

HIGH-VOLTAGE SWITCH REALIZATION POSSIBILITIES FOR THE 3.0 kV DC FED VOLTAGE CONVERTERS

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ABSTRACT

The feeding of rolling stock power converters by high-voltage DC catenary (3.0 kV DC) is complicated by the wide variations of supply voltages (2.0 kV...3.6 kV). The most efficient and simple topology for the rolling stock voltage converters is a two-level VSI, which is directly connected to the traction catenary. This requires primary inverter switches with the high voltage blocking capability to be implemented. Basically, the implementation of high-voltage switch is often a tradeoff between the compactness, complexity, efficiency and cost. In this paper, a comparison between different solutions for the high-voltage switch for the 3.0 kV DC catenary-fed auxiliary power supplies is presented. The main criteria of comparison are the complexity, efficiency and implementation costs. The paper is supplied with the practical design considerations and recommendations.

I. INTRODUCTION

The rolling stock auxiliary power supply (APS) is the power interface between the main supply system of the railway vehicle (catenary) and the low-voltage secondary onboard systems (lighting system, braking system, compressors, blowers, air conditioning system, etc.). It is obvious that a failure within this system would render the whole vehicle non-operational, resulting in a financial loss, operational problems to the transportation system and discomfort to passengers. Some specifications of the APS for the 3.0 kV DC fed trains are submitted in Table 1.

Table 1. Some specifications of APS converters

Parameter	Value
Nominal input voltage	3.0 kV DC
Input voltage variations	2.0...3.6 kV DC (EN50163)
Nominal output voltage	110, 300 or 350 V DC (upon requirements)
Output voltage tolerance	5 %
Input/output isolation voltage	10.2 kV/1min

The design of such converters must be coordinated with the end-user (rolling stock owners) requirements [1]. To

decrease investments costs the development steps must concentrate on a simplification of both the applied converter circuits and mechanical constructions. Increased efficiencies will enable lower operating costs. These all lead to searching for new solutions and design optimization possibilities.

II. EXPERIMENTAL APS TOPOLOGY

In the present paper the half-bridge (HB) isolated DC/DC converter topology will be firstly examined as candidate topology for the auxiliary power supply (APS) to be used in 3.0 kV DC commuter trains. Overall, HB topology has gained an interest because of the following advantages:

- only two primary switches are required;
- half-bridge inverter output voltage rating is reduced to half of input (isolation transformer simplification - reduced primary turns number);
- no centre-tapped transformer is required for the input stage.

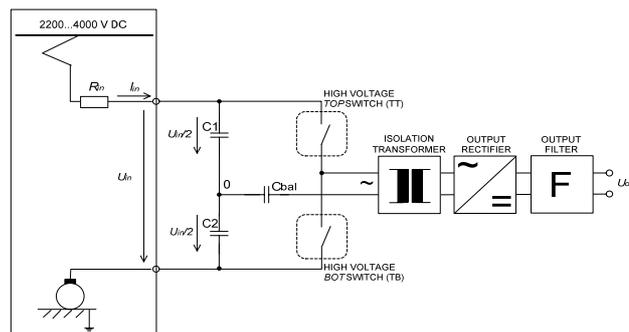


Figure 1. Half-bridge isolated DC/DC converter topology for the rolling stock APS

The input side of the converter is assumed to be connected directly to the traction supply grid with the voltage tolerances from 2.0 kV DC ($U_{in(min)}$) up to 3.6 kV DC ($U_{in(max)}$). The most demanding operation point is at the minimum input voltage and at the rated load conditions (i.e., maximum duty cycle operation). It is essential to prevent even short-time simultaneous conduction of TT and TB switches in these demanding conditions - it leads

to the short circuit across the supply voltage and to the destruction of the converter. It means that the maximum on-state time $t_{on(max)}$ of each switch in the half-bridge must be set at 80 % of a half-period to ensure that this does not happen. Pulse width at the maximum input voltage is minimal and may be determined as

$$t_{on(min)} = \frac{U_{in(min)}}{U_{in(max)}} t_{on(max)} = \frac{2000}{3600} t_{on(max)} = 0.44 \left(\frac{T_{sw}}{2} \right) \quad (1)$$

Operation voltage ranges and inverter switch on-state times of the half-bridge topology in this application are presented in Table 2. Simulated primary voltage waveforms of the isolation transformer with the different input voltages (and corresponding t_{on}) and at rated load are presented in Figure 2.

Table 2. Operation voltage ranges vs. inverter switch on-state time for the HB topology

Converter input voltage U_{in}	2.0 kV	3.6 kV
Switch on-state time t_{on}	$0.8(T_{sw}/2)$	$0.44(T_{sw}/2)$

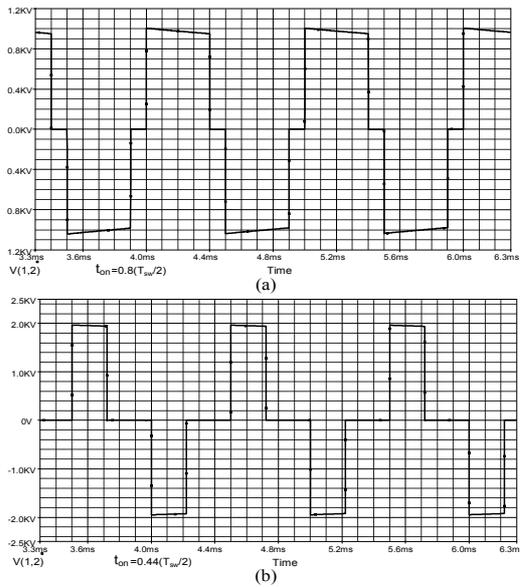


Figure 2. Isolation transformer supply voltage waveforms for maximum (a) and minimum (b) duty cycle operation

III. HIGH-VOLTAGE SWITCH REALIZATION POSSIBILITIES

As it was stated before, the main design and development problem of the converters with such high input voltage level is voltage blocking capability of primary inverter switches (TT and TB in Figure 1). To guarantee safe operation for all operation points (input voltage range is 2000...3600 V DC), selection criteria for the voltage blocking capability of the switching devices used in rolling stock converters must be twice the nominal catenary voltage. Regarding to this design rule, converters based on the IGBT technology for the catenary voltages of 3.0 kV DC are only possible with IGBTs with the U_{ds}

values not lower than 6.0 kV. Up to today, this blocking voltage capability requirement was successfully fulfilled by the series connection of IGBTs (Figure 3) [2]. In that case, the total input voltage blocking capability of the inverter is equal to the sum of the blocking capabilities of series IGBTs:

$$U_{b.c., \Sigma} = U_{b.c., IGBT} \times n, \quad (2)$$

where $U_{b.c., IGBT}$ is the input voltage blocking capability of a single IGBT and n is the number of series connected transistors.

The second item to be taken into account is the nominal value of the converter DC-link voltage (U_{DC}). As the converter must operate in the extended supply voltage limits the selection criteria for the DC-link voltage U_{DC} is regulated by the continuous maximal voltage $U_{in(max)}$ (3600 V, see Table 1). Thus, the number of IGBTs selected for the series connection must be coordinated to keep the nominal DC-link voltage level for each IGBT in accordance with the voltage class of the IGBT.

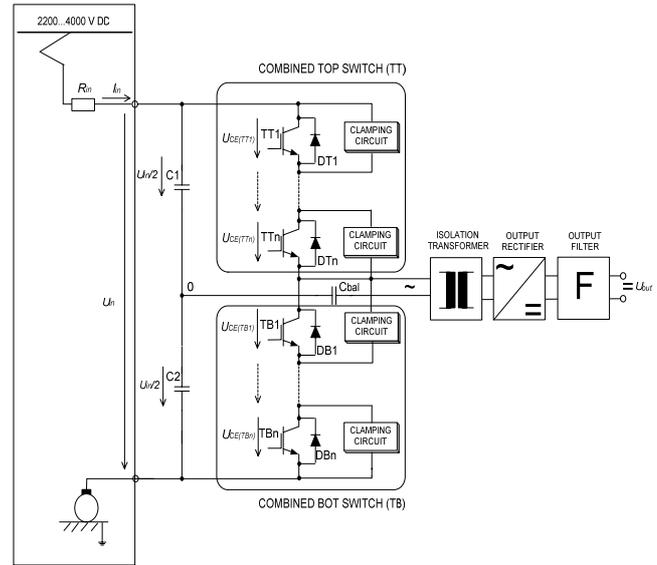


Figure 3. Example of APS with n series-connected IGBTs

Today's conventional IGBT are basically available in 1200 V and 1700 V configurations up to currents 2400 A. From the high-voltage IGBTs the most widespread are 3300 V as well as lately emphasized 6500 V IGBTs. Actually, connecting IGBTs in series allows fast high-power/high-voltage semiconductor switches with operating voltages of several kilovolts to be realized. Depending on the voltage blocking capability of the single transistors to be connected in series (1.2 kV, 1.7 kV, 3.3 kV or others), the total number of interconnected IGBTs varies from 6 to 2 (see Table 3). Such combined high-voltage switch can operate with the nominal DC-link voltage level of 3600 V ($\pm 20\%$). The 6.5 kV IGBT modules (EUPEC, ABB, IXYS, DYNEX, etc.) recently implemented are basically designed for 3.0 kV DC rolling stock applications with their high demands on reliability

concerning thermal cycling capability. A single IGBT has the voltage blocking capability two times the nominal catenary voltage level, which copes with the requirements for the rolling stock power electronics. Such transistors give an attractive possibility to avoid series connection of IGBTs, achieving better efficiency, power density and reliability compared to the combined HV switch designs. Today's state-of-the-art 6.5 kV IGBT modules are available in three basic configurations: with 200 A, 400 A and 600 A collector current capabilities. For such middle-power applications like onboard auxiliary power supply (50...60 kW), the implementation of only two 200 A 6.5 kV IGBT modules (one for the TOP and one for the BOT switch, see Figure 1) is sufficient to fulfill all the design requirements.

Table 3. Evaluation of Different Candidate IGBTs for the High-Voltage Switch

IGBT type	Nominal value of U_{DC} , kV ($\pm 20\%$)	Max. blocking voltage U_{CEmax} , kV	Min. number of series connected for HV switch
1.2 kV IGBT	600	1.2	6
1.7 kV IGBT	900	1.7	4
3.3 kV IGBT	1800	3.3	2
6.5 kV IGBT	3600	6.5	1

Series combination of low-voltage IGBTs is directly connected to the minimum installation surface required. The presented evaluation of IGBTs suitable for the high-voltage switch application is connected to the even number of single IGBTs to be implemented. The most economically feasible solution is to use dual IGBT modules. The IGBT parameter mismatch in this case tends to be minimal (which is very important in the series connection) and space-weight constrains should be optimized with the reduced number of elements installed. Figure 4 gives an overview of installation surface area requirements for the different high-voltage switch solutions. It is obvious, that high-voltage IGBTs (3.3 kV and 6.5 kV) give a result of smaller casings as compared to combined HV switches based on 1.2 kV or 1.7 kV IGBTs (Figure 5). But actually, the picture of installation surface requirements can change to the opposite direction dramatically, if the cooling requirements for different IGBT types will be taken into account.

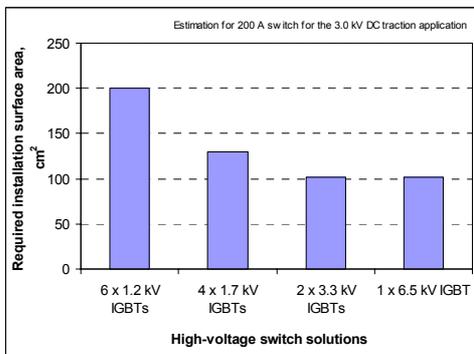


Figure 4. Installation surface area requirements for the different high-voltage switch solutions

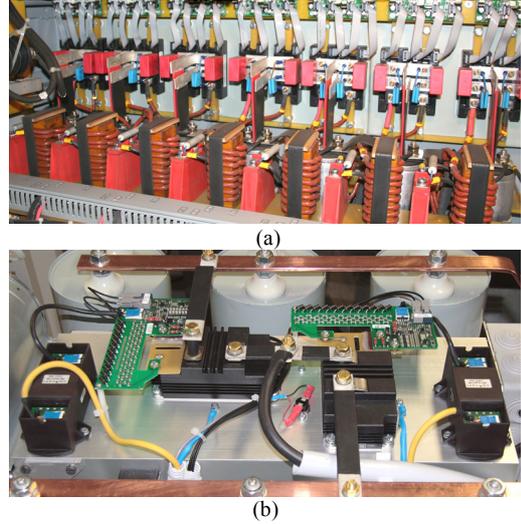


Figure 5. Series connected 1.2 kV IGBTs (a) and simplified 6.5 kV IGBT-based inverter (b)

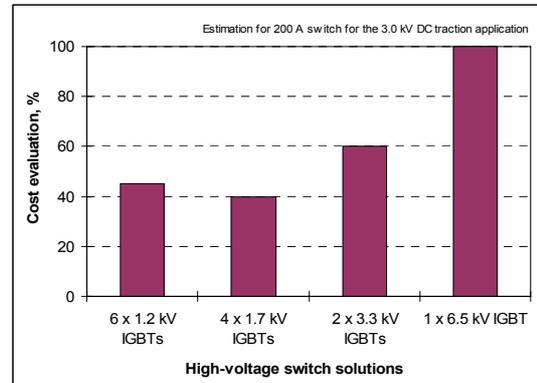


Figure 6. Cost evaluation for the different high-voltage switch solutions

Another aspect, which is very emphasizing from the designer's point of view is the per switch price for the different high-voltage switch solutions. IGBT is one from the major components of such devices and their price gives a sufficient impact on the final price and, hence, on the overall competitiveness of the produced device. Figure 6 shows the cost comparison for the different high-voltage switch solutions. Here must be noted, that the 6.5 kV IGBT technology due to its relative novelty and high manufacturing costs has a lack of competitiveness compared to other IGBT types. Formally, the designer's "solution of choice" for the recent days is the series connection of 1.7 kV IGBTs as more economically and technically feasible.

IV. 6.5 kV IGBT VS. SERIES CONNECTED IGBTs: A COMPARATIVE EVALUATION

A. Operation limits for the different high-voltage switches

Despite such advantages of APS converters with the 6.5 kV IGBTs like simplicity and reliability, the overall design of it involves several limitations. They are mostly

related to the specific properties of 6.5 kV transistors and need to be taken into account during the development routine. The switching dynamics of IGBTs generally depends on such parameters as stray inductance and parasitic capacitance of the module as well as on the resistance of the gating circuit. The average per pulse turn-on (E_{on}) and turn-off (E_{off}) energy losses of IGBTs with the different voltage blocking capabilities in the hard-switching mode are compared in Figure 7.

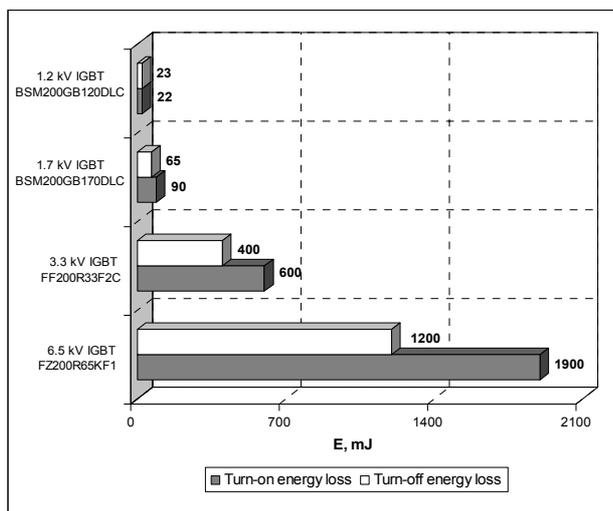


Figure 7. Average per pulse turn-on and turn-off energy losses of different IGBTs (produced by EUPEC)

The comparison was based on the on-market available IGBTs produced by EUPEC. They are BSM200GB120DLC (1.2 kV IGBT), BSM200GB170DLC (1.7 kV IGBT), FF200R33KF2C (3.3 kV IGBT) and FZ200R65KF1 (6.5 kV IGBT). The dual IGBT-modules were preferred for the combined high-voltage switch as more economically and technically feasible. Actually, an implementation of 200 A 6.5 kV IGBTs for the 50...60 kW half-bridge converters look like an overdimensioning. But such IGBT with 200 A collector current is only the lowest-power representative in the 6.5 kV IGBTs' family. Thus, for the simplification of discussion other IGBTs were selected to combine a simply similar 200 A 6.5 kV switch. As it seen from Figure 7, the switching energy losses of the 6.5 kV IGBT are dramatically increased compared to the 1.2 kV and 1.7 kV IGBT and even to another representative of HV-IGBT class - the 3.3 kV IGBT. The typical turn-on transient of the 200 A 6.5 kV IGBT takes about 1.1 μ s. Since hard turn-on transients are basically determined by the turn-on transient of the IGBT internal MOSFET the occurring switching times, the di/dt , and the dU/dt can be adjusted by the gate drive [3]. The minimum gate resistances for turn-on transients depend essentially on the DC-link voltage and the stray inductances of the circuit. Slower current rise and higher DC-link voltage result in a nearly negligible voltage drop for the 6.5 kV IGBT. Therefore, the turn-on loss of the 6.5 kV IGBT is relatively high, but the voltage spike at the freewheeling

diode is very low. Actually, the IGBT turn-on speed is limited by the peak power of the diode. Comparing the single 6.5 kV IGBT with n -series connected low-voltage IGBTs, the lower current droop for a 6.5 kV device results in less stored energy in the stray inductance and a smaller relative overvoltage at the turn-off.

B. Estimation of cooling requirements for the high-voltage switches

Basically, the operating frequency of the switched-mode power supply should be selected to obtain the best balance between switching losses, total transformer losses, size and cost of magnetic components and input/output capacitors. Since 6.5 kV IGBTs have relatively high switching losses, the switching frequency must be carefully adjusted. Figure 8 demonstrates average loss curves for the different high-voltage 200 A switch solutions. The estimation was done with the 60 A RMS collector current of a switch with the DC-link voltage level of 3.6 kV. Only the hard switching mode was examined. All the maximum possible switching frequencies were selected upon the practical limits for the standard IGBTs for the hard switching [4]:

- IGBT-modules, 1.2 kV: up to 20 kHz;
- IGBT-modules, 1.7 kV: up to 10 kHz;
- IGBT-modules, 3.3 kV: up to 3 kHz;
- IGBT-modules, 6.5 kV: up to 1.5 kHz.

The result of comparison is that the switching dynamics of the 6.5 kV IGBT is significantly reduced due to the effect of the absolute voltage vs. current. It is evident, that connecting low-voltage IGBTs in series allows fast high-power/high-voltage semiconductor switches to be realized. However, operation with the maximum switching frequencies is connected with the intolerable power dissipation even with the low-voltage IGBTs. Thus, considering the 800 W as maximum allowable per switch power dissipation, the boundary switching frequencies for the different high-voltage switch configurations (for this particular application) are as follows:

- 6 x 1.2 kV IGBTs: up to 9.5 kHz;
- 4 x 1.7 kV IGBTs: up to 4.5 kHz;
- 2 x 3.3 kV IGBTs: up to 2.4 kHz;
- 1 x 6.5 kV IGBT: up to 1.3 kHz.

Anyway, with the drastically increased power dissipation of HV switches the only high-performance heatsinks should be used for the improvement of converter dimensions. Figure 9 demonstrates a comparison between general specifications of the different cooling techniques. For the power loss range of 2000 W (half-bridge inverter is considered here) the hollow-fin cooling aggregates with blowers seems to be the most attractive solution. In spite of slightly decreased cooling properties the forced cooling about three times outpace the fluid coolers in terms of cost and complexity.

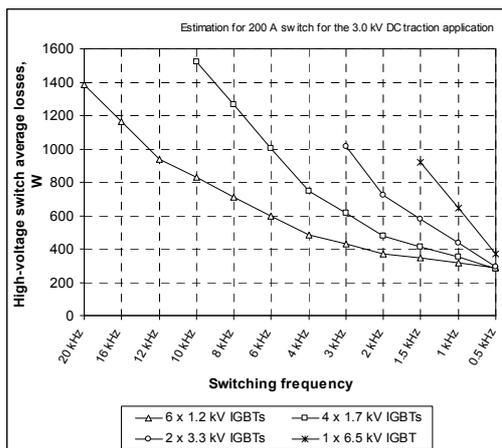


Figure 8. Comparison of average losses for the different high-voltage switch solutions with attention to the maximum possible switching frequency

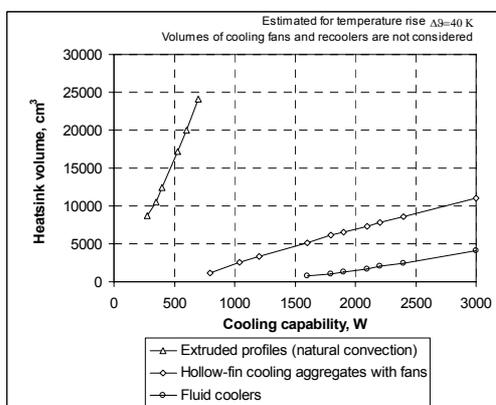


Figure 9. Cooling capability comparison of different cooling techniques

V. CONCLUSION

This paper has discussed common problems and solutions connected with the high-voltage switch to be implemented in the 3.0 kV DC catenary-fed auxiliary power supplies for the rolling stock. The implementation of new 6.5 kV IGBT transistors as HV switches helps to solve common problems of converter power scheme complexity and reliability. However, in the design of high-power converters with the 6.5 kV IGBTs the main attention must be paid to a proper selection of a switching frequency of transistors. In the majority of applications designers use the hard-switching mode of 6.5 kV IGBT, which is more optimal in terms of power circuit complexity and maintainability. However, implementing soft-switching the IGBT energy losses can be reduced significantly down to 8% (turn-on) or 30% (turn-off) of the hard-switching level [5]. Overall, this gives an effect of 20-30% reduced IGBT losses, which means that the cooling effort and therefore costs can be sufficiently reduced. Connecting IGBTs in series allows fast high-power/high-voltage semiconductor switches with operating voltages of several kilovolts to be realized. The operating voltage across the

whole series circuit is higher than the real voltage blocking capability of each single IGBT and must be shared between them. Due to unequal and variable IGBT-parameters (i.e. collector-emitter capacitance, leakage current, switching delays and storage times) and with real gate drive circuits for each single element (with unmatched delay times and supply voltages), voltage-sharing of the whole switch is not balanced across all the elements. The transient (during turn-on and turn-off) and static (in off-state) divergent collector-emitter voltages introduce a risk of element destruction due to voltage and power dissipation stress [6-7]. Furthermore, the current rise di/dt and the voltage rise dU/dt increase with higher operating voltages and currents in the investigated hard switched circuit configurations. This introduces extra EMC problems and increases the electrical stress of the freewheeling diodes. All this leads to auxiliary voltage-balancing circuits to be implemented on the high-voltage primary inverter, increasing the complexity and decreasing the overall reliability of the designed system.

The bottom line is that the selection between different HV switch solutions must be performed in accordance with the custom design requirements and must be precisely analyzed to achieve better price-weight-efficiency-reliability ratio.

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