Single-Stage Reconfigurable DC/DC Converter for Wide Input Voltage Range Operation in (H)EVs

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Abstract A single-stage reconfigurable isolated DC/DC converter\textsuperscript{(1)} is proposed for use in hybrid and electric vehicles (EVs and HEVs) to supply a 12 V automotive network from the HV battery. The purpose of the proposed topology is to increase the converter efficiency at the higher voltage range of the HV battery. A zero voltage transition (ZVT) phase shift (PS) full bridge (FB) converter is the basis for the reconfigurable topology, which is adapted to operate as a push-pull converter. The ZVT PS FB configuration covers the upper range of input voltages, in which an increased converter efficiency has more effect. It is furthermore reconfigured into the less efficient, hard-switching, push-pull configuration to cover the lower, less significant voltage range. The reconfiguration voltage is chosen to maximize the average efficiency according to the histogram of the HV-battery voltage during a typical driving cycle. Experimental validation of the proposed converter and its efficiency improvement are also presented.

Keywords: (H)EVs, phase shift converter, push-pull converter, reconfigurable, wide input voltage range, ZVT

1. Introduction

In the application of the high voltage (HV) to low voltage (LV) DC/DC converter in hybrid and electric vehicles (HEVs), a zero voltage transition (ZVT) phase shift (PS) full bridge (FB) DC/DC converter (Fig. 1) is commonly used. This topology presents a good compromise between efficiency and power density. One of its advantages is soft switching behavior during turn-on of the HV side switches\textsuperscript{(2)(3)}. In Table 1 from\textsuperscript{(4)}, converter specification recommended by the automotive industry is presented.

When operating in the wide range of input voltages and load currents, the converter cannot maintain the high efficiency in all operating points. Since the transformer turns ratio is chosen according to the minimal specified input voltage $V_{\text{in,min}}$, the converter will have reduced efficiency at higher input voltages, due to increased freewheeling losses. This topology exhibits the highest efficiency when the converter is designed for a ‘tight’ input voltage range, when it operates with duty cycle close to one.

Approaches to improve the efficiency of buck-based isolated DC/DC converters for operation in wide input voltage range can be divided into two main groups:

1) two-stage converters (that use non-isolated voltage regulator as input stage)

2) single-stage modifications of topology or control method in commonly used topologies.

![Fig. 1. Conventional ZVT phase shift full bridge DC/DC converter from\textsuperscript{(2)}](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(PH)EV</th>
<th>HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{in, min}}$</td>
<td>240V</td>
<td>180V</td>
</tr>
<tr>
<td>$V_{\text{in, max}}$</td>
<td>420V</td>
<td>310V</td>
</tr>
<tr>
<td>$P_{\text{out}}$</td>
<td>3kW</td>
<td></td>
</tr>
<tr>
<td>energy flow</td>
<td>Unidirectional</td>
<td></td>
</tr>
<tr>
<td>$V_{\text{acc, min}}$, $V_{\text{acc, max}}$</td>
<td>10.6...16V</td>
<td></td>
</tr>
<tr>
<td>$V_{\text{acc, clip}}$</td>
<td>$&lt;0.2$ Vpp</td>
<td></td>
</tr>
</tbody>
</table>

In certain carefully optimized designs, the reduced amount of total losses and the reduction of the converter volume can be achieved with a two-stage topology in automotive applications with wide input and output voltages\textsuperscript{(5)}. Still, an additional hard-switching converter in series that is required in such cases is usually undesirable due to additional components and power losses\textsuperscript{(6)}. Furthermore, with a HV-battery pack at the input of the converter, there is no need for a power factor correction stage (PFC) typical for front-end converters. This is the additional reason against the use of pre-regulating stage in HV to LV DC/DC converter.

Single-stage topologies adapted for wide input voltage
range comprise multiple power transformers and/or rectifiers\textsuperscript{(7)-(11)}. In addition, their control strategy may require modifications as well (e.g.\textsuperscript{(8)-(12)-(13)}).

Another approach to increase the efficiency of wide input voltage range single-stage converters is the attempt to improve different resonant topologies (e.g. series-parallel, LLC described in (14)). Resonant converters, when designed for the narrow range of operating points, exhibit extremely low switching losses and consequently high efficiency at the price of an additional passive resonant tank. The design of the resonant tank becomes more complicated when the converter operates in a wide range of operating conditions. Several adaptations of resonant converters for improved operation at wide input voltages have been recently proposed in the literature\textsuperscript{(15)-(17)}. Still, the applications in focus are intended for considerably lower load currents compared to the specification from Table 1. This fact makes offered solutions less efficient when used as HV to LV DC/DC converters in (H)EVs.

Most of the methods reviewed here are either focused on fuel cells\textsuperscript{(18)-(19)} or photovoltaic applications\textsuperscript{(12)-(17)-(20)} as typical examples of applications with wide input voltage range. Other solutions are optimized based on the hold-up requirements for front-end converters\textsuperscript{(8)-(11)}. They do not exactly match the application requirements in (H)EVs, where the distribution of input voltages is determined by the discharge behavior of a HV-battery pack, usually the Lithium Ion (Li-Ion) or the Nickel-Metal Hydride (NiMH) battery type. Methods to optimize electric machines\textsuperscript{(22)} or power electronic components in (H)EVs (e.g. a main inverter\textsuperscript{(23)} or a boost stage\textsuperscript{(24)} according to standard driving cycles have been proposed.

Operation of a DC/DC converter that supplies the 12 V system from the HV-battery is not directly affected by the vehicle’s mission profile in the sense of output power that has to be delivered. It is affected rather indirectly, through the variations of the HV-battery voltage during its discharge cycles.

This paper will present an idea of reconfiguration of single-stage converter topologies based on the ZVT PS converter, especially developed for use in (H)EVs. The reconfiguration is enabled by addition of minimal number of semiconductor switches. The control strategy of proposed reconfigurable topologies stays unchanged, whereas only gate driving patterns have to be extended to control the additional switches. To optimize the average converter efficiency over the whole battery discharge cycle, common converter design procedure is modified to consider the specific nature of HV battery discharge curve (Fig. 2).

The remainder of the paper is organized as follows: Sect. 2 gives the background of the battery voltage behavior during a typical discharge cycle in EVs and plug-in HEVs, Sects. 3, 4 and 5 present the proposed single-stage topologies reconfigurable at both HV and LV sides and methods for their implementation. Section 6 deals with the proposed design procedure that maximize the voltage-weighted average efficiency of the HV-side reconfigurable converter, according to the histogram of battery voltages. Section 7 gives the experimental validation of the proposed solution and discusses the efficiency improvement. Section 8 concludes the work.

2. Operating Conditions of HV to LV DC/DC Converter

The voltage of an automotive HV battery pack at the input of the DC/DC converter is changing during the driving cycle depending on the battery state of charge SoC, but also affected by the temperature and the discharge current. The voltage discharge curve defines the range (\(V_{\text{in,min}}\) to \(V_{\text{in,max}}\)) but also the distribution of converter’s input voltage inside this range. The specific form of the voltage discharge curve is the motivation for the idea of converter’s reconfiguration in this paper. The voltage distribution is also dependent on the specific operation strategy of different electrified vehicle types.

2.1 Battery Electric Vehicles

Battery electric vehicles (BEVs) are driven only by electric motor, thus they operate in the charge depleting mode\textsuperscript{(24)}, i.e. they are characterized by deep discharge cycle with SoC dropping down during the full cycle almost linearly (Fig. 2(a), red trace). For such a discharge mode, assuming one of available typical driving cycles, the histogram of HV battery voltages can be easily derived. Using an example of Li-Ion battery, with simplified battery model from\textsuperscript{(25)}, typical discharge curve of today’s automotive batteries (Fig. 2(a), blue trace) is estimated. From presented voltage discharge curve it can be concluded that, in BEVs, battery voltage remains close to a certain value in the most of the driving cycle, while in a significantly shorter part its voltage varies more notable (up to \(V_{\text{in,max}}\) or down to \(V_{\text{in,min}}\)). Furthermore, based on the voltage discharge curve, the voltage histogram in one discharge cycle is derived and presented in Fig. 2(c). From the presented histogram, it can be concluded that the highest converter efficiency would be the most beneficial in the range of mostly present battery voltage, and not at \(V_{\text{in,min}}\) (what is the situation in buck derived converters). For the further analysis in this chapter, weight factors, \(k_{\text{Vin}}\), are derived from histogram for different values of \(V_{\text{in}}\) in the range from \(V_{\text{in,min}}\) to \(V_{\text{in,max}}\). Their purpose is to describe the relation between battery voltage histogram and converter efficiency. They give the information on the effect of a certain value of \(V_{\text{in}}\) on the converter operation during one complete discharge cycle. They will be used in Sect. 5 to evaluate average efficiency of proposed
reconfigurable solution compared to the ZVT PS FB converter.

### 2.2 Plug-in Hybrid Electric Vehicles

Unlike the BEVs, hybrid electric vehicles (HEVs) operate in the charge sustaining mode\(^{(24)}\), since they have no possibility to charge the HV battery from external source. In such a mode, SoC may increase or decrease over a driving profile, but on average remains on its initial level. On the other hand, another group of electrified passenger vehicles, PHEVs combine the charging mode of both BEVs and HEVs\(^{(24)}\). The point of transition from the charge depleting to the charge sustaining mode can depend on several factors. In the example presented in Fig. 3, PHEV operates first in the charge-depleting mode until defined SoC is reached. After that, it transfers to the charge sustaining mode. According to the illustration of the SoC in an PHEV from Fig. 3, it can be concluded that in the phase of charge depletion, the battery voltage will have approximately the same form as presented in Fig. 2(a). Furthermore, the voltage histogram in this operation mode can be assumed the same as the one presented in Fig. 2(c). After that, while battery SoC is maintained at the constant level, changes in the battery voltage will be in the narrower range around specific value. Therefore, the second peak in the battery voltage histogram of PHEV can be expected in addition to the one presented in Fig. 2(c), and will be dependent on the nature and duration of the charge sustaining mode. Such voltage distribution will not be the focus of the analysis of reconfigurable converter proposed in this work.

### 3. Proposed Reconfiguration of ZVT PS FB Converter

The idea of a reconfigurable topology based on the ZVT PS FB converter in this paper is motivated by several different conclusions from previous work\(^{(26),(27)}\). First, it has been shown in (26) that the wide range of operating conditions does not allow to design and utilize the ZVT PS FB converter with its full potential. Except the negative effect on the losses in the HV-side H-bridge, it has been concluded in (27) which dealt with the choice of the rectifier stage, that the blocking voltage rating of rectifier switches is negatively affected as well. For example, the full bridge rectifier compared to the full wave rectifier has the advantage of the lower blocking voltage rating of switches but at the same time the disadvantage of higher number of components. The topology in which, for example, the full bridge rectifier would be reconfigured into the full wave rectifier in the higher part of input voltage range, could lead to the better adaptation of transformer’s turns ratio and blocking voltage of switches to the input voltage. It could consequently result in improved overall converter efficiency. The same conclusions could be as well transferred to the HV-side circuit. In case of HV side, full bridge rectifier would be then equivalent to an H-bridge, and full wave rectifier to the converter’s input stage known as ‘push-pull’. The possibility to optimize ZVT PS FB converter for the higher voltage would be highly beneficial for converter’s efficiency over whole discharge cycle of HV battery. Since ZVT PS FB converter operates with its best performance exactly in the ranges close to the minimum specified operating voltage, it would be useful to divide the input voltage range into two narrower ranges. In that way, by reconfiguration of either HV- or LV-side circuit, converter operation is optimized in higher, more present input voltage range.

Bearing in mind the above discussion, the converter topology proposed in Fig. 5 can operate in the upper input voltage range with the full wave rectifier. The transformer covers this range with the turns ratio of \(n : 1 : 1\) and has the center tapped secondary winding. In the lower voltage range, the transformer can operate with disconnected center tap in the secondary winding. In such case, the turns ratio is \(n : 2\) and the bridge rectifier configuration can be used with the help of additional switches. First of all, the turns ratio achieved in that way suits more to the lower voltage range, and second, switches of full wave rectifier can be used in the bridge rectifier (with addition of two more identical switches to form the full bridge). The following goals can be achieved in this way: the transformer with adaptable turns ratio is used and the switches with lower blocking voltage rating can be applied in the rectifier stage. Both will beneficially affect the efficiency in the higher input voltage range. An additional two-position switch needs to be implemented that will enable reconfiguration of rectifier topology depending on the input.
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**4. Implementation of Proposed Topologies**

### 4.1 Reconfiguration at LV Side

In the proposed LV-side reconfigurable topology (Fig. 5), the converter operates in both modes as ZVT PS FB topology, but with different rectifier configuration. The rectifier can be either full bridge or full wave rectifier depending on the value of \( V_{in} \). The two-position switch can be implemented using two additional MOSFETs \( S_{R5} \) and \( S_{R6} \) as depicted in Fig. 6. The MOSFET \( S_{R6} \) conducts in the upper range of \( V_{in} \) to enable the full wave rectifier mode. In this configuration, the transformer operates with the center-tapped secondary winding with its middle point connected to the output filter. In the lower range of \( V_{in} \), to operate the rectifier in the full bridge mode, MOSFET \( S_{R5} \) conducts. In the higher range of \( V_{in} \), \( S_{R5} \) needs to disable the conduction of body diodes of \( S_{R1} \) and \( S_{R4} \) that are not needed in the full wave rectifier configuration.

The main benefit of both operating modes is the duty cycle longer than 50%. Both \( S_{R3} \) and \( S_{R4} \) must be able to conduct the total specified output current of the converter. Their blocking voltages should be high enough to block \( V_{out} \). The value is not critical as they always block in series with one of the rectifier switches \( S_{R1} \) to \( S_{R4} \). The switch \( S_{R5} \) has to be turned on when rectifier is configured as full bridge and turned off in full wave rectifier. The switch \( S_{R6} \) has to be turned on in the full wave rectifier mode. Its control in the full bridge rectifier can be implemented in two ways. If \( S_{R6} \) is turned off continuously in the full bridge mode, its body diode will conduct in the freewheeling period, taking over a certain part of freewheeling current through other conducting switches.

The simplified control will then be paid by additional conduction losses caused by the body diode conduction. On the other hand, if \( S_{R6} \) is used as a synchronous rectifier during the freewheeling, its channel will take over the current. In such case, presence of \( S_{R6} \) will not affect total conduction losses, and switching losses will not occur. To summarize, the simplest implementation of the LV side reconfigurable converter employs single MOSFET (\( S_{R5} \) in position 2), which is constantly on during the full wave rectifier configuration. Second solution, which overcomes the disadvantage of the body diode conduction of \( S_{R5} \), requires active control of \( S_{R6} \) that has to be turned on during the freewheeling in each period.

### 4.2 Reconfiguration at HV Side

Figure 4 presents the proposed HV-side reconfigurable topology based on ZVT PS FB converter (11). The two-position switch from Fig. 4, with the aim to switch from one configuration to the other can be implemented in following way: in the upper range of \( V_{in} \), the conventional ZVT PS FB converter is extended by addition of a diode \( D_{add} \) (Fig. 7). The diode \( D_{add} \) will conduct the input current in the upper range of \( V_{in} \). In lower range of \( V_{in} \), where the converter operates as the push-pull converter (Fig. 7.), the transformer operates with center-tapped primary winding, and its middle point is connected to the voltage source (battery) through the additional active switch.
S<sub>add</sub>. This switch is continuously on and no switching losses occur during operation in push-pull configuration. In lower range of V<sub>in</sub>, D<sub>add</sub> needs to disable the conduction of free-wheeling diodes parallel to IGBTs S<sub>1</sub> and S<sub>2</sub>, not used in the push-pull configuration. The switch S<sub>add</sub> in the ZVT PS FB configuration has to be able to block specified V<sub>in, max</sub>. In both operating modes, the proposed converter operates with duty cycle longer than 50%, allowing much better duty cycle utilization. Standard phase shift modulation strategy is used to produce gate driving signals for the ZVT PS converter. The modulation strategy required for the push-pull configuration is considerably simpler and can be easily derived from the driving signals already produced for ZVT PS configuration. Two diagonal switches in HV-side H-bridge (e.g. S<sub>1</sub> and S<sub>3</sub>, or S<sub>2</sub> and S<sub>4</sub>) are always conducting simultaneously during power transfer period in the phase shift modulation, and they are used to generate gate driving signal for the corresponding push-pull switch. For that purpose, in e.g. analog implementation of the controller, two additional AND gates can be activated when converter starts its operation in the push-pull mode.

5. Model-based Evaluation of Potential for Efficiency Improvement

Potential for efficiency improvement using two variants of reconfigurable ZVT PS FB topology proposed in Sect. 4 will be evaluated here based on the loss model. Design parameters have to be calculated for both reconfigurable variants (with assumed V<sub>reconf</sub> = 300 V, justification for the selection of this value will be discussed in the later sections) taking into account the converter specification from Table 1. First, the transformer turns ratio n : 1, required minimum values of filter inductor L<sub>out</sub> and capacitor C<sub>out</sub> will be discussed. The results are compared for standard ZVT PS FB topology, its HV-side reconfigurable as well as LV-side reconfigurable derivative in Table 2. In the rest of Sect. 5, the values from Table 2 are further discussed.

5.1 Design of Power Transformer

The transformer turns ratio n of all buck derived isolated converters depends on the minimum specified operating input voltage and maximum allowed duty cycle.

\[
\frac{2 \cdot (V_{in,min} - V_{drop,prim}) \cdot D_{max,fb}}{V_{out,max} + V_{drop,sec}} \geq \frac{2 \cdot (V_{reconf} - V_{drop,prim}) \cdot D_{max,pp}}{V_{out,max} + V_{drop,sec}} \quad \text{full bridge rectifier config.} \\
\frac{2 \cdot (V_{reconf} - V_{drop,prim}) \cdot D_{max,pp}}{V_{out,max} + V_{drop,sec}} \quad \text{full wave rectifier config.}
\]

In the reconfigurable converter that incorporates two different topologies into one, this choice is dictated by the worst case. In case of the LV-side reconfigurable converter, if n is the number of turns of the primary winding considered for the one turn of the secondary winding in the full wave rectifier mode (n : 1 : 1), the same numbers of turns (Eq. (1)) will be used but with twice the higher number of turns at the secondary side in the full bridge rectifier (n : 2).

In the HV-side reconfigurable converter, the principle of the transformer turns ratio choice is the same as in the case of its LV-side counterpart. Transformer turns ratio is chosen for the ZVT PS configuration as the main one (minimum input voltage corresponds to V<sub>reconf</sub>), whereas the proper operation with the same turns ratio (but using the middle point) at V<sub>in,min</sub> of converter in push-pull operating mode has to be ensured (Eq. (2)).

\[
n \leq \min \left\{ \frac{2 \cdot (V_{in,min} - V_{drop,prim}) \cdot D_{max,pp}}{V_{out,max} + V_{drop,sec}} \quad \text{push-pull config.} \\
\frac{2 \cdot (V_{reconf} - V_{drop,prim}) \cdot D_{max,zvt}}{V_{out,max} + V_{drop,sec}} \quad \text{H-bridge config.} \right\}
\]

In the push-pull mode, transformer will be used with turn ratio n/2 : n/2 : 1.

The transformer in the proposed HV side reconfigurable topology differs from the one in the conventional converter in the number of primary winding turns n<sub>p</sub> as well as in the presence of the center tap. Furthermore, the maximum RMS current of the primary winding is reduced.

Although different approaches are possible to design the transformer for the proposed converter, the case with the goal to maintain the same core losses P<sub>core</sub> and the same copper losses P<sub>cu</sub> as in the conventional one is analyzed here. The core losses are determined by Eq. (3) from(1): \[ P_{core} = \frac{K_{Fe} \cdot \Delta B^\beta \cdot A_c \cdot l_m}{P_{core}} \] \[ \Delta B = \frac{N}{2 \cdot n_1} \cdot \lambda, \quad \text{full wave rectifier config.} \]

\[ \lambda = \frac{V_{out}}{D \cdot T_s} \quad \text{full bridge rectifier config.} \]

The transformer turns ratio choice is the same as in the case of its LV-side counterpart. Transformer turns ratio is chosen for the ZVT PS configuration as the main one (minimum input voltage corresponds to V<sub>reconf</sub>), whereas the proper operation with the same turns ratio (but using the middle point) at V<sub>in,min</sub> of converter in push-pull operating mode has to be ensured (Eq. (2)).

Table 2. Calculated design parameters: conventional vs. proposed topologies with V<sub>reconf</sub> = 300 V for the converter specification from Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conventional</th>
<th>HV-side reconfigurable</th>
<th>LV-side reconfigurable</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>20:1</td>
<td>20:1 (10:10:1)</td>
<td>20:2 (20:20:1)</td>
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<td>I&lt;sub&gt;out&lt;/sub&gt; (A)</td>
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<td>0.95</td>
<td>0.95</td>
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<td>C&lt;sub&gt;out&lt;/sub&gt; (μF)</td>
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<td>V&lt;sub&gt;D&lt;/sub&gt; (V)</td>
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<td>60</td>
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<td>Additional switches</td>
<td>/</td>
<td>IGBT 650V/50A</td>
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<td></td>
<td></td>
<td>Diode 650V/50A</td>
<td>Mosfet 20V/200A</td>
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</table>
less than twice the peak volt-second product in the conventional converter. Due to the two times higher \( n_1 \) in the proposed converter, the peak \( AB \) in the proposed converter will not be higher than in the case of the conventional one. Therefore, the core size and core losses will not be higher in the proposed converter compared to the case of the conventional one.

The second constraint in this analysis is to maintain the same \( P_{\text{copper}} \) (defined by Eq. (6)) from \( \text{[16]} \) as in the conventional transformer:

\[
P_{\text{copper}} = \frac{\rho \cdot \text{MLT} \cdot n_1^2 \cdot I_{\text{prim}}^2}{W_a \cdot K_a}. \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cd \]
conduction losses by factor 2. Still not all the losses are reduced by this factor as this topology is hard-switching, and both turn-on and turn-off losses of used switches occur (whereas ZVT H-bridge has reduced switching losses). Furthermore, the secondary side body diodes of the push-pull configuration exhibit additional losses due to the reverse recovery, differently from the rectifier stage in the ZVT PS FB converter.

In the LV-side reconfigurable topology, reduced number of rectifier switches is used in the higher range of \( V_{in} \). At HV side, all four switches are conducting, whereas at LV side two rectifier switches are conducting plus the additional switch used for the purpose of reconfiguration. In the lower range of \( V_{in} \) on the other hand, higher number of switches is used on the LV side than in the conventional topology: the number of rectifier switches is increased to four plus additional switch for the reconfiguration. As a result, in the lower range of \( V_{in} \), expected efficiency of the LV-side reconfigurable converter is not only decreased compared to the standard ZVT PS FB converter, but also lower compared the HV-side reconfigurable converter in the same range. The disadvantage of the LV-side reconfiguration compared to the HV-side reconfiguration is the presence of additional switches at the side where higher currents occur. This leads to a slightly lower performance regarding the efficiency. Based on the analysis of potential for efficiency improvement from this section, the HV-side reconfigurable topology is chosen for further investigation and experimental validation in the remainder of this chapter.

### 6. Design Procedure for Proposed HV-side Reconfigurable Converters for Operation in BEVs

The improvement of the converter’s efficiency is a function of the chosen reconfiguration voltage. Thus, the value of the voltage when the reconfiguration should occur depends on the targeted efficiency improvement. Furthermore, several additional constrains that have to be considered will be pointed out. Figure 9 gives the flowchart of the steps required to properly determine reconfiguration voltage.

**Step 1—Definition of operating conditions.** The design procedure of the proposed converter takes into account requirements given in Table 1. From the typical discharge curve of the Li-Ion battery in Fig. 2 it can be concluded that the voltage range around the voltage plateau is the most present at converter’s input. In this range of input voltages, it is beneficial that converter operates with more efficient...
ZVT PS configuration. During the search for maximum $\eta_{\text{HV}}$, $V_{\text{reconf}}$ is incremented by the voltage step $\Delta V_{\text{in}}$ until maximum input voltage is reached. In this specific case, an increment of 20 V is used in the analysis.

Step 2—Calculation of $\bar{\eta}$ for different values of $V_{\text{reconf}}$. The losses and the efficiency for both converter configuration are calculated in this step: in the range from $V_{\text{in,min}}$ to $V_{\text{reconf}}$ for the push-pull configuration and in the range from $V_{\text{reconf}}$ to $V_{\text{in,max}}$ for the ZVT PS configuration. The $V_{\text{reconf}}$ is being increased by $\Delta V_{\text{in}}$ defined in step 1. For that purpose, the transformer turns ratio and the size of the output filter inductor $L_{\text{out}}$ are calculated for each considered value of $V_{\text{reconf}}$.

The parameter calculation based on $V_{\text{reconf}}$ was addressed in Sect. 5 in detail. Based on the calculated efficiency of the reconﬁgurable converter for the complete range from $V_{\text{in,min}}$ to $V_{\text{in,max}}$, the average converter efficiency (Eq. (10)) is calculated using voltage weighting factors $k_{V_{\text{in,m}}}$ defined in Sect. 2.

Figure 10 presents results of $\bar{\eta}$ calculation over different values of $V_{\text{reconf}}$.

$$\bar{\eta} = k_{V_{\text{in,1}}} \cdot V_{\text{in,1}} + \ldots + k_{V_{\text{in,m}}} \cdot V_{\text{in,m}, \ldots}$$

Step 3—Parameter calculation for chosen reconfiguration voltage $V_{\text{reconf,final}}$. Figure 10 can be used to decide on $V_{\text{reconf,final}}$ and final design parameters can be calculated accordingly.

When choosing the reconfiguration voltage, there is a special constraint for the choice of blocking voltage rating of the HV-side switches imposed by operation in the push-pull configuration. The HV-side switches must be able to block two times $V_{\text{reconf}}$ (plus margin for the voltage overshoot caused by interaction of the transformer $L_{\text{leak,prim}}$ and $C_{\text{oss}}$ of the HV-side switches). When IGBTs are used on the HV-side (with 650 V maximum blocking voltage as it is the case in the study of this paper), the choice of $V_{\text{reconf}}$ is thus practically limited to 300 V (Fig. 10).

7. Experimental Validation of HV-Side Reconfigurable Converter

Details of the prototype used for experimental validation of the proposed converter can be found in Appendix. The measured efficiency of the conventional ZVT PS converter for several values of $V_{\text{in}}$ is compared to the efficiency of the converter proposed in this work in Fig. 11. The switching frequency in both converters is set to 100 kHz. It is confirmed that in the upper range of $V_{\text{in}}$, with values close to the nominal battery pack voltage, the proposed reconfigurable topology operates with increased efficiency (curves from 300 V to 400 V). In the lower range of voltages, e.g., at 250 V, the reconfigurable topology operating in the hard-switching push-pull configuration indeed cannot reach the efficiency of the conventional converter.

Nevertheless, the overall converter operation is barely affected by this fact knowing that this operating voltage is present at the converter input for a significantly shorter period of time compared to higher voltage values.

To quantify the efficiency improvement obtained with the proposed reconfigurable converter during one battery discharge cycle, the voltage-weighted average efficiency of both converters is calculated based on Eq. (10) and the data measured from Fig. 11. Figure 12 shows that when the converter efficiency is quantified in this way, the proposed reconfigurable converter offers improved voltage-weighted average efficiency compared to the conventional ZVT PS in the complete range of load currents. In this way, up to 50% of losses that occur at the HV side switches can be saved in the considered example, with further positive impact on the chip temperature swing and lifetime. From the converter cost optimization point of view, the increase of the effective converter’s efficiency up to 2% presents the potential to use a smaller chip size.

Loss distribution is roughly determined using the efficiency measurements for both the proposed and the conventional converter from the example of $V_{\text{in}} = 350$ V in Fig. 13. At this
value of $V_{in}$, the reconfigurable converter operates as well in the ZVT PS configuration with $D_{add}$ conducting. It can be concluded that the main contributor to this efficiency improvement achieved with the proposed converter are reduced HV side currents and shorter freewheeling period. This leads to significant reduction of both switching and conduction losses at the HV side (Fig. 13(a)). Furthermore, in both reconfigurable and conventional converter prototypes, the same LV side switches are used, and thus no considerable difference in losses can be observed (Fig. 13(b)). Still, under the considered operating conditions the proposed reconfigurable converter allows the use of LV side switches with 25% lower blocking voltage capability. Therefore, the additional loss reduction on the LV side of the proposed converter can be assured.

8. Conclusion

In this paper, a method is presented for efficiency optimization of HV to LV DC/DC converter in EVs. The same optimization procedure can be used for converters for PHEVs, by taking into account different battery voltage histogram during its operation. The standard topology, ZVT PS FB converter is modified here, so that it can be easily reconfigured to work in the push-pull configuration. The possibility to operate the converter in push-pull mode at lower input voltage allows the ZVT PS FB converter to be designed with increased transformer turns ratio, what significantly raises the efficiency in higher range of input voltages.

Furthermore, together with the new reconfigurable topology, optimization procedure is proposed that helps finding the point of reconfiguration at which the average efficiency of the proposed converter will be maximized, taking into account the histogram of battery voltages in BEVs. The fact that the proposed topology can improve the average converter efficiency compared to the standard solution of ZVT PS FB converter in the complete load range up to 2% and even more at nominal battery voltage is experimentally verified using prototype of both converters. The design parameters of the proposed converter are proven not to differ significantly from the standard ZVT PS FB converter, so that the price for increased efficiency is paid only through two additional switches in the converter’s power stage and minor additional changes in gate driving circuitry.

In order to further increase the efficiency of the proposed converter, as a direction for further improvement, the additional effort may be spent on operating the converter in ‘soft-switching’ push-pull configuration. This would also help to avoid shortcomings such as overvoltage and voltage oscillations over HV switches in the freewheeling period.

References

(11) H. Wu, P. Xu, W. Liu, and Y. Xing: “Series-input interleaved forward converter with a shared switching leg for wide input voltage range applications”,

Fig. 12. Voltage-weighted average efficiency of the proposed converter compared to the conventional one calculated based on prototype measurements from Fig. 8.

Fig. 13. The comparison of losses distribution in the reconfigurable and the standard ZVT PS FB converter at $V_{in} = 350$ V (no difference in case of c) since the LV side switches with the same blocking voltage are applied in both cases.)

**References**

(1) S. Zeljkovic, T. Reiter, and D. Gerling: “Single-stage reconfigurable DC/DC converter for wide input voltage range operation in HEVs”, Interna

power electronic generation 1 for electric power trains”, Working Group 2 Power


(5) F. Krister, J. Biela, and K. Kolar: “A comparative evaluation of isolated bi-

directional DC/DC converters with wide input and output voltage range”, in


(6) I. Barbi and R. Gules: “Isolated DC/DC converters with high-output volt-

age for TWTA telecommunication satellite applications”, IEEE Trans. Power


DC/DC converter with high efficiency over a wide input voltage range”, IEEE


(8) X. Wu, W. Lu, J. Zhang, and Z. Qian: “Extra wide input voltage range and

high efficiency DC/DC converter using hybrid modulation”, in Proc. 41st


(9) J.-Y. Lee: “Single-stage AC/DC converter with input-current dead-zone con-


(11) H. Wu, P. Xu, W. Liu, and Y. Xing: “Series-input interleaved forward converter with a shared switching leg for wide input voltage range applications”,


Appendix

Components of the prototype converter used for the experimental verification in Sect. 7 are as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV IGBTs/ diodes</td>
<td>F4-50R07W1H3 B11A</td>
<td>Vd = 650V</td>
</tr>
<tr>
<td>LV MOSFETs</td>
<td>IPB019N08N3 G (x2 per switch)</td>
<td>Vd = 80V</td>
</tr>
<tr>
<td>Transformer</td>
<td>CoilCraft NA6237-AL</td>
<td>n = 10:10:1</td>
</tr>
<tr>
<td>Lm</td>
<td>TDK T7921-51</td>
<td>1.7μH</td>
</tr>
<tr>
<td>Cm</td>
<td>3x TDK B41792B7158Q</td>
<td>3x 1500μF</td>
</tr>
</tbody>
</table>

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