Power Electronic Concepts for Auxilliary Power Converter on Rolling Stock

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Abstract:
Modern train concepts show an increasing electrical power demand for the auxiliary loads. The design of an auxiliary power converter (APC) is mainly governed by topics like reliability, weight, ruggedness, and – of course – costs.
The APCs' main function is to provide stabilized AC and DC output voltages out of the variable input voltage from the railway supply. In order to serve this functionality, several power conversion stages are utilized.
This paper deals with some topologies which make use of high blocking voltage IGBT devices to fulfil the above mentioned demands.
It will be shown how 6.5 kV IGBTs can be used in medium frequency converters.
Special attention will be put on protective measures that have to be realized to deal with the ambient conditions faced on rolling stock.

Introduction:
To handle the different input voltages of auxiliary power converters it is advantageous to make use of a service proven topology. Due to the latest development of IGBT semiconductors, it is possible to transfer the topology of low voltage designs to converters with medium to high input voltage.

Basic structure:
The basic structure of an APC with DC input is shown in Figure 1, see below.

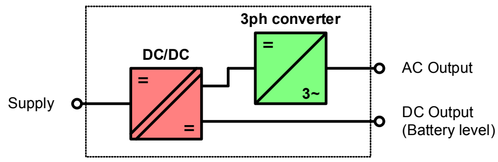


Figure 1: Basic structure of APC with DC Input

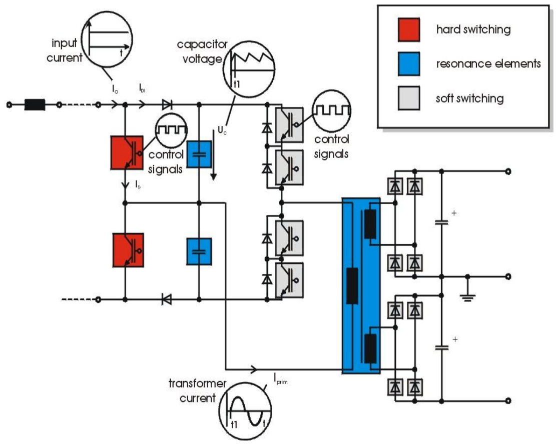


Figure 2: Principle circuit diagram of the input DC / DC converter

Figure 2 shows the circuit diagram of the DC / DC converter which can be operated at a nominal input voltage of 750 V DC.

Typical supply voltages for APCs are 750V, 1.5kV and 3kV. These values are nominal values which vary during operation in a range from -30% to +25%.

This variable input voltage is stabilized by the input DC / DC converter as shown in Figure 2 which also realizes the required galvanic isolation. The boost converter is feeding a medium frequency converter running at a fixed duty cycle of 50%.
The AC and DC output voltage are established by separate units.

Figure 3 shows some basic modules that can be combined in order to realize customer tailored converters by using standardized components.

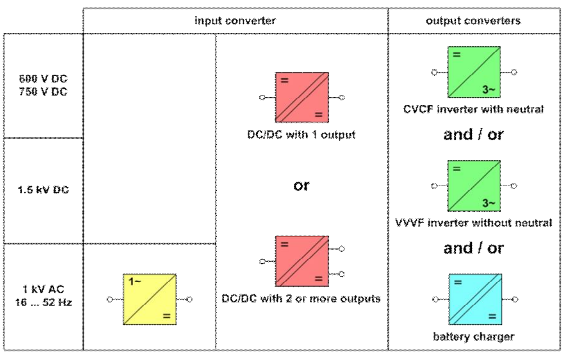


Figure 3: Basic modules
In the following, the focus is set to an input converter that can be used for 3kV input voltage.

DC/DC converter with 3kV input voltage

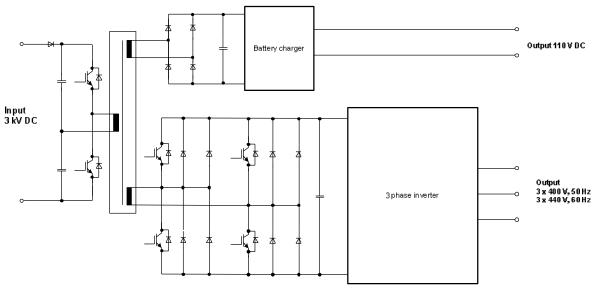


Figure 4: Converter for 3kV input voltage

To realize high reliability of an input converter in rough net environments, as will occur in 3 kV DC applications, a minimum number of IGBTs should be connected electrically to the high voltage side of the converter. Furthermore, the high operating voltage requires high insulation voltage capability against ground potential of the semiconductors. Both requirements can be easily fulfilled by 6.5 kV IGBTs for APC applications.

Basically, 6.5 kV IGBTs are designed for hard switched topologies typically used for propulsion converters in rolling stock applications. Depending on the cooling system of the semiconductors, switching frequencies up to 1 kHz can be achieved. To reach higher switching frequencies, resonant switching methods have to be applied. In the topology shown in Figure 4 a series resonant topology is used to reach a switching frequency of e.g. 4 kHz.

The DC link capacitors of the half-bridge topology together with the leakage inductance of the transformer build up a series resonant circuit. The current wave form in the semiconductor and the transformer is nearly sinusoidal. The switching transition of the semiconductor is done at nearly zero current.

Due to non-ideal switching behavior of the 6.5 kV IGBT special attention has to be drawn to the turn-off behavior of the semiconductors. The 6.5 kV IGBTs have a rather long carrier life time. In case the IGBT is turned-off at zero current conditions, actually a desired effect in resonant topologies, a clearing time of the charge carrier of approximately 20 µs has to be taken into account due to the time required for recombination. This means that the interlock time between switching pulses of half bridge IGBTs has to be set to approximately 20 µs. Such a long interlock time results in increasing current amplitudes during the conduction phases.

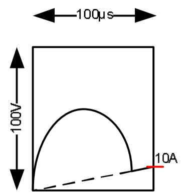
Non-considering this effect of the residual carrier charge leads to an increase of the switching losses of the half bridge IGBTs even reaching double value.

A reduction of the interlock time can be achieved by using suitable measures.

On the one hand, the gate driver technology can be chosen in a way that the conductivity of the IGBT is modulated via the gate during the conduction phase.

On the other hand, external measures can help to support the recombination of the remaining carriers. Here, the magnetizing current of the connected transformer helps to remove the stored charge.

The magnetizing current of the transformer is determined by the voltage applied to the transformer during the on-state of the IGBT, the turn-on time of the IGBT and value of the main inductance. Figure 5 depicts the calculation for magnetizing current for the chosen main inductance of 10 mH. A value of 10 A is an empirically determined value of the current at which the 6.5 kV IGBT has to be turned off in order to achieve an optimal turn-off behavior.



$$dI = \frac{U}{L} \cdot dt = \frac{1000V}{10mH} \cdot 100\mu s = 10A$$

Figure 5:

Calculation of magnetizing current

The commutation will never be ideal and thermal power losses are unavoidable, but proper dimensioning will minimize the switching power losses.

A critical situation in terms of power losses can appear, when the resonant switching state of the semiconductors is not possible e.g. during start-up with pre-charging the secondary side of the converter or by accidental cut off of the IGBT switching during steady state operation. In both cases the switching power losses are low compared to the total power losses, as both cases are limited in time. More critical is a short-circuit on the secondary side of the transformer. This leads to a sinusoidal current wave form only limited by the resonant circuit. A special protection mechanism has to be introduced to prevent failure by over current in the semiconductor.

Further Applications

The above mentioned input stage can be used with some modifications to realize a converter system that can be operated at the AC catenary voltage of 15 kV / 16.7 Hz.

On the grid side, the system is based on a serial connection of eight cascade modules with 3.6 kV DC link based on 6.5 kV IGBTs (see Figure 6). The cascade modules convert the 16.7 Hz input frequency to a significantly higher fundamental transformer frequency of 5 kHz. The 5 kHz transformer frequency is the technical realistic compromise between the volume and weight of the transformer and the switching losses of the semiconductors processing this frequency. The cascade modules consist of a controlled, hard switching 4-quadrant converter operating with 1 kHz, an intermediate DC circuit on the grid side and a resonant half-bridge on the transformer side.

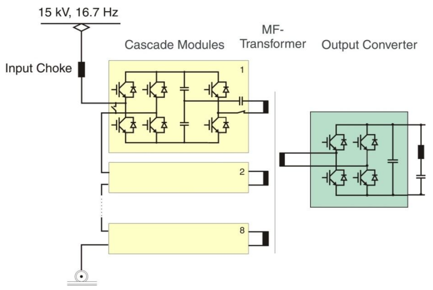


Figure 6: Basic topology of the energy supply system

Each cascade module is connected to one primary winding of the main transformer. The primary leakage inductances result in resonant circuits with the serial capacitors. The secondary winding of the transformer is connected to an output converter based on 3.3 kV IGBTs. This converter feeds the intermediate 1.65 kV DC circuit (train line). A filter circuit on the secondary side dampens the 33.3 Hz power pulsations caused by the single-phase feeding from the railway grid and transmitted by the transformer.

SMA realized a system for Alstom Transportation with the main data shown in the Table 1.

Input voltage	15kV / 16,7Hz
Output voltage	1,65kV
Rated power	1,5MW
Efficiency at rated power	96%
Overload	2,25 MW / 30s
Total weight	3,6t

Table 1: Main data of realized system

Efficiency and power loses

The system reaches an efficiency of 96 % at nominal conditions. Despite of the high efficiency a power dissipation of 4 %, resulting in 60 kW, requires an analysis of the power loss sources in order to achieve a good cooling system performance. The table below lists the power dissipation of all important components.

Primary input converter	23 kW	470 W per hard switching IGBT of 4-Q-Converter 500 W per resonant switching IGBT
Secondary resonant converter	8 kW	
MF transformer	15 kW	Efficiency of 99 %
Input choke	10 kW	
2-f filter	2 kW	
Other components	2kW	

Table 1: Main data of realized system

Insulation coordination

Regarding to the standard EN50124-1 the primary side of the converter has to be designed for insulation voltage of 34.5 kV AC 60 s. As the insulation capability of 6.5 kV IGBTs is not sufficient to fulfill this requirements, the cooling plates of the cascade modules and the cooling system have to be insulated against ground potential.

The most critical component in terms of personal safety is the transformer providing the energy for the electronic supply of cascade modules. It has to separate the battery potential from the high voltage potential of the cascade modules. A double insulation is needed at this point in order to fulfill the requirements of personal safety.

Cooling

The system is liquid-cooled in order to achieve a high power density. The chosen coolant is Midel, a syntactic esther known from traction transformer cooling systems. It provides a high insulation capability that allows coping with different voltage levels between the cooling plates. The cooling pipes between modules and magnetic components consist of material with high insulation capability as well.

Weight

The total weight of the system results in 3300 kg. The table below shows the weight of the single system components.

8 Cascade modules	530 kg
Secondary converter	75 kg
Transformer + Input choke	540 kg
Output filter	450 kg
Cooling system	255 kg
Cooling liquid (MIDEL)	260 kg
Container	970 kg
Other	220 kg

Table 2: Weight overview

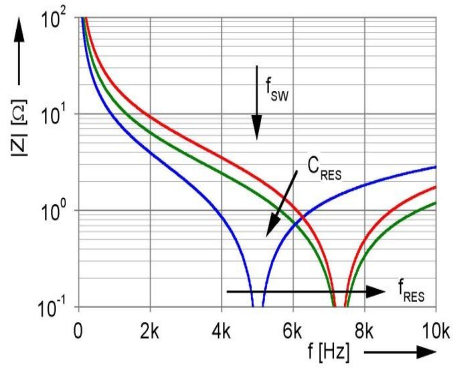
Reliability
A high availability of the feeding system is achieved with redundancies even though the system consists of a high number of electronic components. Even the deactivation of a malfunctioning cascade module is taken into account, so that the system can operate in seven-module mode without limitations.

Design of resonant circuit
The main transformer is the central element of the resonant circuit. It consists of eight primary windings and one secondary winding all covering one ferrite core. Depending on the direction of the flow of energy, the transformer is either fed from the eight half bridges of the cascade modules on the primary side or from the converter on the secondary side. The converters are switched in a resonant mode due to the high fundamental frequency for this kind of IGBTs of 5 kHz. A serial resonance capacitor installed in each cascade module and the leakage inductance of the transformer results in a resonant circuit, so that the IGBTs are switched nearly at zero current and therefore do not cause high switching losses.

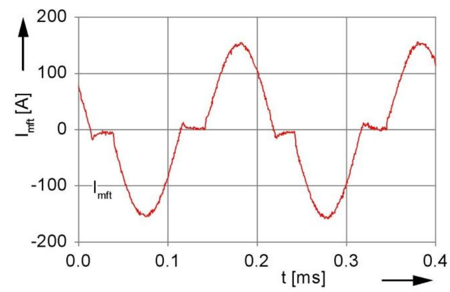
The magnetic link of the cascade modules via the main transformer allows undesired equalizing currents between the cascade modules. This has to be reduced with a suitable sizing of the resonance circuit in order to avoid high destructive temperatures resulting from the high frequency.
The equalizing currents have 3 main causes:

- differences between the current values of the voltages of the intermediate circuit on the primary side, resulting from the time shifted control of the grid side converters,
- unsymmetrical conditions within the resonant circuit,
- run-time differences of the control signals for the output half bridge.

The effects resulting from these causes must be reduced by increasing the decoupling impedance Z between the cascade modules. First of all, this was accomplished by selecting the resonance frequency above the switching frequency f_{sw} and second of all by optimizing the decoupling by increasing the resonance capacities C_{RES} at a given resonance frequency f_{RES} (see Figure 7). The influence of the tolerances between the resonance capacities or the leakage inductances on the primary side with about 5 % that cannot be avoided are reduced as well.



a)



b)

Figure 7: Decoupling impedance (a) and transformer current (b)

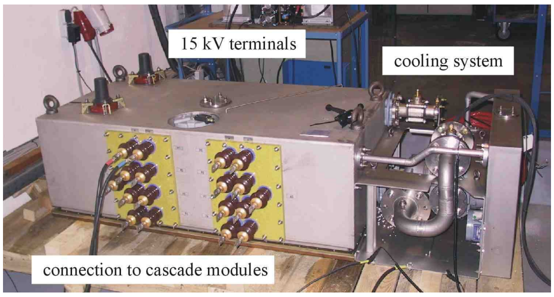


Figure 8: Windings container including input choke and medium frequency transformer (730x490x2000 mm³)

Figure 7 shows the respective measurements for the transformer current IMFT on the secondary side. The super-resonant switching results in a dead time between the positive and negative current curve. The transformer current on the secondary side at these times is not zero, due to the fact that in traction operation the magnetizing current of the transformer completely commutates to the secondary side and equalizes itself with the counter voltage of the intermediate output circuit.

Summary:

Power electronics on rolling stock are exposed to rather rough ambient conditions. Especially the varying input voltage results in high component stress.

This paper presented some topologies that can be used to realize customer-tailored auxiliary power converters by using a modular approach.