Advantages of a Variable DC-Link Voltage by Using a DC-DC Converter in Hybrid-Electric Vehicles

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Abstract— **In electric and hybrid-electric vehicle applications, power electronic converters are used to couple the traction machine with the battery stack. The simplest topology consists of an inverter between the battery stack and the machine. In an often discussed alternative, a DC-DC converter is used to feed the traction machine with a higher and stable voltage level. This paper deals with the differences which arise in terms of the applied control strategy and identifies operating regions of improved efficiency.**

Keywords—DC-DC converter; efficiency; hybrid vehicle; electric vehicle

I. INTRODUCTION

Within the scope of the „EuropaHybrid" project, funded by the German Federal Ministry of Economics and Technology (BMWi), a hybrid-electric vehicle (HEV) is designed and built. One completely new developed component is the Integrated Power Unit (IPU), which is in the focus of this paper. The IPU consists of an inverter to feed the Interior Permanent Magnet Synchronous Machine (IPMSM) as well as a DC-DC converter. With the DC-DC converter it is possible to adapt the inverter supply voltage dependent on the machine's operating point in order to improve the overall efficiency.

This paper will point out necessary changes to the control strategy as well as benefits due to the DC-DC converter. For vehicle drive systems, it is essential to improve the system efficiency over an entire driving cycle. In the first chapter, the electric part of the drive train is presented. After discussing reasons to integrate a DC-DC converter, the control strategy of both components and their interaction is presented. Based on simulations, regions with improved efficiency are shown and correlated with the New European Driving Cycle (NEDC).

II. SYSTEM OVERVIEW

The HEV considered in this project is based on a parallel-hybrid topology. Hence, the IPMSM and the internal combustion engine (ICE) are connected in parallel via a transmission gear. Thus it is possible to shift gears of the ICE as well as of the IPMSM without interrupting the traction force, similar to double clutch transmissions. A more in-depth analysis of the transmission technology is presented in [1].

With the help of system simulations the required energy and power of the battery stack was calculated. Based on this data, commercially available battery cells were selected and the stack voltage was determined. This leads to a voltage level of 235 V to 350 V of the battery stack. After the electromagnetic design of an electric machine, the number of windings should be chosen in such a way that the peak power can be reached at minimum DC-link voltage level. Using the battery voltage level, this would lead to a winding configuration with increased losses due to eddy-current and proximity effects [10]. The additional losses caused by this effects ($P_{losses,AC}$) are depicted in Figure 2. The "loss factor" is defined as the ratio between the AC and DC losses ($P_{losses,AC}/ P_{losses,DC}$).

Keeping the machine's losses in mind a DC-link voltage level, higher than the battery voltage, seems to be beneficial. Furthermore, due to a higher number of windings the currents in the inverter are decreased. Using more than 10 turns, the additional losses also at the highest frequency (speed) stay low. Therefore a DC-link voltage of 600V is needed.

Designing the whole system including the battery for a high voltage, a large number of battery cells would be needed. If Li-Ion cells are used, the monitoring system should cover each cell independently. That implies a high complexity and costs for the battery monitoring system. Hence, this kind of system should not be used in modern electric and hybrid-electric vehicles.
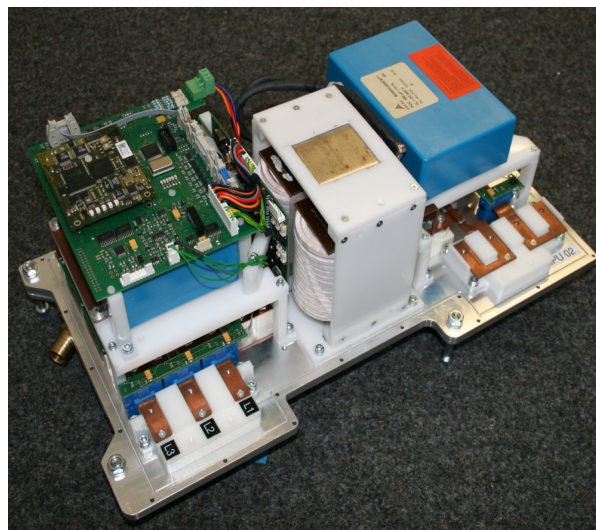

Figure 1. Integrated Power Unit (IPU) including DC-DC converter

By comparing a system with DC-DC converter and a system with reduced number of windings it turns out, that a system with DC-DC converter has efficiency and control

advantages. To limit the complexity of the prototype, only a single-phase DC-DC converter was designed and realized. Although with a multi-phase topology further benefits, like smaller current ripple and improved dynamics [7], are possible. The IPU with the integrated DC-DC converter is shown in Figure 1.
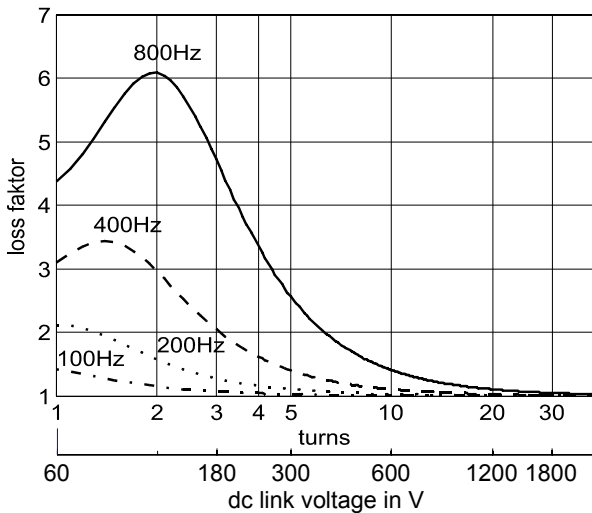

Figure 2.   AC loss increase due to skin and proximity effects

Hence, in many cases the voltage levels between battery and machine differ significantly after a first separate optimization. The question arises, whether a design trade-off should solve the problem or a DC-DC converter should be used. The main arguments for the application of a DC-DC converter are as follow:

- The machine does not have to be designed for minimum battery-stack voltage level occurring during operation.

- The machine's number of winding turns and the battery-stack voltage level can be optimized independently in a wide range.

- At a higher DC-link voltage level, an adaption of winding turns leads to smaller inverter currents.

- With the DC-DC converter it is possible to adjust the DC-link voltage. Due to this, the DC-link voltage can be adjusted depending on the machine's operating point.

- Exchanging the battery pack with a different voltage level has only to meet the limits of the DC-DC converter and the machine can be kept unchanged.

III.   CONTROL STRATEGY

For optimum utilization of the IPU and the built-in converters, a suitable control scheme needs to be developed. The presented control strategy focuses on the interaction between DC-DC converter and machine inverter. Initially, the control strategy of both converters is described.

A.   IPMSM

The control of the IPMSM works according to the principles presented in [6] and [3]. In the base speed region, the i_d and i_q current is controlled on the basis of Maximum-Torque-per-Ampere (MTPA) regime. Once the machine reaches the voltage limit, the field-weakening regime is applied. In this case an eye has to be kept on the current limit of the inverter. Furthermore, it is possible to change the voltage modulation from space-vector modulation (SVM) to six-step mode (SSM) [11], [13]. This provides the opportunity for further field weakening until the Maximum-Torque-per-Flux (MTPF) limit is reached.

B.   DC-DC Converter

The setup of the DC-DC converter is shown in Figure 3. This topology was selected, because of the voltage variation between in- and output, the simple setup as well as the not required galvanic isolation.
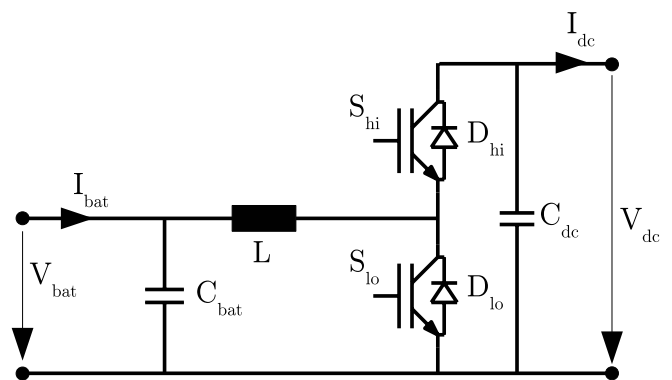

Figure 3.   Setup of the DC-DC converter

The control of the DC-DC converter is based on a cascaded control. The inductor current is controlled in an inner loop whereas the voltage control is added on top of the former. Due to this control loop structure, the control design could be realized according to the „symmetrical optimum" regime. To improve the DC-DC converter's efficiency at low loads, the Discontinuous Conduction Mode has to be used [14]. As mentioned before, the output voltage of the controller can be adjusted between battery-stack voltage level $U_{Bat} + 10$ V (minimum) and the designed maximum DC-link voltage level U_{dc}^{max}.

C.   Coupling of both Converters

Due to the possible adaptation of the DC-link voltage, several new control algorithms are possible. By adjusting the voltage depending on the operating point, system losses can be significantly reduced. At low speeds, only a relatively low voltage is required. The required voltage depending on speed is shown in Figure 6. The calculation of the required DC-link voltage U_{dc}^* is shown in Figure 4. At first, the desired DC-link voltage U_{dc}^* is calculated based on the stator flux linkage corresponding to the requested torque on the MTPA trajectory, the current machine speed ω_m and the Modeswitcher signal. The latter is a binary value which indicates the modulation technique, i.e. SVM or SSM. If the calculated DC-link voltage

is smaller than its maximum value U_{dc}^{max}, the IPMSM will be working in the MTPA range. This control strategy leads to the smallest inverter currents and according to that a high efficiency of the inverter. Furthermore, two different cases have to be distinguished in terms of the desired DC-link voltage level. If the resulting voltage is smaller than the battery-stack voltage $U_{Bat} + 10$ V, this value will be chosen and the modulation technique will be set to SVM. To set the exact battery-stack voltage level as a reference is not possible due to duty-cycle and control limitations of the DC-DC converter.
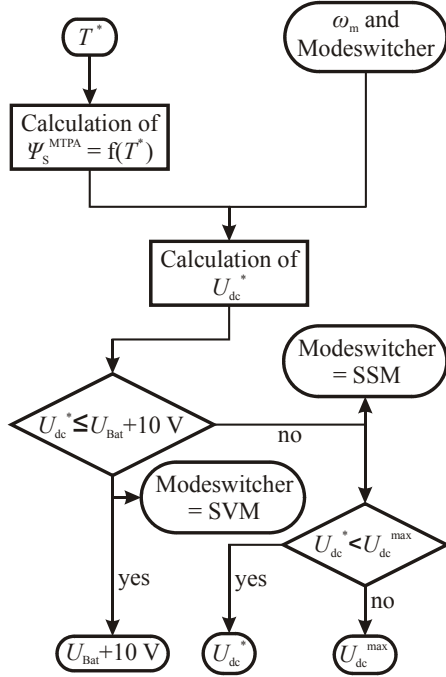

Figure 4. DC-DC Converter Control

However, to realize this, the converter has to be switched off, so that the current can flow through an additional bypass switch. The second case deals with a resulting reference voltage larger than the aforementioned limit. In this case, the calculated value is passed as a reference to the voltage control of the DC-DC converter. There the voltage value is limited to the maximum DC-link voltage level U_{dc}^{max}. In this case the converter is stepping up the battery-pack voltage to a higher value. To fully utilize the adapted DC-link voltage, SSM is used as modulation technique and the Modeswitcher signal is set accordingly. Of course, a hysteresis is implemented to prevent the machine inverter from toggling between SVM and SSM technique in the threshold region. Due to the utilization of the torque value requested by the user for the DC-DC converter control, cross coupling of both controllers is avoided. Afterwards, the measured DC-link voltage U_{dc} is used to determine the optimum operating point with the IPMSM control.

As shown in Figure 5, it is checked first whether the actual voltage is sufficient to drive the IPMSM in the MTPA range. For this reason, two stator flux-linkage values are calculated. The maximum value Ψ_S^{max} is determined by taking the current DC-link voltage U_{dc}, the machine speed ω_m and the Modeswitcher flag into account. The requested torque value T^*

is applied to the MTPA lookup table and leads to Ψ_S^{MTPA}. If the latter value is smaller than the current maximum stator flux linkage, the DC-link voltage level will be sufficient for MTPA operation.
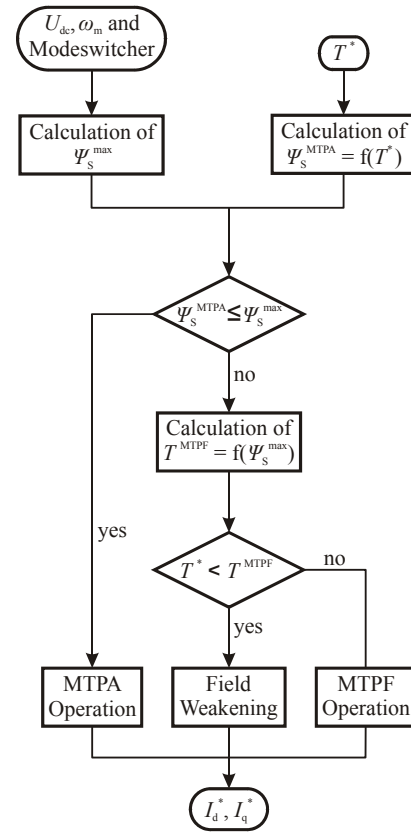

Figure 5. IPMSM Control

If both stator flux-linkage values are equal, MTPA operation is also feasible. In the third case, the current flux-linkage value does not suffice for MTPA operation and the IPMSM must be driven in the field-weakening range. Here, two different modes have to be distinguished, i.e. the "normal" field-weakening mode along the possible part of the constant stator flux ellipsis and the Maximum-Torque-per-Flux (MTPF) mode [9] or the limit of maximum inverter currents. To decide which one has to be applied, the maximum feasible torque value T^{MTPF} is read from the MTPF lookup table. If the requested torque value is smaller, the machine control determines the operating point which matches T^*. If it is equal or larger, the machine cannot provide the requested torque value and the control algorithm chooses the maximum available torque value T^{MTPF}.

The machine-current control could also easily be used as a criterion to toggle between SVM and SSM voltage modulation technique. As long as the actual maximum stator flux linkage is bigger than Ψ_S^{MTPA}, the SVM technique has to be used. If both values are equal the limit of SVM is reached and SSM can be used. To drive the IPMSM in the field-weakening range, SSM technique is also applied.

The presented control strategy has two major advantages. Firstly, the switching losses in the machine inverter are reduced

due to fewer switching actions in SSM and a better matching of the DC-link voltage in SVM mode. In the latter case, the current ripple is reduced additionally. Secondly, it is possible to switch to SSM earlier by applying an optimal DC-link voltage level. These regions are marked red and yellow in Figure 6 and directly correspond to those regions where the additional DC-DC converter has advantages.
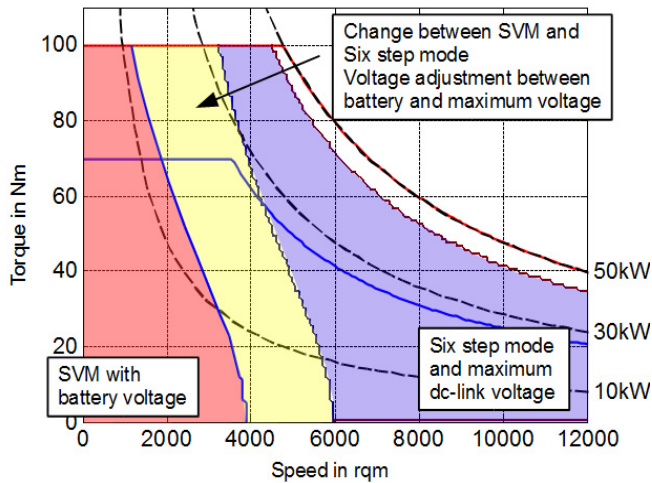

Figure 6.   Operating Areas

Measurements of the machine and inverter efficiency are shown in Figure 7 and Table I. This result shows improvements by reducing the DC-link voltage at a constant operating point at 1000 rpm and 80 Nm. The DC-link voltage was reduced from 400 to 200 V. The reduction of the machine losses was even higher than simulated because of reduced current ripple.
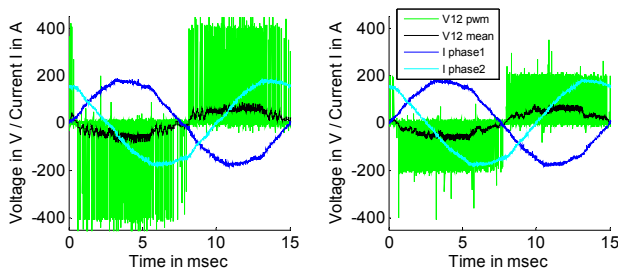

Figure 7.   Measurements with 200 and 400 V DC-link

TABLE I.   REDUCED DC-LINK VOLTAGE TO IMPROVE EFFICIENCY

Efficiency at low speeds	DC-link voltage		
	400 V	*300 V*	*200 V*
machine	95,8 %	96,1 %	96,9 %
inverter	86,3 %	86,9 %	87,4 %

IV.   SYSTEM SIMULATIONS

With regard to the realized design of the mechanical "EuropaHybrid" drive train, which basically utilizes the IPMSM at lower speeds (see Figure 8), the IPU with built-in DC-DC converter shows remarkable efficiency benefits. At high speeds, the system without a DC-DC converter gains slight advantages. Depending on the variation of components the border between benefits and slight disadvantages varies, but the general behavior remains unchanged. Considering a specific driving cycle, a high density of operating points apparently occurs at low speeds. The distribution of operating points can be changed by varying the gear-shifting strategy of the IPMSM. While assuring that all operating points of the ICE remain the same, a second shifting strategy was derived. But for both gear-shifting strategies the system with integrated DC-DC converter has advantages. Due to an early gear-shift transition into a higher gear, the efficiency gain is getting larger. Also fuel cell vehicles show similar results [8].
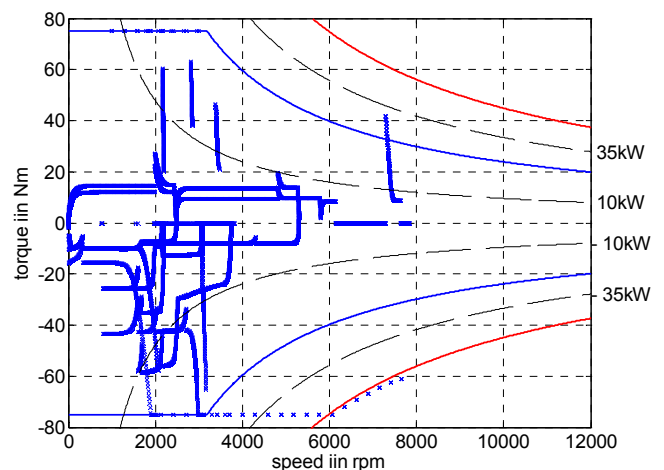

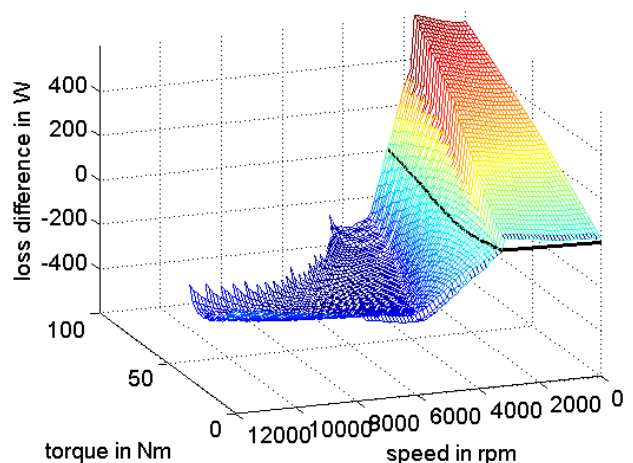Figure 8.   Operating points using NEDC

Figure 9.   Loss difference between a system with and without DC-DC converter

The loss difference presented in Figure 9 includes the inverter and DC-DC-converter losses. Both systems were designed for the same battery voltage and the machine was adjusted by the number of windings. Machine losses were neglected in this simulation, due to inexact simulation models.

But the presented measurements show, that also the machine losses can be reduced by a higher number of turns and a voltage reduction at low speeds. Due to better visibility the speed axis is inverted. A positive difference in Figure 9 denotes advantages of the system with DC-DC converter. The biggest advantage for a system with DC-DC converter occurs at low speeds and high torque. At higher speeds in the field weakening area, the system with DC-DC converter looses the benefits and produces even more losses. Maybe there are other reasons based on the battery stack or the machine design and it might turn out, that a DC-DC converter is beneficial even at higher speeds. Unfortunately, this has not been investigated yet.

Looking at the distribution of operating points in Figure 8, the major portion of operating points is in the area where a system with DC-DC converter is beneficial. The operating point distribution depends mainly on the gear-shifting strategy, so different driving cycles lead to similar results. However, the operating points at higher speeds are very important for the drivability. These points are only needed during acceleration and hence do not influence the overall efficiency significantly.

V. CONCLUSION

In many hybrid and full electric vehicle applications the question about the proper DC-link voltage level arises. The core components are the battery stack and the traction machine with its inverter. A uniform voltage level of both components is often opposed to a system with different voltage levels connected with a DC-DC converter. This paper depicts the differences and explains the advantages of using a DC-DC converter between the battery stack and the machine inverter. Designing the battery stack and the machine independently often yields different optimum voltage levels, like in this project. The bigger the voltage difference, the larger are the advantages of a DC-DC converter.

Especially in the base speed range of the machine, a higher efficiency can be achieved with a DC-DC converter. Therefore, the control has to adapt the DC-link voltage to the required machine voltage. The control strategy and the operating points with increased efficiency are presented in this paper. Comparing the different topology options it is shown, that in this project the distribution of machine operating points during a driving cycle matches regions with increased efficiency of an additional DC-DC converter between battery stack and machine inverter. Therefore, the DC-DC converter reduces the overall losses of the underlying hybrid drive train.

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