IGBT-based High Voltage to Low Voltage DC/DC Converter for Electric and Hybrid Vehicles

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M. Sc. Sandra Zeljkovic

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Vorsitzender:	Prof. Dr. Berthold Lankl
1. Berichterstatter:	Prof. Dr.-Ing. Dieter Gerling
2. Berichterstatter:	Prof. Dr. rer. nat. Ludwig Brabetz

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Sandra Zeljkovic

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Abstract

The subject of this thesis is a high voltage (HV) to low voltage (LV) DC/DC converter in hybrid (HEVs) and electric vehicles (EVs). The focus is on use of an IGBT-based zero voltage transition (ZVT) phase shift (PS) full bridge (FB) topology for this application. Not only the high switching frequency is a challenge when designing the IGBT-based ZVT PS FB converter, but also the wide input voltage range and wide range of load currents during operation of the converter pose additional difficulty for its design and operation. In order to use the available energy of the HV battery of (H)EVs more efficiently, cost-effective loss reduction is one of the main objectives in the development of automotive HV to LV DC/DC converters, and therefore the significant portion of this work is focused in that direction.

The research starts with the question if improved, trench fieldstop IGBT switches with tailless behavior, optimized for high frequency switching ('high speed' IGBTs), have potential to substitute superjunction MOSFETs that are nowadays commonly used at HV-side of the DC/DC converter at switching frequency of 100kHz. The efficiency of the IGBT-based converter is analyzed in detail in order to identify the most critical loss mechanisms and to propose efficiency improvement methods accordingly. Furthermore, one of the issues due to the required wide input and output voltage range is the voltage overshoot during turn-off of rectifier switches. A model is developed and experimentally validated for three different rectifier topologies to simulate turn-off voltage waveforms. Based on this model, the choice of the rectifier and its impact on the overall converter operation is discussed. In addition, design considerations to improve efficiency of the ZVT PS FB converter that were successfully applied in MOSFET-based designs are analyzed in the converter designed with 'high speed' IGBTs. The focus is on use of an external inductor to eliminate turn-on losses in the lagging leg of the HV side H bridge, and capacitive snubbers to reduce the turn-off losses. The effect of such additional components on switching losses of IGBTs and overall converter efficiency is analyzed. The results showed that the advantage of modern IGBTs over superjunction MOSFETs and older IGBT technologies is their optimal performance without external inductive and capacitive components. Thanks to their reduced turn-off losses, and at the same time low turn-on losses, the loss of ZVT in the lagging leg is not anymore critical to converter's efficiency. Since the investigated approaches are not efficient in IGBT-based ZVT PS FB in (H)EVs, and different approaches had to be developed to further improve the efficiency.

Finally, to offer a solution for the problem of reduced efficiency due to the wide input voltage range, a new efficiency optimized single-stage reconfigurable topology is proposed. The proposed topology solves the problem of reduced converter efficiency in the upper range of HV battery voltages by adapting the transformer turns ratio depending on the input voltage. The topology is based on the ZVT PS FB converter that is during its operation, depending on the instantaneous value of battery voltage, reconfigured into a push-pull converter. The ZVT PS FB - the more efficient configuration covers upper range of input voltages whereas the hard-switching push-pull - the less efficient configuration covers the lower, less significant range. The ZVT PS configuration, due to tighter voltage range and more suitable transformer turns ratio, operates with reduced turn-off losses, significantly decreased circulating current in the freewheeling period as well as improved efficiency of the rectifier stage. The point of reconfiguration is chosen to maximize the average efficiency according to the histogram of HV battery voltage during a typical driving cycle. The proposed reconfiguration principle is

also applicable to the rectifier stage at the LV side of the same converter. Operation of the proposed converter and the efficiency improvement are validated experimentally.

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Commonly Used Symbols of Physical Properties

Symbol	Unit	Description
B	T	Flux Density
C	F	Capacity
C_{oss}	F	MOSFET's Output Capacitance
C_{oes}	F	IGBT's Output Capacitance
D	-	Duty Cycle
ΔT_j	K	Junction Temperature Ripple
dv/dt	V/s	Slope of Voltage Rise
di/dt	A/s	Slope of Current Rise
E	Ws	Energy
η	%	Efficiency

f	Hz	Frequency
I	A	Current
L	H	Inductance
n	-	Transformer Turns Ratio
P	W	Power
R	Ω	Resistance
T_j	K	Junction Temperature
T_{vj}	K	Virtual Junction Temperature
T_a	K	Ambient Temperature
T_h	K	Heatsink Temperature
T_c	K	Case Temperature
T_s	s	Switching Period
t	s	Time
t_d	s	Dead Time
V	V	Voltage

Indices

Index	Description
$\boldsymbol{add}$	additional
$\boldsymbol{aux}$	auxiliary
$\boldsymbol{ave}$	average
$\boldsymbol{BD}$	body diode
$\boldsymbol{bat}$	battery
$\boldsymbol{block}$	blocking
$\boldsymbol{CD}$	current doubler
$\boldsymbol{ce}$	collector to emitter
$\boldsymbol{copp}$	copper
$\boldsymbol{D}$	diode

d_{loss}	loss of duty cycle
$\boldsymbol{ds}$	drain to source
$\boldsymbol{ESR}$	equivalent series resistance
$\boldsymbol{FB}$	full bridge rectifier
$\boldsymbol{frw}$	freewheeling period
$\boldsymbol{FW}$	full wave rectifier
$\boldsymbol{ge}$	gate to emitter
$\boldsymbol{in}$	input
$\boldsymbol{k}$	coefficient
$\boldsymbol{lag}$	lagging leg
$\boldsymbol{lead}$	leading leg
$\boldsymbol{leak}$	leakage
$\boldsymbol{min}$	minimum
$\boldsymbol{max}$	maximum
$\boldsymbol{nom}$	nominal

off	turn-off
on	on-state
out	output
prim	primary
pt	power transfer
reconf	reconfiguration
ref	reference
res	resonant
RMS	effective
S	switch
SR	synchronous rectifier
sat	saturation
sec	secondary
t	transformer