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Digital Object Identifier (DOI): 10.1109/ISIE.2017.8001535

26th International Symposium on Industrial Electronics

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Suggested Citation

G. Buticchi, L. Costa and M. Liserre, "Resilient multi-bus distribution in more electric aircraft by means of dual active bridges," 2017 IEEE 26th International Symposium on Industrial Electronics (ISIE), Edinburgh, 2017, pp. 1874-1878. doi: 10.1109/ISIE.2017.8001535

Resilient multi-bus distribution in More Electric Aircraft by means of Dual Active Bridges

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Abstract—The actuation system of an aircraft relies heavily on hydraulic actuation. In order to improve the reliability of the system while improving the power density, researchers have investigated the possibility to increase the penetration of electric system. In this scenario, the electrical power distribution system (EPDS) becomes very important. This paper proposes an architecture of the EPDS based on dual active bridge converters, virtual resistors are used to share the power and to handle faults. Simulation results show the good behavior of the EPDS, that can withstand faults in the buses and still supply the critical loads.

I. INTRODUCTION

One of the concepts of the More Electric Aircraft (MEA) is the gradual substitution of hydraulic system with more versatile and efficient electric ones [1]. To this aim, the power requirements of future aircraft will increase, with a consequent increase in power electronics demand. In this framework, the transmission of this great amount of power becomes critical. High dc voltage (HVDC) electrical power transmission network with low current and low conduction losses enables significant energy savings. Additionally, the novel distributed power system configurations like smart grids increase the efficiency as lines are shorter and enhanced electrical management techniques are adopted. High power-density DC/DC converters are essential in order to provide power to the variety of applications in aircrafts. In this way, significant weight and volume savings may be realized, as the power rating of the converters and main conductors may be reduced. This would result in decreased fuel consumption, noise and gaseous/environmental pollutants emission as well as more simple and cheap structural repairs since lower rated equipment may be provided at a reduced price.

High efficiency and high reliability [2] are still the main design goals for aerospace applications. In this framework, solutions based on the variable frequency AC transmission or on monolithic DC/DC converters have been proposed, however they present limitations regarding the distribution and the overall efficiency. For these reasons, the newer standard, like MIL-STD-704F [3], has agreed on a multi-bus transmission system (Figure 1), where a high voltage bus at 270V is used to transmit the power, and a low-voltage 28V distribution feeds the loads. Galvanic isolation for security purpose is mandatory in each interface stage between different buses.

This paper describes the possibility to realize the aircraft EPDS with a DC distribution system with multiple single-input-single-output DC/DC converters. The resiliency of the

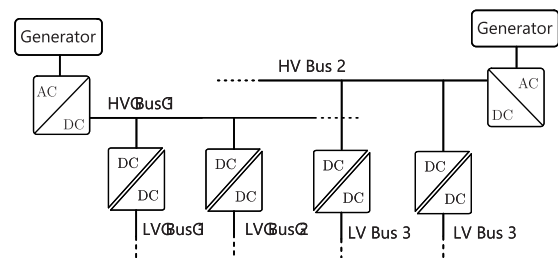


Fig. 1: Multi-bus architecture of More Electric Aircraft grid.

solution, so the capability of the system to continue operation even in case of faults, will be discussed.

II. PROPOSED ARCHITECTURE AND CONTROL

The envisaged architecture for the EPDS comprises at least two HV buses fed by the generators connected to the engines, and two LV buses. In particular, one of these buses feeds the critical equipment and its safety should be prioritized. Loads can be connected both at the HV and at the LV side. In the case of high demand and low power availability, it is possible that the low priority loads are disconnected to preserve the essential systems. Bi-directional capability is highly desired, in order to recover the energy from the electric actuators, re-configure the grid and eventually perform the start of the engines.

For security purposes, the buses should be electrically insulated from each other. Considering this requirement, high-frequency link DC/DC converters are the most adopted solution. Several topologies can be found in literature, they will be shortly reviewed. Employing a full-bridge converter connected to a transformer and a diode bridge rectifier on the secondary side was among the first attempts to realize a high-frequency link DC/DC converter, a bi-directional version is also possible [4]. At the beginning the pulse-width modulation was used, then the phase-shift modulation was proposed to achieve zero-voltage switching [5].

In order to fully expand the soft-switching capabilities of the full-bridge converter, full resonant solutions like the series-resonant-converter (SRC) were proposed [6]. A capacitor connected in series to the transformer forms a resonant tank that allows the converter to operate in zero current switching. Although exhibiting good voltage transfer characteristic even in open loop, the fine regulation of the output voltage and current is difficult.

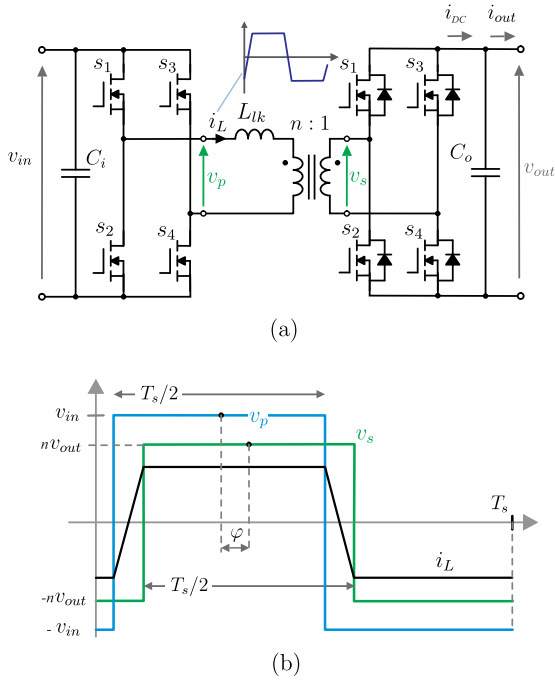
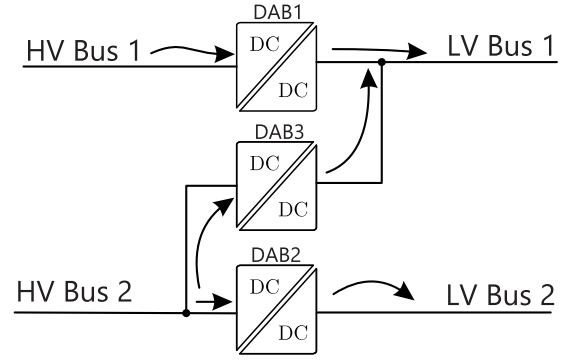


Fig. 2: Dual Active Bridge Converter: (a) schematic and (b) idealized waveforms.

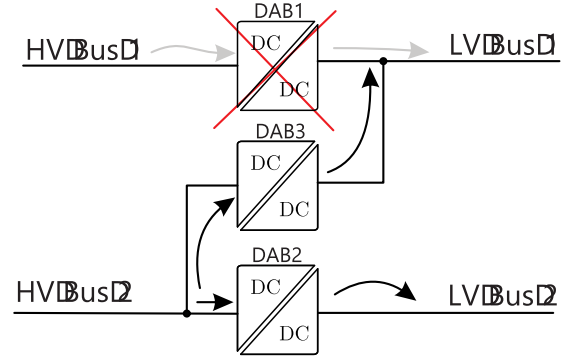
The dual active bridge (DAB) converter, shown in Fig. 2, presents a full-bridge even in the secondary side. By applying a 50% square wave to both primary and secondary bridges, the phase displacement between these two waveforms can be used to control the power transfer. This solution offer ZVS at turn on, and only the turn-off losses needs to be considered. Although this constitutes a disadvantage, if compared to full-resonant solutions, the DAB allows a very good voltage/current control, shows bi-directional characteristic and will therefore be chosen for this application. The characteristic equation of the DAB is shown in eqn. (1), where the power P processed by the DAB is expressed through the input/output voltage, the leakage inductance of the transformer L_{lk} and the phase-shift φ , between primary and secondary waveforms (see Figure 2a) expressed in radians. $f_{sw} = 1/T_s$ is the switching frequency of the converter.

$$P = \frac{nv_{in}v_{out}}{2\pi L_{lk}f_{sw}} \varphi \left(1 - \frac{\varphi}{\pi}\right) \quad (1)$$

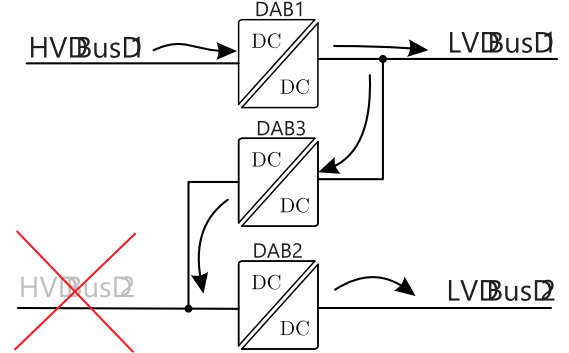
Fig. 3 shows the architecture of the proposed system, comprising of three DAB converters interfacing the four buses. LV Bus 1 is the critical one, and should always be powered. This architecture allows feeding the two LV buses from the two generators, and an additional DAB cross-connected between HV bus 2 and LV bus 1 ensures the redundancy. This is highlighted in Fig. 3b, where despite a fault of DAB1, DAB3 powers the critical bus. The flexibility offered by this architecture can be exploited to keep the system energized even in the case of a fault on the generator feeding HB bus 2. DAB3 can re-route the power from LV bus 1 to LV bus



(a) Normal operation with 3 DAB Converters interfacing the four buses.



(b) Fault in the HV Bus 1, HV bus 2 supplies LV bus 1.



(c) Fault in HV bus 2, the power is re-routed from HV bus 1 or LV bus 1 to LV bus 2.

Fig. 3: Configuration of the proposed EPDS.

2. This is exemplified in Fig. 3c. Of course, power may be limited by the sizing of the power converters.

The phase-shift control is adopted to drive the transistors of the H-bridge, and this paper proposes to use a voltage control with virtual resistors [7]. Different control targets are chosen for the different DABs, in particular DAB1 and DAB2 have a output voltage reference, while DAB3 performs the balancing between input and output (keeping the 270/28 ratio). These two controls are shown in Fig. 4. Virtual resistors allow a de-centralized and automatic power sharing, in fact, changing the virtual resistor changes the power processed by the parallel units. This allows also for a semi-decentralized management of the EPDS, where virtual resistors are changed

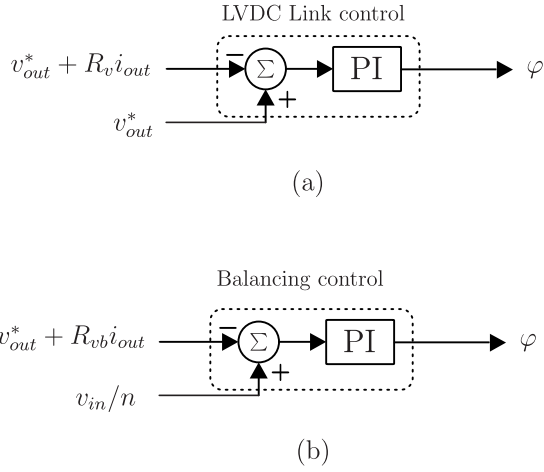


Fig. 4: Control of the DAB. (a) control of DAB1 and DAB2, (b) control of DAB3.

by a supervisor.

This feature is particularly attractive, because the on-line change of the virtual resistor allows prioritizing some loads during different flight phases, paving the way for a re-configurable EPDS, that can still operate in a de-centralized way.

III. STABILITY ANALYSIS

In this manuscript, the topology of the DC grid is made more complex by the insertion of an additional DC/DC regulator with a balancing controller, in this section the impact on the stability of the system is analyzed.

Equations (2)-(4) describe the generalized capacitor voltage balance at the LV bus and at HV 2 bus and equations (5)-(7) describe the regulators in Fig. 4. During normal operation, the voltage at the HV buses is assumed to be controlled (and modeled by an ideal voltage source) and the tuning of the DAB controllers can be performed in a standard way, i.e., symmetrical optimum criterion. From the stability point of view, DAB3 and DAB1 supply LV bus 1 and are independent from DAB2. In the case of a fault in HV bus 2, DAB3 will balance the voltage, allowing DAB2 to supply LV bus 2. This situation is the most challenging from the stability point of view, because all three controllers interact with each other and it is assumed that the control is not changed after the fault occurrence. Since this condition is the most challenging for the system stability, it will be analyzed in the following.

$$V_{LV1} = \frac{1}{C_o^{DAB1} + C_o^{DAB3}} \int (i_{DC}^{DAB1} + i_{DC}^{DAB3}) dt \quad (2)$$

$$V_{LV2} = \frac{1}{C_o^{DAB2}} \int (i_{DC}^{DAB2}) dt \quad (3)$$

$$V_{HV2} = \frac{1}{n(C_i^{DAB2} + C_i^{DAB3})} \int -(i_{DC}^{DAB2} + i_{DC}^{DAB3}) dt \quad (4)$$

$$i_{DC}^{DAB1} = K_P^{LV} (V_{LV}^* - V_{LV1} + R_v i_{out}^{DAB1}) +$$

$$- K_I^{LV} \int (V_{LV}^* - V_{LV1} + R_v i_{out}^{DAB1}) dt \quad (5)$$

$$i_{DC}^{DAB2} = K_P^{LV} (V_{LV}^* - V_{LV2} + R_v i_{out}^{DAB2}) +$$

$$- K_I^{LV} \int (V_{LV}^* - V_{LV2} + R_v i_{out}^{DAB2}) dt \quad (6)$$

$$i_{DC}^{DAB3} = K_P^{bal} (V_{HV2}/n - V_{LV1} + R_{vb} i_{out}^{DAB3}) +$$

$$- K_I^{bal} \int (V_{HV2}/n - V_{LV1} + R_{vb} i_{out}^{DAB3}) dt \quad (7)$$

In a similar way of [7], the state-space model can be derived and the roots of the characteristic polynom represents the poles of the closed-loop transfer function. The corresponding pole-zero map is shown in Fig. 5, showing that the balancing controller introduces two underdamped poles. It will be seen in the Results section that in the case of a fault in the HV bus, oscillations appear.

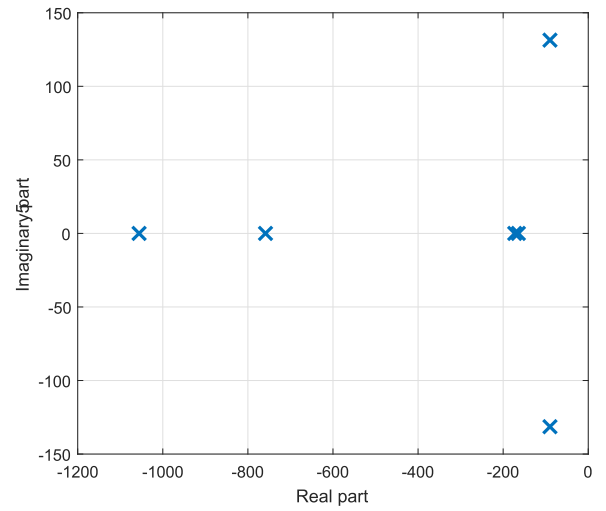


Fig. 5: Root locus of the system when bus HV2 is not powered.

IV. RESULTS

The proposed system architecture and control has been implemented with the Simulink/PLECS software. The parameters are listed in TABLE I.

f_{sw}	30 kHz s	T_s	1e-4 s
L_{lk}	0.010 mH	R_{load}	0.3 Ω
$R_{v1} = R_{v2} =$	0.001 Ω	R_{v3}	0.001 Ω
C_{in}	1 mF	C_{out}	100 mF

TABLE I: Simulation parameters.

Fig. 6 shows the primary and secondary waveforms of the DAB operating at 2.6 kW. As can be noted, the ZVS condition at turn-on are respected for both bridges.

The first scenario to be analyzed is the fault on HV bus 1 at $t = 0.2$ s, that forces the disconnection of DAB1. This is shown in Fig. 7. As can be seen, the LV Bus 1 current is equally shared between DAB1 and DAB3, because of the virtual resistor chosen. Of course, different virtual resistors

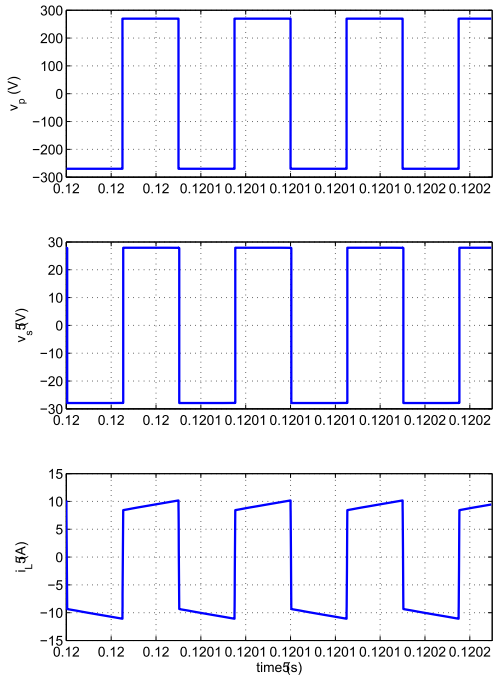


Fig. 6: Basic waveforms of the DAB converter when operating at 2.6 kW.

would change the power sharing. After the fault, all the current is provided by DAB3, and the current of DAB1 goes to zero.

Another scenario that may be of interest is a fault in HV bus 2, that can be caused by the generator or by a power curtailment, see Fig. 8. If the power provided by HV bus 1 is enough, it may be of interest to provide a good service even to LV bus 2. In this case, after the fault, the control of DAB3 tries to keep at the nominal voltage the HV bus 2, and DAB2 can work normally. In this case, there is an increase of the power processed by DAB1, a condition that could not be practical in all cases. As expected from the stability analysis, a small oscillation appears due to the underdamped poles.

After the fault there is a transient of the system, leading to an undervoltage. This condition does not persist for too long, and could be mitigated by choosing a bigger capacitance (C_{out} in the current configuration is only 100 mF) or by a different tuning of the regulators (tuned for a bandwidth of 150 Hz with the symmetrical optimum criterion).

The capability of the proposed system to handle different conditions and change on-line the power sharing is shown in Fig. 9, where the virtual resistance of DAB3 is varied from 0.01Ω to 0.001Ω at $t = 0.2$ s. In this case DAB1 and DAB3 achieve a steady-state solution where both converters are providing the same power to LV bus 1.

A prototype has been realized and its picture is shown in Fig. 10. The goal is to show that a potentially high efficiency can be achieved just by adding SiC MOSFETs at

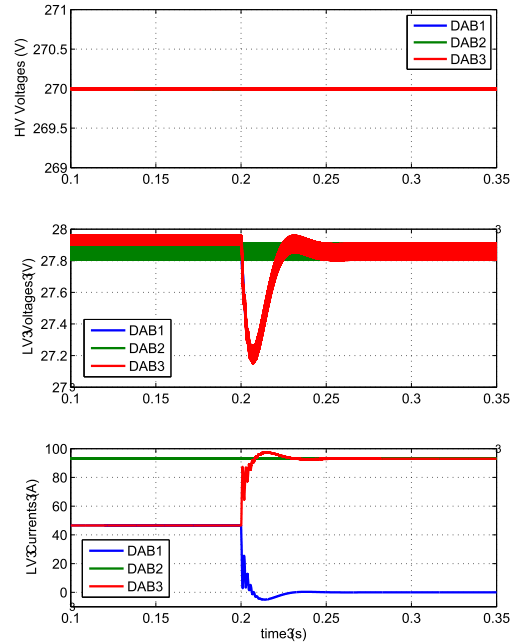


Fig. 7: Behavior of the system during a fault of HV bus 1.

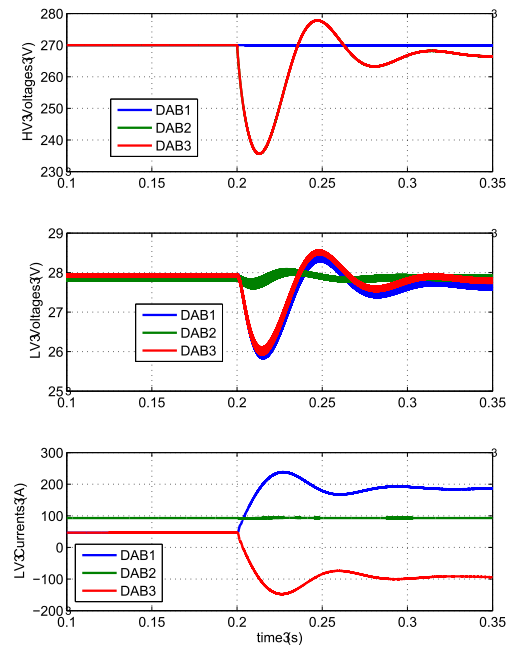


Fig. 8: Behavior of the system during a fault of HV bus 2.

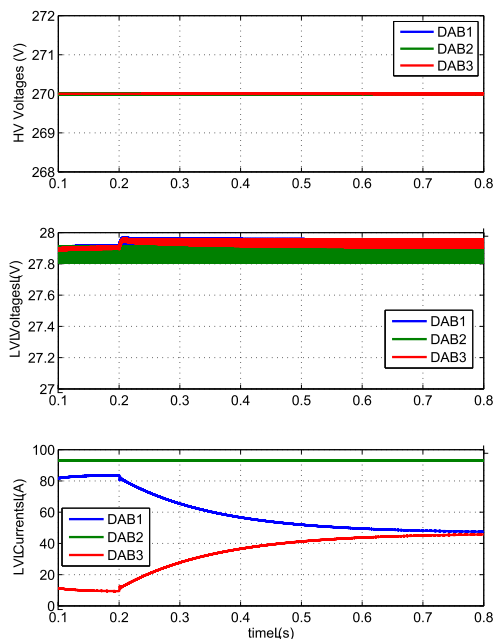


Fig. 9: Variation of the virtual resistance of DAB3 to change the power sharing.

the primary side. This approach has already been tried by other researchers with good results [8]. The devices chosen for the primary side are the Wolfspeed C2M0025120D for availability reasons. The breakdown voltage of these devices is 1200V, that is over-designed. 600V MOSFETs would be preferable and could present lower on-state resistance, and will be chosen for the final prototype. At the low-voltage side, MOSFETs IRFP4368PbF and Schottky diodes STPS80L60CY are employed. The switching frequency is 30 kHz.

Experimental results are shown in Fig. 11 at 1 kW output power. Maximum efficiency of 95.8 % is reached at 520W of output power, then it decreases to 94.4 % at 900 W .

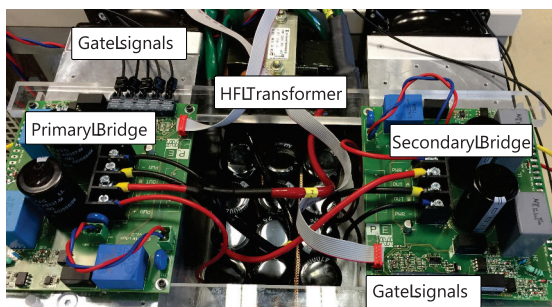


Fig. 10: Picture of the DAB Prototype.

V. CONCLUSION

A system based on DAB converters was proposed to realize a resilient Aircraft Electrical Power Distribution System. An

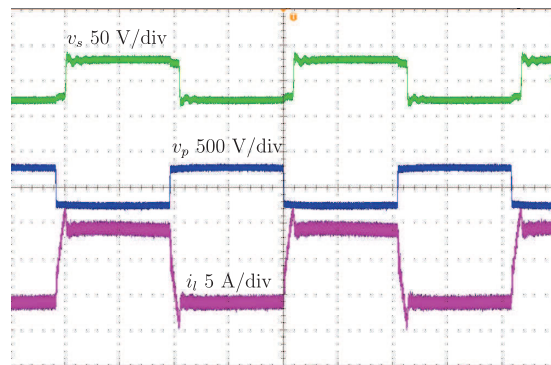


Fig. 11: First experimental results.

architecture based on 2 DABs interfacing four buses enables a redundant EPDS. A control based on virtual resistors allows to control the power sharing of the different units in a decentralized way. The on-line change of the virtual resistor can be used to address different load priorities during the different flight phases.

VI. ACKNOWLEDGEMENT

This work was supported by the European Union/Interreg V-A - Germany-Denmark, under PE:Region Project.

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