voltage and phase current for the requested torque output of the machine.

The step by step calculation of the overall system losses in each operation point is according:

- Step 1: Execute MTPA strategy to calculate required phase current, phase voltage and dc voltage
- Step 2: Calculate IPMSM losses based on phase current, phase voltage, rotational speed
- Step 3: Calculate voltage source inverter losses based on phase current and phase voltage and dc voltage
- Step 4: Calculate DC to DC converter losses based on dc current, dc voltage, battery current and battery voltage
- Step 5: Calculate battery losses based on battery current
- Step 6: Summation of all loss shares following equation (8)

With the descried procedures to calculate the machine, power electronic and battery losses the overall system losses are calculated and listed in the next section of this paper.

3.2. System loss simulation results

The starting point for the simulations is a well-designed drivetrain with a 200 V battery. The system losses for that system are used as a benchmark for the corresponding system with DC to DC converter.

Figure 6, Figure 7 and Figure 8 show the simulation results for variant 1. The simulations were done in Matlab/Simulink. From the diagram it is obvious that the system losses increase basically at every operation point. The biggest increases are located at mid speed ranges and low torque ranges. The overall system losses increase about +25% at maximum. At the high speed and low torque region decreasing system losses occur by about -3%. A long the maximum torque curve, there is also a slight decrease in system losses by -5%. If we split the system losses in EM losses and power electronics losses, then we can see which component is contributing the additional losses more in detail.

It is obvious in Figure 8, the DC to DC converter contributes additional losses to the system and leads to overall increasing power electronics losses. These losses cannot be compensated by the loss improvements from the EM, Figure 7, especially because the EM losses stay the same over a wide operating area. There is an area around the maximum torque curve with a reduction of EM losses by -30%, but in the area of mid speed and low torque the EM losses increase by + 15%.

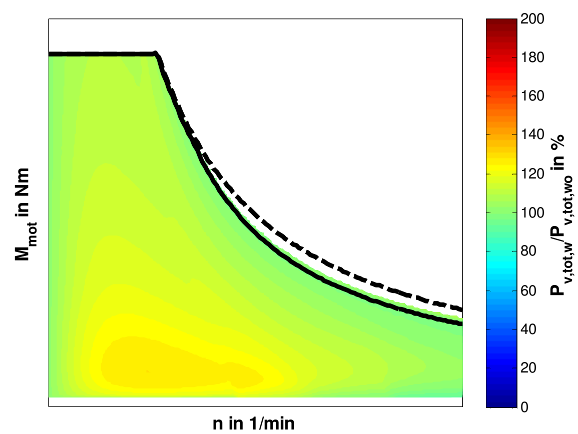

Figure 6: Change in system losses (battery, IPMSM, VSI and DC to DC converter) for variant 1

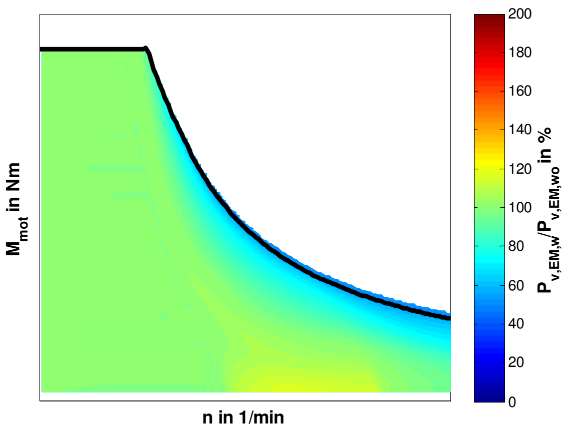

Figure 7: Change in EM losse

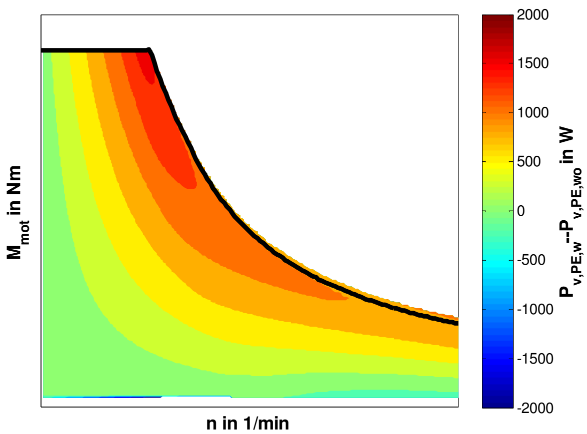

Figure 8: Change in VSI + DC to DC losses

In the next simulation step the battery voltage was reduced to 150 V compared to the 200 V from variant 1. Variant 2 is intended to show the battery voltage influence on the EM performance and how to compensate that with a DC to DC converter. In Figure 9 you can see how the performance of the drivetrain is degrading because of the too low battery voltage of 150 V. The dashed line in Figure 9 shows the potential performance of the drivetrain by boosting the battery voltage with a DC to DC converter.

The overall system losses are still increasing, but larger areas of loss improvements are recognizable. Above medium speed ranges a loss improvement between -10% to 20% is achieved. There is still a hotspot at low speeds and low torque levels with a loss increase of about 25 %. It is to mark out that especially in the high power regions (high speed and high torque) a loss reduction and efficiency increase is achieved.

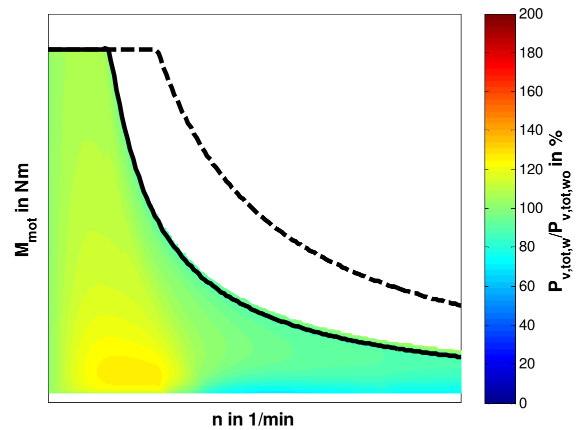

Figure 9: Change in system losses (battery, IPMSM, VSI and DC to DC converter) for variant 2

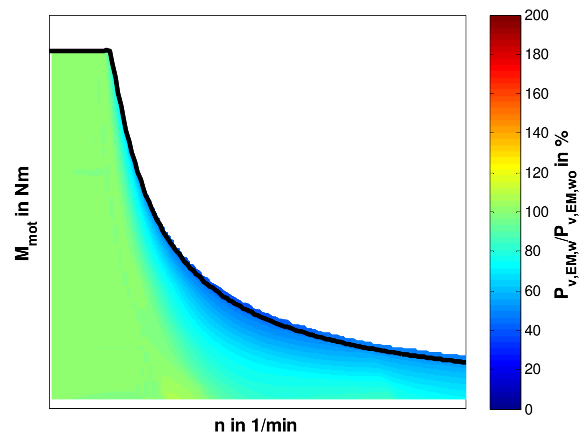

Figure 10: Change in EM losses

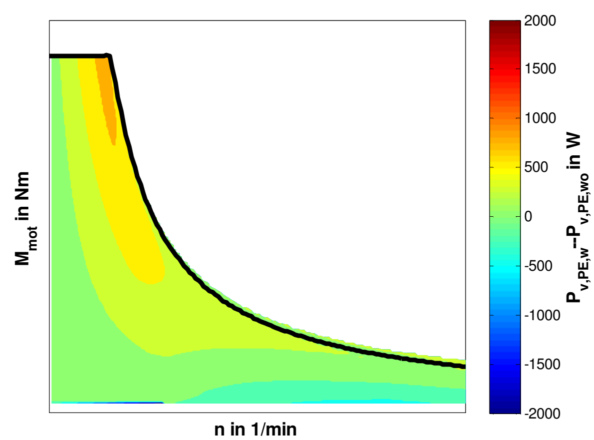

Figure 11: Change in VSI + DC to DC losses

The third simulation stages a system with an increased battery voltage and a DC to DC converter used to adjust the DC-link voltage in every operation point to its optimal value for best efficiency. That system is again compared to the original system with a 200 V battery.

As seen in Figure 12 the system losses improve over a wide range of operation points. There is still a small band of increasing losses (+20% in his hotspot) at mid speed levels and low torque, but over a wide area the system losses are decreasing up to -20%, especially in the area around the maximum torque output curve. In Figure 14 we see the DC to DC converter is still adding additional losses to the overall power electronics. In the low speed area and the low torque area the power electronic losses are especially low. This is due to low switching losses of the VSI because of the lower DC-link bus voltage in that area.

If we compare the Figures form variant 3 to variant 1 we see nearly the same behavior regarding EM losses and power electronics losses. The major difference for the system losses is caused by the battery losses. The higher battery voltage in variant 3 causes significant lower battery currents, which results in lower battery conducting losses. The negative effects regarding the higher battery voltage causing higher switching losses are neglected by the DC to DC converter. The DC to DC converter is adjusting the DC-link voltage to its optimal point between 0 V and the maximum available battery voltage. The higher available DC-link voltage improves the EM efficiency too, as seen in Figure 13.

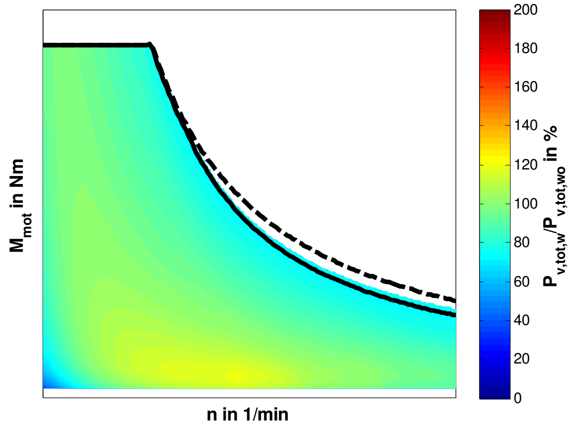

Figure 12: Change in system losses (battery, IPMSM, VSI and DC to DC converter) for variant 1

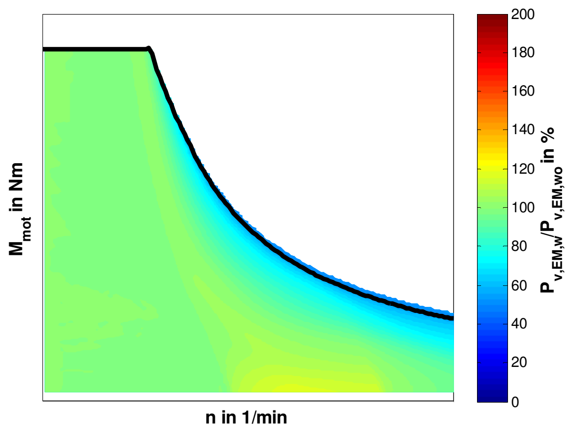

Figure 13: Change in EM losses

To see how the result calculated for variant 1 and 3 impacts the energy demand during a drive cycle, a NEDC, US06, FTP72, Artemis Road and Artemis Motorway 130 were simulated with both variants. The results show that variant 1 with a DC to DC converter leads to increasing energy consumption for each drive cycle. The energy increase during the drive cycle is in an average about +10%. The simulation with variant 3 shows a different situation. For a low demanding, low performance drive cycle variant 3 leads to minor energy consumption advantages. The energy consumption is decreasing between -1% and -4% depending on the drive cycle. For higher demanding drive cycles like US06 and Artemis motorway 130 the energy consumption improvements are significant. The energy consumption is decreasing by about -11%.

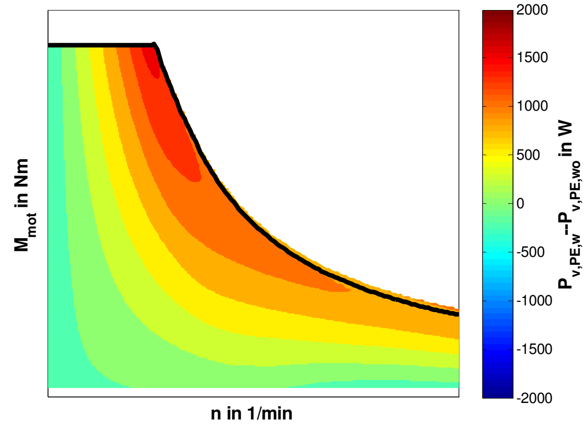

Figure 14: Change in VSI + DC to DC losses

The results show that a high voltage DC to DC converter contributes benefits to the drivetrain architecture for certain types of applications. In a low performance battery electric vehicle, intended for an urban environment and a majority of city drive cycles over the lifetime, a high voltage DC to DC converter does not contribute a reasonable efficiency advantage to the overall system drivetrain. The other extreme would be a high demanding, performance application. In such a case a high voltage DC to DC converter would add additional benefits to the overall drivetrain. A DC to DC converter would lower the system energy losses during the drive cycle combined with a high voltage battery application, especially for motor motorway drive cycles and high demanding drive cycles.

4. SYSTEM DESIGN OPPORTUNITIES

Besides the efficiency benefits, are there any other advantages and opportunities for the overall system design to be leveraged?

By the nature of a DC to DC converter it adds an additional degree of freedom to the system design. The DC to DC converter decouples his input voltage level from the output voltage level. A boost DC to DC converter can reach an output voltage level higher than his input voltage level. A buck DC to DC converter can reach an output voltage level lower than his input voltage level. The combination of both is a bidirectional buck/boost converter. The next sections will talk about the opportunities related to the decoupling between the battery voltage level and the vehicle DC-link bus voltage.

4.1. Opportunities for the electrical machine design

Designing an electrical machine for a drivetrain means handling a variety of different discrepancies and boundaries in order to find the best solution. A major influence to the electrical machine design have the torque demands, the maximum speed requirements, the power and efficiency requirements, the packaging requirements and the operating voltage level. Most of them are opposing to each other, which makes the electrical machine design very complex. Today this mainly results in complex gear sets/architectures, oversizing the machine and compromising between torque, efficiency, maximum speed and power. Down the road we end up with less efficiency, bigger packaging and higher weights. The machines are then made to be highly specialized for their application and this leads to a huge variety of components for different production programs.

A high voltage DC to DC converter can help reduce complex situations by taking the operating voltage out of the equation, because now the operating voltage is adjustable and decoupled from the battery voltage level. Adding a degree of freedom helps improve the system design.

The induction machine (IM) will particularly benefit from an increased DC-link voltage because of a DC to DC boost converter. It is required that the IM is operating over a wide speed range for modern electric vehicles. The effect is that the ratio between the base speed point (point of decreasing maximum torque because of voltage limitations) and the maximum speed of the IM is about 1:3 or even higher [7]. To meet power requirements at high speed regions the IM needs to be oversized at the base speed point. In some applications complex gear sets are applied in order to increase the base speed torque and decrease the king pin inclination.

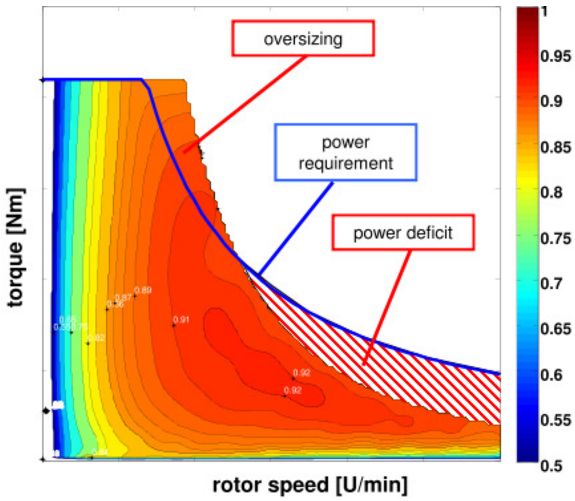

Figure 15: Oversizing situation for IM

Figure 15 shows the area of oversizing and the area of a power deficit compared to the power requirements for the IM. With a higher DC-link voltage the situation can be improved and the areas of oversizing and power deficit can be erased. That could open a wider field of applications for IM as traction motor solution. The IM has advantages compared to an IPMSM, which are appealing. IMs are a more cost effective, robust and non-rare earth material consuming alternative to IPMSM.

One issue related to IPMSM is the so called back-EMF induced to the stator winding because of the rotating magnetic field of the rotor. In a failure situation (IGBTS are not working, loss of flux orientation, loss of speed signal and so on) and the car is towed or even when the car is rolling down a hill and the rotor is spinning, the magnetic field will still induce a phase voltage. If this induced phase voltage is higher than the DC-link voltage, the freewheeling diodes will conduct. This leads to an uncontrolled rectifying situation, which could cause significant damage to the system. To prevent this from happening, the VSI would short circuit the three phase of the IPMSM. A short circuit current is now flowing through the VSI IGBTs and the IPMSM phases, associated with conduction losses in the VSI and IPMSM and a short circuit torque at the output shaft. To prevent such situations, the IPMSM can be designed in such a way, that the back-EMF does not go beyond the DC-link bus voltage. Or the DC-link bus voltage needs to be higher than the back-EMF at all time. A DC to DC boost converter can prevent that kind of safety relevant situations by extending the area of freewheeling, because of an increased DC-link bus voltage.

4.2. Opportunities for the voltage source inverter design

One important parameter to design a voltage source inverter (VSI) hardware is the needed semiconductor area to carry the current load through the IGBTs. We can derive this value from the power requirement for the VSI during the system design. In order to drive an electrical machine with an output power of 40 kW, we obviously need a VSI with 40 kW plus the overall VSI and EM losses. If we consider a well-designed system, we can estimate an efficiency of about 90% for the VSI and EM combined. That leads us to an estimated power requirement of about 45 kW for the VSI. Unfortunately we are talking about alternating currents and a system with inductance and capacity. We must be more specific about which power we discuss because of this item. The important requirement for the VSI design is the apparent power demand for the system. If we assume the power factor of the system is 0.9, it leads us to an apparent power demand of about 50 kW.

Assuming that the vehicle DC-link voltage is 220 V and the VSI is operating in space vector modulation, the required phase current through each IGBT is about 151 A_{eff}. Unfortunately the DC-link voltage is changing regarding to the battery voltage, as described earlier. Assuming a load related battery voltage drop, the battery voltage could change to 160 V instead of 220 V at a no load situation. This results in a required IGBT current of about 208 A_{eff} instead of 151 A_{eff}. That is a phase current increase of about +37% just to compensate the varying battery voltage. That situation gets even worse at high rotational speeds, there additional apparent power is needed because of insufficient DC-link voltage in order to reduce the magnet flux for IPMSM.

The VSI needs to be oversized to compensate the voltage drop from the battery voltage in order to be able to supply the needed apparent power to the system. This is directly related to a cost increase for the VSI hardware. A DC to DC converter could keep the DC-link voltage at a dedicated voltage level or even optimize the DC-link voltage. This would result in higher efficiency, lower cost and an optimized VSI hardware design considering an optimal DC-link voltage at all times.

A DC to DC converter could be used to adjust the DC-link voltage to its optimal operation points, as described earlier. That results in positive effects for the switching losses of the VSI. The strategy could be to adjust the DC-link voltage in a way that the modulation index of the VSI is close to 1. That minimizes the switching losses of the IGBTs. At low rotational speeds the switching losses could be reduced even further by decreasing the switching frequency. Usually this would result in an increase of current ripple. That can be prevented by also reducing the DC-link voltage at low rotational speed. The reduced switching losses could be leveraged to increase the allowed current load for the IGBTs, which are crucial at low speeds with a high torque demand to accelerate the vehicle.

4.3 Opportunities for high voltage auxiliary components

High voltage auxiliary components have to handle a huge range of different input voltages. The reason is because OEM and Tier-1 suppliers tend to handle auxiliary components like PTC heater or high voltage climate compressor as a carryover part (COP) in order to increase the volume and by that decrease the cost for manufacturing and development and engineering. But by the fact that in different programs (pure electric vehicle, plug-in vehicle, range extended vehicle, etc…) the vehicle DC-link voltage is not a fixed value and is changing over the lifetime of a vehicle and different operation points, the hardware design for such auxiliary components has to consider this.

The huge input voltage range requirements lead to a complex and costly hardware design for the power supply voltage board. A solution for that compromised and costly design for a wide input range could be a standardized vehicle DC-link input voltage for auxiliary components. This could be achieved in two possible ways either by standardization or specialization.

A specialized high voltage DC to DC converter could supply a standardized high voltage to all of the high voltage auxiliary components. In this case the power supply voltage circuit design would not require a wide input range but would actually mean to have one more high voltage bus within the vehicle. This might not be a suitable solution.

A standardized high voltage DC-link bus voltage could solve that issue. A high voltage DC to DC converter would guarantee a certain required DC-link voltage and keep that in a small range to accommodate the voltage range need for the auxiliary components.

4.3 High voltage DC to DC converter and fuel cells

Compared to a high voltage battery pack (e.g. Lithium-Ion battery pack) the fuel cell, as a source of power for electrical drivetrains, is marked with a low dynamic response to transient power demands. This is the reason why fuel cell vehicle architectures are a combination of a fuel cell with a secondary power source like Lithium-Ion battery or super capacitors. In such architecture the fuel cell is the primary source for energy (low dynamics) and the secondary ESS is the primary source of power (high dynamics). Further discussion focuses on a combination of a fuel cell with a lithium-ion battery pack.

The battery voltage and the fuel cell voltage are different because of physical and chemical boundaries. At least one DC to DC converter is required in order for both to work on the same vehicle DC-link bus and feed the same electrical drivetrain. This leads to three major architectures.

The first architecture describes a DC to DC converter between the battery pack and the DC-link bus. The fuel cell is directly connected to the DC-link bus.

The second architecture describes a DC to DC converter between the battery pack and the DC-link bus and also between the fuel cell and the DC-link bus.

The third architecture describes a DC to DC converter between the fuel cell and the DC-link bus but not between the battery pack and the DC-link bus.

The goal of each of this architecture is to control the DC-link voltage and the power and energy flow within the system. The high dynamic power demands and transients need to be kept away from the fuel cell, otherwise premature wear at the fuel cell membranes can occur.

As described above a DC to DC converter is highly recommended and common sense in a vehicle drivetrain architecture involving a fuel cell as source of energy to decouple and control the energy flow to and from the DC-link bus.

4.3 Opportunities for new concepts

The opportunity to decouple the vehicle DC-link bus voltage form the ESS voltage level gives the system designer an additional degree of freedom to be leveraged from.

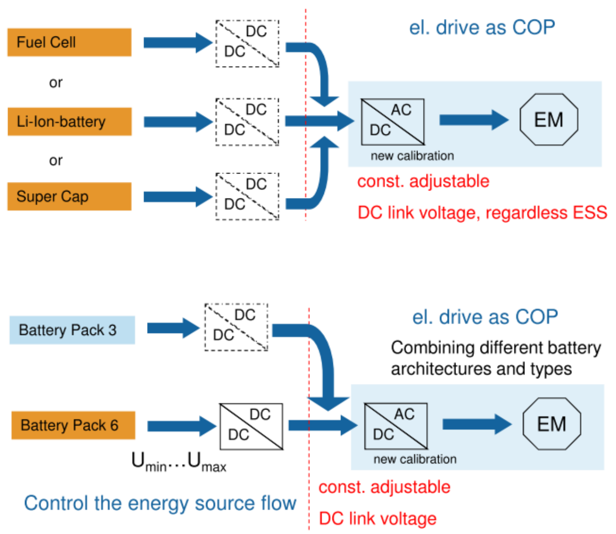

Figure 16: Controlling the energy and power flow from different ESS on the same vehicle DC-link bus

As shown in Figure 16 different types of ESS could be combined in one drivetrain like a fuel cell and a super capacitor together. It also opens the opportunity to combine the same electrical drivetrain with the different types of ESSs. The electrical drivetrain could be a carry-over part for different variants of the same vehicle model by only changing the ESS. It is imaginable to have a low cost vehicle model without any DC to DC converter and just a lithium-ion battery pack for a low performance application. A more advanced and performance focused model of the same vehicle uses the same drivetrain as a carry-over part but with a substituted battery pack and an additional high voltage DC to DC converter to increase the overall drivetrain performance.

It is also imaginable to have different types of battery packs. One battery pack is more performance oriented (high power density) and one pack is more vehicle range oriented (high energy density). Each variant is available for the same vehicle and can be substituted by each other. The different voltage levels of both batteries and the voltage variations are neglected by a DC to DC converter.

In summary a DC to DC converter could help to increase the number of available ESSs for the same electrical drive train to meet different customer needs without changing the electrical drivetrain by changing the power electronics and the electrical machine.

5. CONCLUSION

In the previous sections it was demonstrated that a DC to DC converter can contribute an efficiency improvement to the system by adjusting the overall DC-link voltage to its optimal operating point. Significant efficiency improvements are measurable, especially for performance demanding applications and high demanding drive cycles. Besides this fact and less apparently, a DC to DC converter leads to less power losses especially at high power operating points for both power electronic and electrical machine. This fact is measurable for high and low power demanding applications.

Besides the efficiency aspect, we can find a variety of different areas which benefit from a DC to DC converter. Remarkable is the necessity for a DC to DC converter in fuel cell applications for traction applications. Also the outlined facts regarding electrical machines endorse the benefits of a DC to DC converter for modern drivetrain architectures.

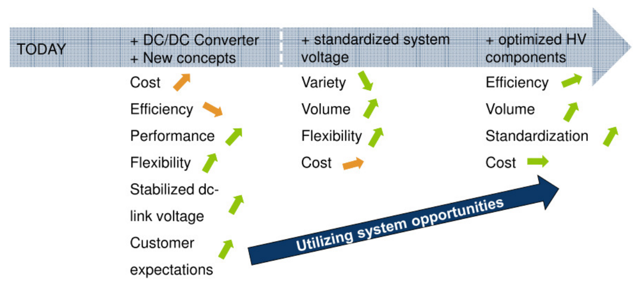

Figure 17: Future path for DC to DC converter application in electrical drivetrains

In a first step and near term scenario a DC to DC converter could be useful for high-performance demanding drive cycles to meet customer expectations and performance requirements, while less focusing on cost and efficiency. In a mid and long term perspective the DC to DC converter could help to standardize the DC-link bus voltage and utilize the outlined system opportunities. This would be related to a decreasing variety in component designs, increasing volume, increasing flexibility and reduced cost situation. By optimizing the high voltage components and leveraging the outlined opportunities for the design of components and the overall system an efficiency improvement is expected.

4. ACKNOWLEDGMENTS

In acknowledge to my colleagues from IAV I want to thank them for their support and discussions. Especially I want to thank Karsten Mueller for funding this research and promoting that topic both internal at IAV and to the public. I also want to thank my colleagues form the VT-S department for their support and open discussions on that topic and their great remarks while reviewing my work. Especially I want to thank Stephan Paul for supplying me with the required electrical machine simulations as input to my overall system loss calculations. I also want to acknowledge the support from Whitney Liftig from the IAV marketing department, who reviewed this paper too.

4. REFERENCES

[1] Hsu, J.S., Ayers, C.W., Marlino, L.D.,Miller, C.W., Ott Jr., G.W., Oland, C.B. "Evaluation of 2004 Toyota Prius Hybrid Electric Drive System-Interim Report" U.S. Department of Energy, 2006

[2] Staunton, R.H., Ayers, C.W., Marlino, L.D., Chiasson, J.N., Burress, T.A. “Evaluation of 2004 Toyota Prius Hybrid Elctric Drive System” U.S. Department of Energy, 2006

[3] Tenner, Stephan, Guenther, Stephan, Hofmann, Wilfried „Loss Minimization of Electric Drive Systems Using a DC/DC Converter and an Optimized Battery Voltage in Automotive Applications “ IEEE VPPC, 2011

[4] Schoenen, Timo, Kunter, Markus S., Hennen, Martin D., De Doncker, Rik W. „Advantages of a Variable DC-Link Voltage by Using a DC-DC Converter in Hybrid-Electric Vehicles” IEEE VPPC, 2010

[5] Heinrich, Rico, Cebulski, Bernd, “Optimal DC-Voltage-Control With a Traction PowerSupply DC/DC Converter for Electric Vehicles”, VDE eMobility Conference, 2010

[6] Graovac, D., Pürschel, M. “IGBT Power Losses Calculation Using the Data-Sheet Parameters” Application Note, Infineon – Forschungsbericht, 2009

[7] Bochnia, Dirk, Cebulski, Bernd “Eigenschaften der Asynchronmaschine für Traktionsanwendungen im Automobil“ Haus der Technik Tagung München, 2011

[8] Spring, E „Elektrische Maschinen. Eine Einführung“, Springer, Berlin, Heidelberg, 3, 2009

[9] Steinmetz, C.P. „On the Law of Hystersis“ American Institute of Electrical Engineers Transaction, 9, 1892, pp 3-64