Next generation DC-DC converters for Auxiliary Power Supplies with SiC MOSFETs

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***Abstract*—DC-DC converters are essential and mandatory components for Auxiliary Power Supplies in rail vehicles. Their further development show huge challenges in terms of weight, volume, noise, isolation, EMC, safety and controllability. This article presents motivation for SiC, comparison of different topologies and results of a new innovative DC-DC converter prototype based on these terms by use of SiC-MOSFETs. The main development goals therefore were switching frequencies above audible level, downsized passive components, high integration, reduced mechanics and cabling, soft switching and reduced interlock times to ensure high power density. At the end the prototype is compared to IGBT solutions.**

***Keywords*—SiC MOSFET, DC-DC converter, series resonant converter, boost converter, rail vehicles, Auxiliary Power Supplies**

I. Introduction DC-DC converters for rail vehicles

A typical Auxiliary Power Supply (APS) generates isolated AC and DC voltages for electrical loads in rail vehicles. Those are e.g. air conditioner, heater, fans, compressors, sockets, lights, pumps, loads in kitchen and toilets or batteries.
DC-DC converters for APS are mandatory to isolate the APS to catenary voltage and to build a stabilized voltage for output converters (pulse inverters and battery chargers).
Fig. 1 shows a block diagram of a typical APS system for 750 VDC and 1500 VDC catenary voltage. Typical switching frequencies with state of the art IGBTs are 2-4 kHz for hard switching converters and 10-25 kHz for soft and resonant switching converters.

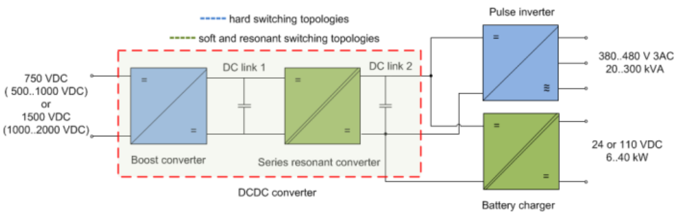

Fig. 1 Typical APS system for 750 VDC and 1500 VDC catenary voltage [1].

The catenary voltage has a wide voltage range (e.g. 1000..2000 VDC for 1500 VDC catenary voltage). In addition to that transient voltages have to be considered in the converter design. Commonly 1200 V or 1700 V power semiconductors are used. Therefore a series connection is often used. In terms of power enlargement a parallel connection is typically. Furthermore passive components like transformers and chokes have an outstanding importance for the design. Based on that and the requirements for railway application the DC-DC converter becomes complex and thereby they have an important relevancy on the whole APS design.

II. Challaenges for DCDC converter design

A. Requirements

In general the output DC voltage has to be isolated to the input DC voltage based on required standards. For an APS application several requirements have to be considered beside that.

The input voltage is variating in a wide voltage range (see I.). The DC-DC converter should generate a stabilized output voltage for optimal operation of output converters (typically 600…750V DC for pulse inverter and battery charger). Furthermore transient overvoltage on the input should not be transformed to the output. Therefor passive components, sensors and control have to be calculated with switching frequencies. Based on these voltages and railway standards the isolation conditions are strict and only special components can be used [4].

Additional requirements based on railway standards are:

- Small inrush current variation
- Pre charging of DC links
- Low Noise emission
- Low EMC
- Defined shut down

B. Potentials by use of SiC MOSFETs

Up to now 1200 V and 1700 V SiC-MOSFET power modules are commercially available by which most of the described requirements can be addressed and optimized [5-7].
First of all switching losses and commutation times can be reduced compared to state of the art IGBTs which allows high switching frequencies and short interlock times [8].

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Fig. 2 shows a comparison of measured switching losses with IGBTs and SiC MOSFETs with same current rating. In a standard commutation loop a switching loss reduction of up to 75 % is possible based on equal overvoltage for hard switching applications.
To exploit the full performance of SiC MOSFETs a reduction of stray inductance is mandatory. This is possible by use of a low inductive dc link connection with interleaved layers, short connections and low inductive capacitors and interfaces.
With that switching losses can nearly be halved again.

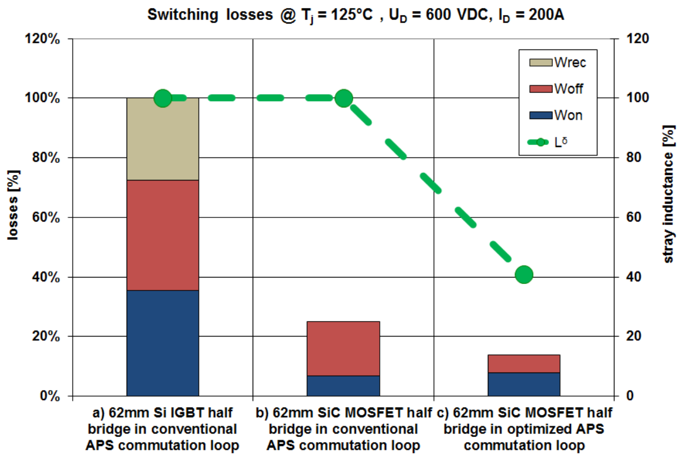


Fig. 2 Comparison of switching loss measurements for an APS DC-DC converter with IGBTs and SiC MOSFETs with same current rating based an equal overvoltage

With an optimized design several advantages can be expected for a DC-DC converter [9-10] compared to a state of the art APS using IGBT:

- High switching frequencies allow downsizing of passive components
  - Chokes, transformers, capacitors
  - Reduction of weight and volume
  - Integration is possible
    - Short connections
    - Reduced cabling
    - Reduced mechanics
- Reduced noise emission by high switching frequencies
  - Frequencies above audible zone
- High switching speed and no bipolar behavior at turn off [12] allow short dead times
  - Higher rms current in transformer circuit
- Small gate charge allow small driver circuits
- Improved efficiency
  - Reduced cooling effort
  - Especially in partial load
- Effective controllability by a nearly linear behaviour of MOSFET
  - Low dependence on operation parameters

Up to now some limitations on 1200 V and 1700 V SiC MOSFETs have to be regarded [12] as:

- Restrictions in terms of gate drive
- Reduced short circuit capability [13]
- Potentially effects of parasitic turn on (PTO) for some SiC MOSFET designs [14]
- Limited lifetime compared to state of the art IGBT modules [15]

For a successful introduction of products in rail vehicles these subjects should be solved.

III. Topology Comparison for DC-DC Converters

A topology research compared various topologies for an APS application [16-21]. In terms of requirements on APS for railway applications two promising topologies are described below. One with a hard switching full bridge without a boost converter and one with a boost converter and a series resonant converter.

A. DC-DC converter without booster

Without a boost converter the principal topology behind an input filter is shown in Fig. 3.

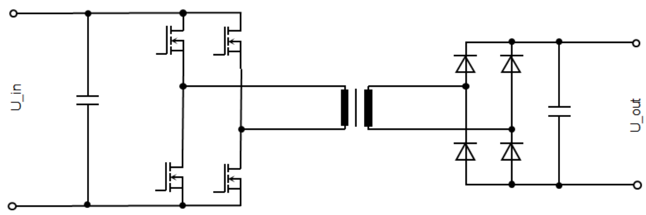


Fig. 3 Principal topology for DC-DC converter without booster

The idea is to use a hard switching SiC full bridge directly driven at catenary voltage to energize a transformer. The output power should be controlled by pulse-width modulation on the primary side. With that no booster is necessary which a great advantage for APS applications is.

This topology shows several drawbacks for rail applications:

- Great SiC chip area is necessary
  - High currents at lowest input voltage
  - Hard switching topology
    - High switching losses
- DC output choke is necessary
  - Current rise limitation
  - Controllability
    - Voltage variation on input
  - Output voltage variation
- Snubber circuits on rectifier diodes necessary
  - With DC choke high overvoltage on rectifier diodes occur

- Costly and complex transformer
    - Transformer has to be designed for Umax x Imax because of transients on input voltage
    - High winding ratio
    - High rms current based on trapezoidal current form
        - High harmonic currents
- Capacitor in transformer circuit necessary to avoid DC voltage on transformer

Considering these aspects a possible solution is shown in Fig. 4 .

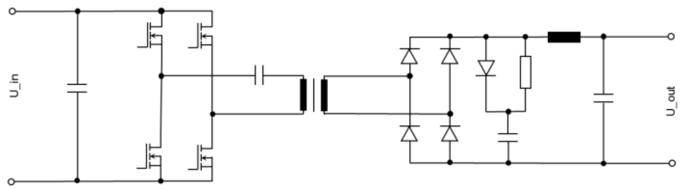


Fig. 4 Possible solution for a DCDC converter for 750 VDC catenary voltage without booster.

As result it can be stated that additional and costly components are necessary to compensate the boost converter.

B. DCDC converter with booster

By connecting a boost converter in series to the full bridge resonant switching with stabilized voltage is possible. With that several advantages occur despite having a booster:

- Voltage is stabilized, resonant and soft switching topologies are possible
    - Small chip area for series resonant inverter
    - High switching frequencies
    - Better EMC, reduced noises
- Transformer can be designed with nominal voltage and current values
    - Optimal winding ratio
    - Sinusoidal current form
        - Low harmonic currents
- No overvoltage on rectifier diodes
    - Standard FRED diodes can be used
    - No snubber circuits necessary
    - Reduced losses
    - Reduced blocking voltage

A possible solution based on these drawbacks is shown in Fig. 5.

The necessary chip area in sum (boost converter plus series resonant converter) can be compared to the topology without boost converter but the transformer and rectifier part is reduced. Booth topologies have a DC choke.

Based on this comparison a DC-DC converter with boost converter is prefered for a prototype.

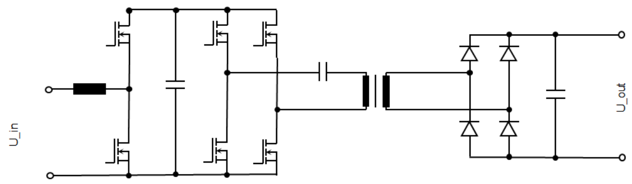


Fig. 5 DCDC converter with boost converter and series resonant converter

IV. RESULTS PROTOTYPE DC-DC CONVERTER

To evaluate the shown potential a complete APS prototype with recent 1200 V SiC MOSFETs was built including two DC-DC converters as shown in Fig. 6. The DC-DC power building blocks can be connected in series or parallel depending on the catenary voltage (750 VDC or 1500 VDC). For results regarding the whole APS prototype see [22].

Fig. 6 Full SiC APS prototype with two integrated DC-DC converters.

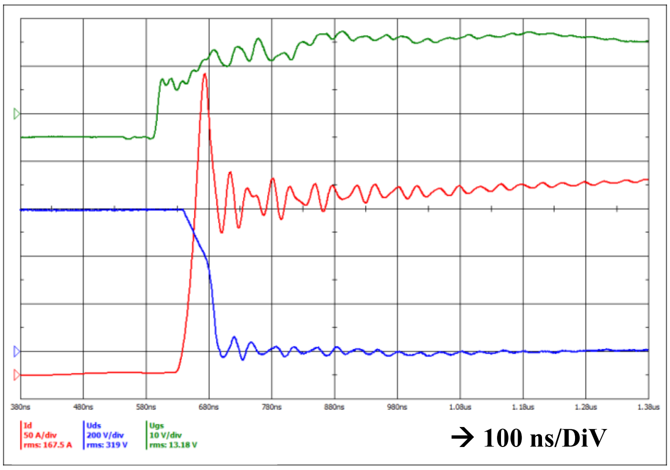
For utilizing the full potential of SiC-MOSFETs a high integrated design including high power PCBs instead of conventional busbars was developed and all components (beside of DC choke) are integrated onto the power building block. Thus mechanics and cabling is remarkable reduced compared to conventional solutions. With a compact and low weight design the units can be integrated easily into the APS converter.

A. Boost converter

The reduced losses as shown in Fig. 2 allow a small dc choke and ripple current frequencies up to 50 kHz are possible for boost converter. This is above audible level. Fig. 8 and Fig. 7 show switching behavior of SiC MOSFET at typical operation point.

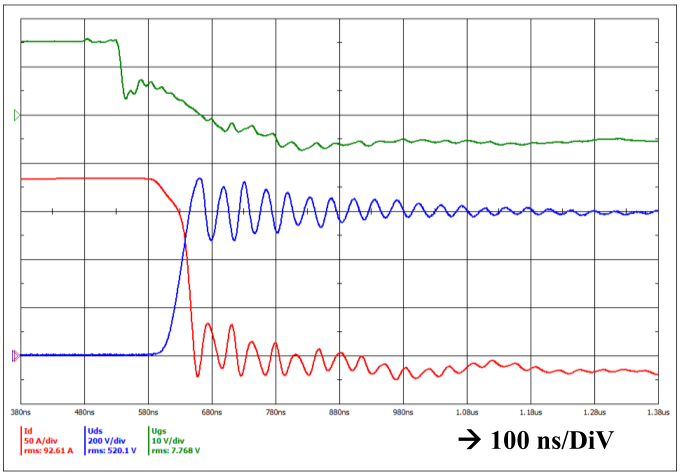
A huge challenge is the measurement of the high dynamic SiC MOSFET drain current. For a correct measurement of typical SiC MOSFET switching gradients oscillation frequencies a high bandwidth of voltage and currents probes is necessary [23].

With a high integrated design switching behavior is relatively soft and no restrictions because of overvoltage or parasitic turn on occur. For choosing correct gate resistors transient voltages, overloads and EMC have to be considered.



Drain current (50 A/Div)	**Drain-Source voltage (200 V/DiV)**
Gate-Source voltage (10 V/Div)	

Fig. 7 Turn on behavior of boost converter @180 A, 600 VDC, 125 °C, Ron=2 Ω



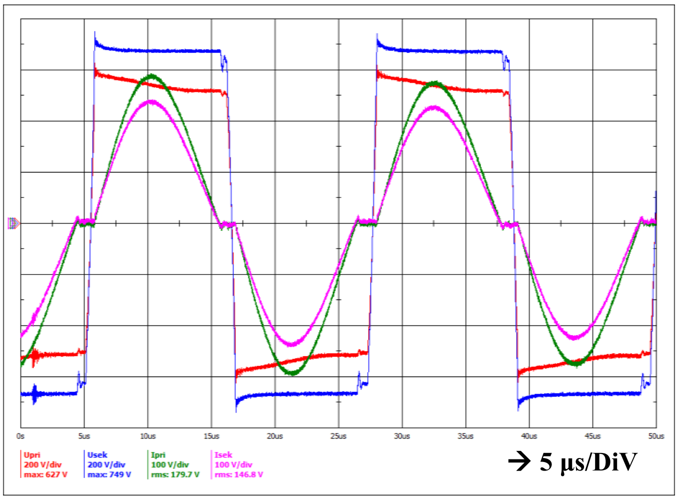
Drain current (50 A/Div)	**Drain-Source voltage (200 V/DiV)**
Gate-Source voltage (10 V/Div)	

Fig. 8 Turn off behavior of boost converter @180 A, 600 VDC, 125 °C, Roff = 3 Ω

B. Series Resonant Converter (SRC)

A series resonant converter operates at a stabilized DC voltage and generates nearly sinusoidal output currents with low harmonic currents. In addition to that short interlock times were chosen to generate a minimal rms current for transformer circuit. Fig. 9 shows waveforms of the SRC on primary and secondary side of transformer.

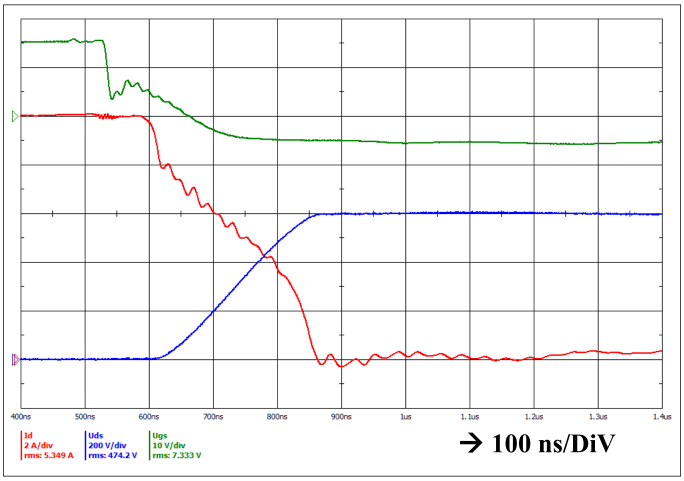
Based on that and on a high switching frequency (around 50 kHz) transformer gets small and small L and C values for resonant circuit are required. With high resonant frequencies it is important to consider tolerances, aging and thermal behavior in component selections for proper operation. For the layout of resonant circuit skin and proximity effects have to be regarded by reason of high frequencies.



u_{pri}: primary voltage (200 V/DiV)	u_{sek}: secondary voltage (200V/DiV)
i_{pri}: primary current (100 A/DiV)	i_{sek}: secondary current (100 A/DiV)

Fig. 9 Waveforms of series resonant converter @ P_a = 90 kW, U_{pri} = 540 V, U_{sek} = 680 V

In this operation mode switching losses only occur at switch off of the magnetization current of transformer. Turn off current should not be too low to ensure short interlock times. Turn off waveforms of resonant converter in typical operation point is displayed in Fig. 10.



Drain current (2 A/Div)	**Drain-Source voltage (200 V/DiV)**
Gate-Source voltage (10 V/Div)	

Fig. 10 Turn off behavior of SRC-DC-DC converter @10 A, 600 VDC, 125 °C, Roff = 3 Ω

C. Comparison to conventional DC-DC converters

Improvements based on optimal use of SiC MOSFETs enable to build a DC-DC converter (booster + SRC) prototype with downsized passive components compared to conventional converters (booster + SRC DC-DC). The main passive components are transformer, DC choke, capacitors and heatsink. Thus a higher degree of integration was reached to further reduce mechanical parts, interfaces and connections.

Fig. 11 displays a comparison with DC-DC converters in conventional technology.

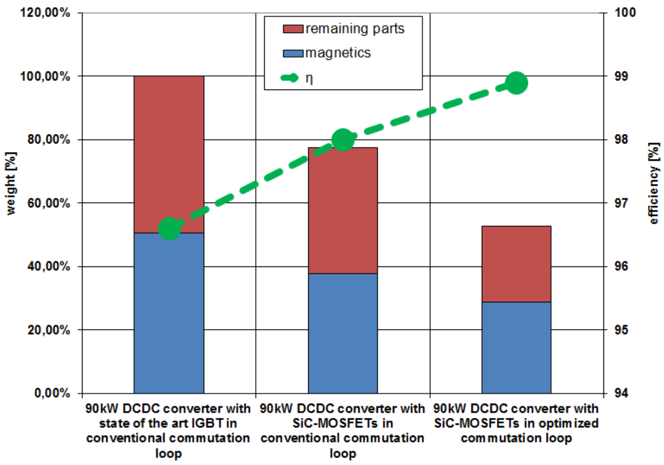


Fig. 11 Weight and efficiency comparison of DC-DC converters prototypes in different configurations

By simply replacing IGBTs by SiC MOSFETs in a conventional commutation loop and just downsizing magnetic components a weight decrease of only around 20 % can be reached. Through an optimal use of SiC MOSFETs in an optimized commutation loop with short connection, downsized and low inductive components a weight reduction of around 50 % was reached with the prototype at same power compared to state of the art IGBT technology.

V. Conclusion

DC-DC converters are essential components for Auxiliary Power Supplies in rail vehicles especially in terms of weight and efficiency. Thus an improved DC-DC converter design will have great influence on complete APS converter design.
Referring to railway requirements it was shown that a boost converter in series to a series resonant converter is a promising topology for an easy and compact converter design.
The utilization of SiC MOSFET power modules shows huge potentials for higher integration and weight reduction in booth DC-DC converter parts – booster and SRC.
By just replacing IGBTs and downsizing magnetics in a conventional commutation loop a weight reduction of 20 % can be reached.
The full potential of SiC MOSFETs can be raised by optimizing converter design to SiC requirements like small stray inductance, short connections and consideration of skin and proximity effects. With that lowest losses and highest power density can be reached.
A DC-DC converter prototype observing these aspects by use of novel SiC MOSFETs was built up and tested. It shows a weight decreasing of 50 % compared to IGBT state of the art technology and losses are decreased onto one third.

VI. Outlook

Further development should remove today’s restrictions on 1200 V and 1700 V SiC MOSFETs like short circuit capability and lifetime for a successful operation in rail vehicles.
Higher blocking voltages of SiC MOSFETs like 3,3 kV show potential for further downsizing and integration like less power semiconductors or remove of series connections.

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