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# Reconfigurable Dual Active Bridge Converter for Aircraft Applications

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**Abstract**— The increase of electrical energy consumption in modern aircrafts stimulates manufactures to install a 540V DC bus in future aircrafts, together with the existing 270V and 28V DC buses. Energy transferred between the high voltage DC bus (HVDC, 270V) and the low voltage DC bus (LVDC, 28V) is made by bidirectional isolated DC-DC converters. A performing topology for these types of converters is the Dual Active Bridge (DAB) given its soft switching properties and the low number of components, which allow the converter to be highly compact. This paper introduces a new topology of DAB (named DABRSP) which uses only 4 switches at the high voltage (HV) side and can be used in 270V and 540V DC buses without oversizing switches. Oversizing is observed if regular Full Bridge (FB) or Neutral Point Clamped (NPC) converters are used in the HV side of the DAB. The proposed topology allows Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) the same way as in a typical DAB converter and it makes uses of a particular transformer to “magnetically” sum up 2-level voltages.

## I. INTRODUCTION

The use of electrical energy in aircrafts has been continuously growing given the need of CO<sub>2</sub> emission reduction (by replacement of conventional pneumatic devices [1]) and the increase on the number and power of electrical devices such as avionics, lighting and entertainment systems [2].

A High Voltage DC (HVDC) bus of 270V is used to distribute electrical energy to different parts of modern aircrafts [2]. However, with the increase of electrical energy consumption, aircraft manufacturers plan to increase the HVDC voltage to 540V in order to reduce the weight of conductors used in the HVDC bus.

Like this, it is essential for future aircrafts to have bidirectional isolated DC-DC converters to interface both the 270V and 540V HVDC buses with the traditional 28V LVDC bus used for most of the electrical devices. A promising topology for this type of converter is a Dual Active Bridge (DAB).

DAB converters are nowadays used in many bidirectional isolated DC-DC applications such as automotive [3] and smart grids [4-7]. This topology is particularly interesting when high compactness and high performance are needed [8]. The most typical configuration is shown in Fig. 1 where a full bridge is used in the Low Voltage (LV) side and another is used in the HV side. A high frequency transformer is used to isolate and

adapt the voltage of both sides and an inductor (which is usually designed as the leakage inductance of the transformer) is used to shape the current. Different modulation strategies can be used to regulate the transferred power and at the same time to control the current flowing in the transformer. The most common strategies allow Zero Voltage Switching (ZVS) [9] and/or Zero Current Switching (ZCS) [6]. They will be explained in the next chapter.

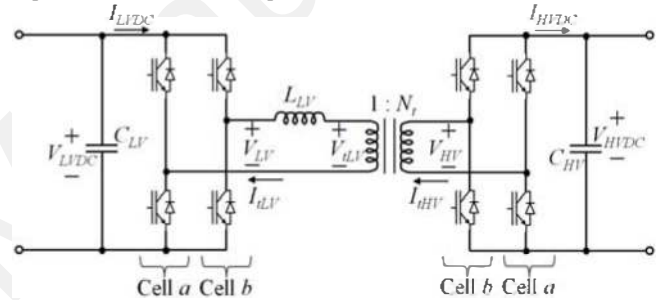


Fig. 1. Typical Dual Active Bridge (DAB) converter.

A single-stage DAB converter can be used in applications where there is a wide range in the bus voltages. Consequently, the same converter could be directly connected to a 270V or 540V DC bus. However, as pointed out in [9], the performance of such converter is severely degraded in such cases. A solution for that is the use of reconfigurable converters as generically shown in Fig. 2. In this figure, 2 converters are designed for a HVDC voltage of 270V and for half the maximum transferred power ( $P_{rated}$ ). If used in a 270V HVDC bus, they are connected in parallel as shown in Fig. 2a. In the other hand, if used in a 540V HVDC bus, the HV side converters are connected in series as shown in Fig. 2b. Like this, each sub-converter may be designed for its maximum performance at the fixed voltage of 270V.

The typical DAB converter of Fig. 1 could be used as the sub-converters of Fig. 2. However the number of components of the total converter would double if compared to a single converter. An interesting solution to reduce the number of components and at the same time to keep the same possibility of soft switching and the same modulation strategies is proposed in this paper and will be explained in Section III and compared to other solutions in Section IV. The basic operation and modulation strategies of a typical DAB converter will be recalled in the next section so the proposed converter, named DABRSP, can be better understood.

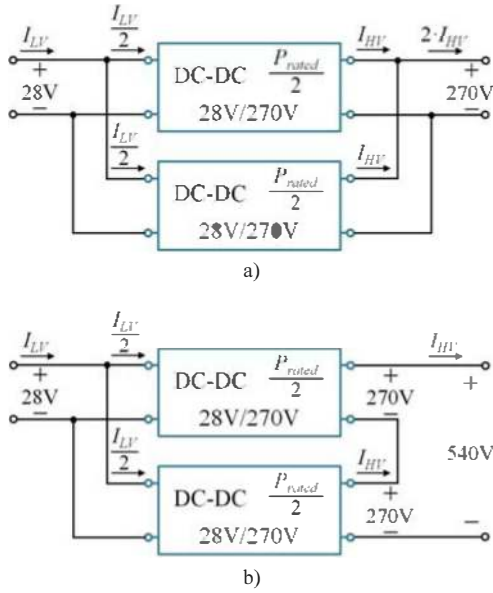


Fig. 2. a) Parallel and b) series connection of the high voltage side of bidirectional isolated DC-DC converters connected to 270V or 540V DC bus of future aircrafts. Low voltage side terminals are naturally connected in parallel since high currents are expected in the LVDC bus. Rated power of the whole converter is  $P_{rated}$ .

## II. DUAL ACTIVE BRIDGE MODULATION

To understand the operation of a DAB converter, a simplified equivalent circuit can be considered, as the one shown in Fig. 3. This circuit is referred to the LV side. Like this, the voltage  $V_{LV}$  applied to the left side of the inductor  $L_{LV}$  by the LV full bridge is a 3-level voltage with duty cycle  $D_{LV}$ . At the right side of inductor  $L_{LV}$ , there is the voltage  $V_{iLV} = V_{HV}/N_t$  connected to the left terminals of the transformer of Fig. 1.  $N_t$  is the turns ratio of the transformer.  $V_{HV}$  and  $V_{iLV}$  are also a 3-level voltage, with duty cycle  $D_{HV}$ .

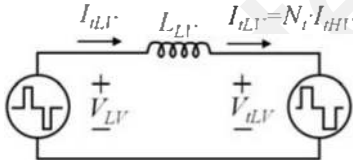


Fig. 3. Simplified equivalent circuit of a DAB converter, referred to the LV side.

DAB converters are classically modulated applying a square wave of 50% duty cycle in each side and changing the phase shift ( $\varphi$ ) between these two voltages. The resulting current in the transformer has a quasi trapezoidal shape as the one shown in Fig. 4a. This modulation allows Zero Voltage Switching (ZVS) in all switches in a certain power range [8] and reduced RMS current through the transformer depending on the maximum phase shift allowed in the system. However, in some cases, the switches in the HV side, which usually have a high breakdown voltage, present poor switching performance and consequently a modulation with ZCS at these switches is desired [6].

Triangular modulation allows ZCS at the HV side switches [6,8] which can be seen by the relevant voltage and current

waveforms shown in Fig 4b. In this type of modulation, the phase shift between  $V_{LV}$  and  $V_{iLV}$  is zero and, in the case where  $V_{LVDC} \cdot N_t > V_{HVDC}$  (where  $V_{LVDC}$  and  $V_{HVDC}$  are respectively the DC bus voltages at the LV and HV sides), duty cycles in the HV and LV sides, respectively  $D_{HV}$  and  $D_{LV}$ , can be calculated as:

$$D_{HV} = \frac{\sqrt{(V_{LVDC} - V_{HVDC}/N_t) \cdot L_{LV} \cdot V_{LVDC} \cdot P_t \cdot T_s}}{(N_t \cdot V_{LVDC} - V_{HVDC}) \cdot V_{LVDC} \cdot T_s} \quad (1)$$

$$D_{LV} = \frac{V_{HVDC} \cdot D_{HV}}{N_t \cdot V_{LVDC}} \quad (2)$$

where  $L_{LV}$  is the inductance in the LV side of the transformer,  $P_t$  is the transferred power and  $T_s$  is the switching period.

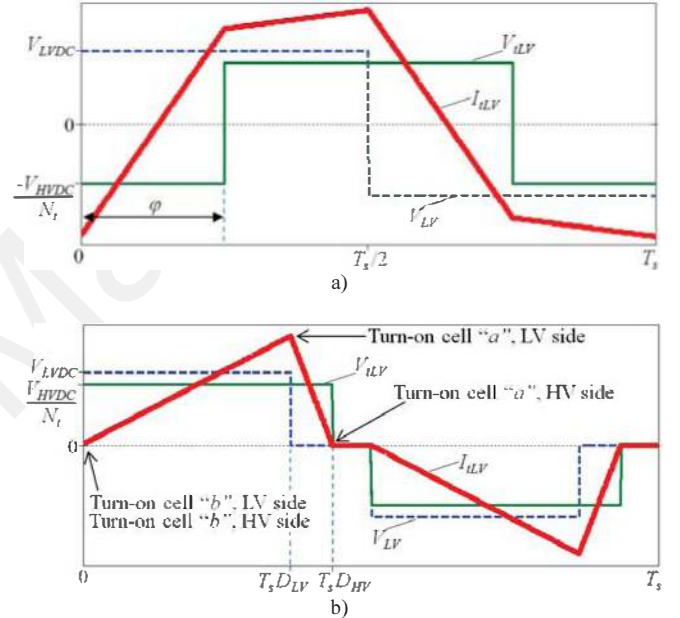


Fig. 4. Relevant voltages and currents of a DAB converter using a) phase shift modulation and b) triangular modulation.

Note that this modulation, although achieving ZCS at the HV side switches, imposes the LV side switches to commute at the maximum value of the current of the switching period.

### A. Three-level converters

The DAB of Fig. 1, composed by two Full Bridges (FB), was used to explain these two modulation strategies. However, regarding the ZVS and ZCS modulation strategies previously explained, any converter producing a three-level voltage could be used in any of the DAB sides. In the cases where the HV side has significant high voltage, Neutral Point Clamped (NPC) converters or Flying Capacitor (FC) converters could be used to reduce the rated voltage of switches, improving switching losses. NPC converter is used in DABs for smart grid applications [5,10] and an example is given in Fig 5. When compared to a full bridge converter, an NPC converter typically uses switches with half the breakdown but carrying the double of the current.

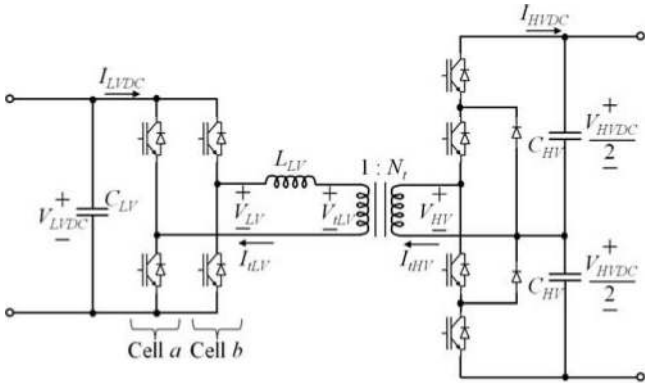


Fig. 5. DAB converter with NPC converter at the HV side.

### III. NOVEL RECONFIGURABLE SERIES-PARALLEL DUAL ACTIVE BRIDGE (DABRSP)

The innovation in the proposed DAB is located in the HV side, where a 3-level voltage is obtained by the sum of two isolated 2-level voltages. This sum is performed magnetically by using a particular transformer which works as a “magnetic adder”, as will be explained below.

#### A. Magnetic Adder

A “magnetic adder” can be defined as a transformer with  $N+1$  legs and  $N+1$  windings, one in each leg, where  $N$  is the number of voltages which will be summed ( $V_1, V_2, \dots, V_N$ ), as shown in Fig. 6. These voltages are applied to windings 1, 2, ...,  $N$ , having respectively number of turns  $n_1, n_2, \dots, n_N$ . Since voltages  $V_{L..N}$  are imposed, the fluxes generated in the corresponding leg ( $\phi_1, \phi_2, \dots, \phi_N$ ) are summed in leg  $O$ . Given that

$$\phi_i = \frac{1}{n_i} \cdot \frac{dV_i}{dt} \quad \text{where } i = 1, 2, \dots, N, \quad (3)$$

the voltage in the output winding  $O$ , if no voltage is imposed to this winding, is

$$V_O = n_O \cdot \int \phi_O dt = n_O \cdot \sum_{i=1}^N \int \phi_i dt = n_O \cdot \sum_{i=1}^N \frac{V_i}{n_i} \quad (4)$$

where  $n_O$  is the number of turns in the output winding. As shown in (4), the voltage in the output winding is equal to the sum of the voltages imposed in the other windings, weighted by the turns ratio. Using this concept, one could think about creating the 3-level voltage needed at the low voltage side of the DAB converter ( $V_{LV}$  in Fig. 1) by adding two 2-level voltages. This can be done by using a transformer with 2 input windings and one output winding, as shown in Fig. 7a. An example of voltage waveforms at the input windings and the resulting output voltage waveform is shown in Fig. 7b. For this example, the number of turns in the input windings ( $n_1$  and  $n_2$ ) is the same as the number of turns in the output winding ( $n_O$ ).

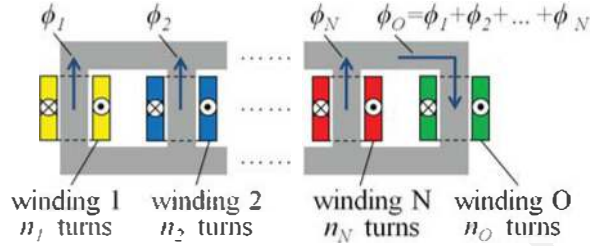


Fig. 6. Magnetic adder with  $N$  winding having imposed voltage and the output winding (winding  $O$ ) having the sum of all the input voltages.

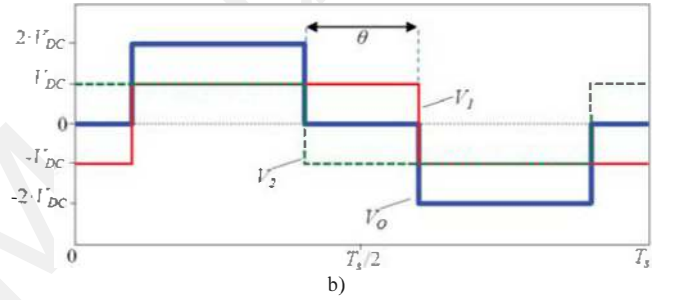
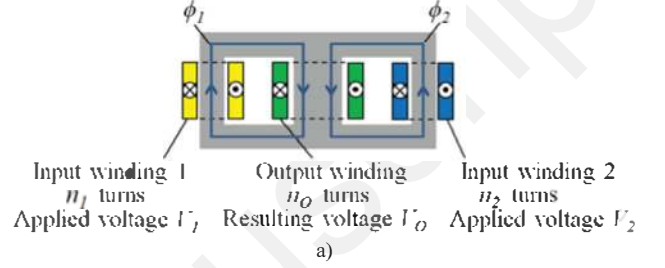


Fig. 7. a) Transformer (or “magnetic adder”) used to produce 3-level voltage at the output winding from two 2-level voltages applied to the input windings; b) example of voltage waveforms applied to the input windings ( $V_1$  and  $V_2$ ) and the resulting output voltage ( $V_O$ ), with turns ratio 1 from each input winding to the output winding.

The design of such a transformer is not so different from a regular transformer. Since both input windings impose the same squared voltage, at the same switching frequency  $f_s$  and at different phase shift  $\theta$  to generate the 3-level voltage in the output winding, when  $\theta=0$ , both fluxes  $\phi_1$  and  $\phi_2$  are equal and consequently the flux in the central leg is the double of the flux in each side leg. Like this, the central leg usually has the double of the cross section of the side legs. Thus, this transformer can be easily built with standard E-cores.

Given the structure of the magnetic circuit and the low reluctance of the core, all windings have practically the same magnetomotive force (MMF) and consequently all the windings have the same current (weighted by the turns ratio). This transformer is the basis of the converter proposed in this paper.

#### B. DABRSP Converter

The Reconfigurable Series-Parallel Dual Active Bridge (DABRSP) is presented in Fig. 8. It is composed by a full bridge in the LV side, although any other type of 3-level converter (such as NPC or FC) could be used. The difference to the typical DAB of Fig. 1 is in the transformer and in the HV

side. The transformer is exactly the same as the one explained in the last sub-section and shown in Fig. 7. The “output winding” is connected to the LV side converter while the two “input windings” are connected to the HV side converter. The HV side converter is composed by 2 independent half bridges imposing squared voltages with duty cycle 0.5, frequency  $f_s$  and at different phase shift  $\theta$  to generate the desired 3-level voltage in the output winding.

The two half bridge legs HB1 and HB2 are connected in parallel if the HVDC bus voltage is 270V and they are connected in series if the HVDC bus voltage is 540V. Like this, each half bridge leg has always a maximum of 270V applied to switches and consequently 600V breakdown voltage MOSFETs or IGBTs can be used in this converter, independently if the HVDC bus voltage is 270V or 540V.

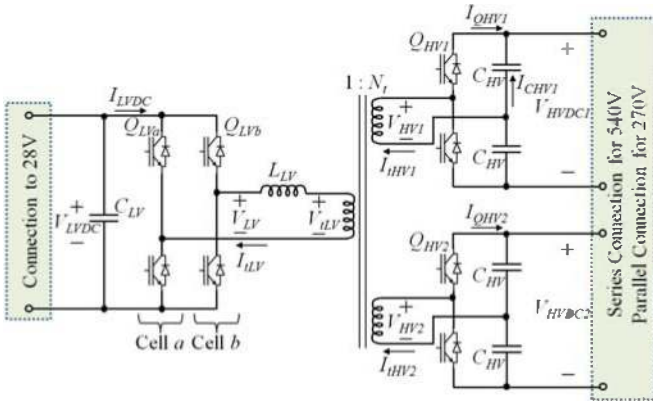


Fig. 8. Reconfigurable Series-Parallel DAB converter (DABRSP). Half bridges on the HV side of the transformer must be connected in series when using the DABRSP in a 540V DC bus and they must be connected in parallel when using the DABRSP in a 270V DC bus.

The modulation of the DABRSP converter is the same as in a regular DAB converter. Triangular and phase-shift modulation strategies explained in Section II can be used the same way since the DABRSP operation imposes 3-level voltages in both sides of the inductor  $L_{LV}$ . Like this, the benefits of ZVS and ZCS obtained with these modulation strategies are also valid for the DABRSP. The relation between the phase shift between the two half bridge gate signals  $\theta$  (in seconds) and the duty cycle  $D_{HV}$  in the HV side converter in a regular DAB [as presented in (1)] is:

$$\theta = (0.5 - D_{HV}) \cdot T_s \quad (5)$$

For the same modulation strategy, the gate signals of the switches in the DABRSP are almost the same as the ones for the regular DAB. The only difference is that the switching signals of HB2 of DABRSP are inverted in comparison to the switching signals of “cell b” of a regular DAB (Fig. 1). This is because the three-level voltage of a full bridge (which is used in a regular DAB) is due to the difference between the voltage of its two half bridges while in the DABRSP the 3-level voltage is due to the sum of the voltages of its two half bridges.

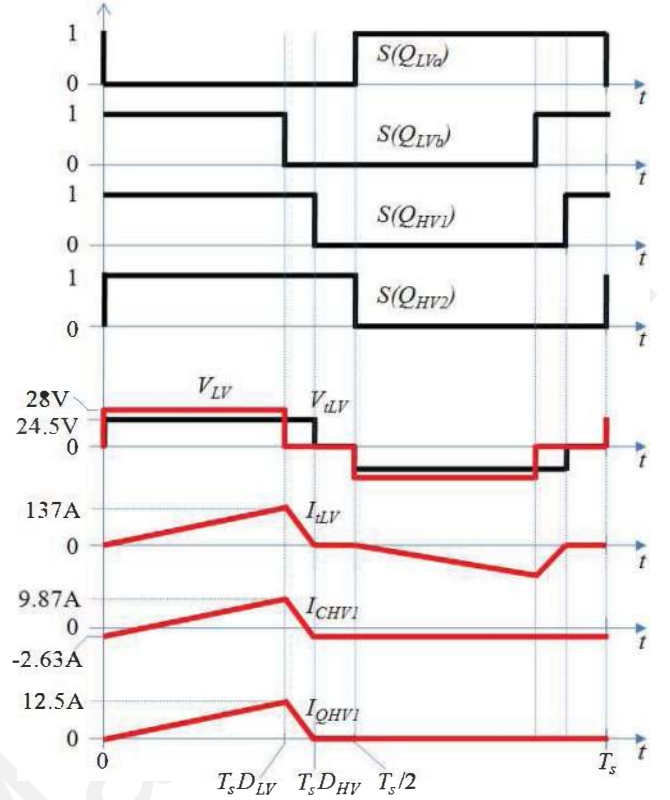


Fig. 9. Main switching signals (S), voltage and current waveforms of DABRSP converter operating with triangular modulation and having parameters shown in Table I.

An example of the main gate signals, voltage and current waveforms related to the DABRSP converter is shown in Fig. 9, for the converter operating at triangular modulation and with the HV side half bridges connected in series and supplied by a 540V HVDC bus. Values related to the operation point of this figure are given in Table I.

Table I. System parameters used to calculate waveforms shown in Fig. 9. Parameters were chosen so the waveforms could be well representative. The maximum transferred power was considered for  $D_{HV} = 0.5$ .

Parameter	Value
HVDC bus voltage ( $V_{HVDC}$ )	540V
LVDC bus voltage ( $V_{LVDC}$ )	28V
Maximum transferred power ( $P_{rated}$ )	2kW
Switching frequency ( $f_s$ )	100kHz
LV side inductor ( $L_{LV}$ )	93nF
Transferred power at operation point ( $P_t$ )	1.42kW
LV side duty cycle ( $D_{LV}$ )	0.368
HV side duty cycle ( $D_{HV}$ )	0.42
Turns ratio (each winding)	1:11

#### IV. COMPARISON BETWEEN THE DABRSP AND OTHER DAB CONVERTERS FOR 270V AND 540V HVDC BUSES

In order to highlight the advantages of the proposed topology in a 270V/540V HVDC bus environment, the DABRSP will be compared to other classical topologies. Triangular modulation will be applied to all topologies in order to ensure ZCS in the HV side switches. All compared topologies have a full bridge in the LV side. However, the HV side can be composed by:

A – Single Full Bridge working at 270V and at 540V (converter of Fig. 1).

B – Single NPC working at 270V and at 540V (converter of Fig. 5).

C – Double Full Bridge connected in parallel at 270V and connected in series at 540V (two transformers are necessary).

D – The DABRSP with HB1 and HB2 connected in parallel at 270V and connected in series at 540V (the three-leg transformer is necessary) (converter of Fig. 8).

The comparison will be made considering that all topologies have a maximum transferred power of 2kW (at duty cycle  $D_{HV}=0.5$ ) and the switching frequency is 100kHz. RMS current calculation in the transformer, switches and capacitor will be omitted for conciseness of this paper. These calculations are well explained in [6,8].

##### A. Single Full Bridge

Given the 540V HVDC, 4 switches with breakdown voltage of 1200V have to be chosen. The transformer turns ratio which minimizes the RMS current in the transformer is 20 (minimum integer value higher than  $540V/28V$ ). Like this, for the switching frequency and maximum power transferred given in Table I, the inductance value  $L_{LV}$  and the RMS current in the LV side of the transformer are, respectively 32nH and 86A. At 270V, the duty cycles of the converter have to be decreased to transfer the same maximum power ( $D_{HV} = 0.259$ ). At this point the RMS transformer current in the HV side is 11.8A and so the maximum RMS current per switch of the HV side is 8.36A. The RMS current in the LV side commutation cells is 236A and they switch a maximum of 569A. The maximum peak-to-peak current flowing in the HVDC bus capacitor is 28.5A at twice the switching frequency, if we consider that no harmonic current flows to the HVDC bus source.

##### B. Single NPC

Given the 540V HVDC, 4 switches and 2 clamping diodes with breakdown voltage of 600V have to be chosen. The transformer turns ratio which minimizes the RMS current in the transformer is 10 (minimum integer value higher than  $540V/2/28V$ ). From the LV side point of view, it works the same as with the Single Full Bridge (case A), so  $L_{LV}$  is 32nH, the RMS current in the LV side commutation cells is 236A and they switch a maximum of 569A. For the HV side, since the

circuit deals with half the DC bus voltage, the current is doubled. Thus, at the point of maximum power transfer, the RMS transformer current in the HV side is 23.6A and so the maximum RMS current per switch of the HV side is 16.7A. Practically no current flow through the clamping diodes since the transformer current is zero when the clamping diodes are active (for triangular modulation only). If we consider that no harmonic current flows to the HVDC bus source, the maximum peak-to-peak current flowing in the HVDC bus capacitors is 57A at the switching frequency.

##### C. Double Full Bridge

At 540V HVDC, both full bridges are in series so the 8 switches with breakdown voltage of 600V have to be chosen. There are two transformers, each with the turns ratio equal to 10, but with half the power, when compared to the single full bridge. Independently if connected to 540V or 270V HVDC bus, the converter has its maximum power delivered at  $D_{HV}=0.5$ . At this point the inductance value  $L_{LV}$  and the RMS current in the LV side of the transformer are, respectively 64nH and 86A. Thus the maximum RMS current per switch of the HV side is 3A. The RMS current in the LV side commutation cells is 86A and they switch a maximum of 150A. The maximum peak-to-peak current flowing in the HVDC bus capacitor is 15A at twice the switching frequency, if we consider that no harmonic current flows to the HVDC bus source.

##### D. DABRSP

At 540V HVDC, both half bridges are in series so the 4 switches with breakdown voltage of 600V have to be chosen. There is one transformer with three legs and two “input windings”, each with the turns ratio equal to 10. Independently if connected to 540V or 270V HVDC bus, the converter has its maximum power delivered at  $D_{HV}=0.5$ . At this point the inductance value  $L_{LV}$  and the RMS current in each winding of the LV side of the transformer are, respectively 32nH and 86A. Thus the maximum RMS current per switch of the HV side is 6A. The RMS current in the LV side commutation cells is 86A and they switch a maximum of 150A. If we consider that no harmonic current flows to the HVDC bus source, the maximum peak-to-peak current flowing in the HVDC bus capacitors is 30A at the switching frequency.

All the comparison made above is summarized in Table II. Note that the 2 solutions with a single converter (either a full bridge or an NPC) at the HV side are penalized by the fact that the turns ratio of the transformer is calculated for the 540V HVDC bus but it has to be used with 270V as well. Like this, the RMS current flowing in the transformer and in the switches at 270V are high due to the high reactive power flowing in the converter.

When compared to the double full bridge (case C), the proposed converter (DABRSP) has half the number of switches but carrying the double of the current. It has only one

transformer (although a little bit bigger than regular 2-leg transformers). The RMS current in the DC bus capacitors is twice higher, however, for the same voltage ripple in the bus, the total capacitance energy ( $0.5 \cdot C/V^2$ ) of both topologies is the same.

Table II. Summarized results from comparison between DAB topologies applied to system with two different voltages in the HV side (270V and 540V). \* The transformer used in the DABRSP is slightly larger than a regular 2-leg transformer.

Topology	Number of switches	Switch rated breakdown voltage	Maximum Switch RMS current	Number of transformers
Single FB	4	1200V	8.35A	1
Single NPC	4 + 2 diodes	600V	16.7A	1
Double FB	8	600V	3A	2
DABRSP	4	600V	6A	1*

## V. CONCLUSION

High voltage DC buses of 270V and 540V are intended to be used in future aircrafts given the growing electrical energy consumption. The power transfer between these buses and the 28V DC bus inside the aircraft is to be made by bidirectional isolated DC-DC converter.

This paper presents a new bidirectional isolated DC-DC converter suitable for the connection to these buses. The converter, which is named DABRSP, has a full bridge connected at the low voltage side (28V) and 2 half bridges at the high voltage side. These half bridges are connected in parallel when used in a 270V DC bus and they are connected in series when used in a 540V DC bus.

In order to obtain zero current switching in the converter to reduce switching losses, 3-level voltages are necessary to be applied to the inductor in the low voltage side. The 3 levels are obtained by “magnetically adding” the output voltages of both half bridges. This is done by a specific 3-leg transformer explained in this paper.

Comparison was performed between the new converter and three different converters commonly considered in these types of applications.

The proposed converter makes use of switches with lower breakdown voltage and lower current capabilities than the switches of a single full bridge converter. When compared to a single NPC converter, the proposed converter needs to carry a maximum current 2.8 times smaller for the same breakdown voltage.

When compared to two full bridges connected in series or in parallel (depending on the HVDC voltage), the proposed topology uses half the number of switches and transformer, although they carry the double of the current.

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