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Design and development of 270 VDC Power Distribution Unit for Feeding essential loads

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Abstract

Clean Sky 2 is an European Union project that tries to transform the air transport industry driving it to a cleaner one. In order to reach this target it is promoted the weight reduction and high efficiency of on board systems. Airbus DS is responsible of the Clean Sky 2's ITD Airframe demonstrator in which it is included new EMAs in main flight control surfaces for increasing aircraft performances safety and reliability. Those flight controls are fed by a HVDC network in order to comply with the CS2 objectives. A Power Distribution Unit (PDU) development is key for this system.

1. Introduction

Clean Sky 2 (CS2 hereafter) is an Technology Program funded by the European Union with the aim of transforming the air transport industry driving it to a cleaner one by reducing the emissions of CO2 and NOx. The emissions are mainly dependant on the efficiency and the volume of operations. Since the volume of flight operations is forecasted to be increasing steadily, the way towards a greener environment is to increase the efficiency of this way of transport.

Regarding on board energy generation and transportation this means increasing the power generated and distributing using the lowest weight possible. This can be achieved by: 1)increased the working voltage level (up to 270VDC) that will enable the reduction in wiring weight, 2) driving more power with less weight, 3) more efficient power distribution and 4) more integrated systems (equipment avoiding transformation stages). On the other hand, other systems are in the same target and they are willing to increase the efficiency of their operation and so reducing the emissions in global terms. As soon as they will need power for performing their missions, an efficient way of producing and distributing power is becoming critical. All in all going towards a More Electrical Aircraft or All Electrical Aircraft will enable the emissions reduction in the air transportation.

Airbus DS is responsible for one of the Clean Sky 2's ITD Airframe demonstrator, called FTB2 being a derivative version from C-295 baseline version (Figure 1). The original electrical network of the FTB2 demonstrator is comprised of a DC main generation, AC variable frequency generation, AC and DC electrical distribution system and an emergency network. In coherence with the CS2 targets an All Electrical Wing is foreseen including the installation of Electro Mechanical Actuators as essential loads in the main aircraft's control surfaces (ailerons and spoilers) in order to improve the roll performance and airbrake capabilities as well as reducing aerodynamic loads and increasing flight control system safety and reliability. These EMAs will be fed by a High Voltage Direct Current (HVDC) system (Figure 2). This HVDC system includes a Power Distribution Unit (PDU) which manage 270 VDC electrical power obtained from two HVTRU units that transform the electrical power up to the mentioned level from 115VAC electrical network that already exist in the C295.

In line with CS2 objectives the design for these units includes using lighter and more efficient materials as Si-C semiconductors, taking new energy management strategies (as energy recovery or other philosophies for electrical protections) and improving the proved techniques in other voltage levels, as new design for getting SSPCs capable of dealing with 270 VDC voltage level instead of using electromechanical contactors for such voltage levels. All these actions contribute to the target of the equipment that is more than 1.15 kW/kg. Safety precautions are requested to this equipment as soon as it will be a flyable equipment so that the equipment reaches TRL 6 at the end of the project.

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Figure 1. Clean Sky 2. ITD airframe demonstrator based on C295

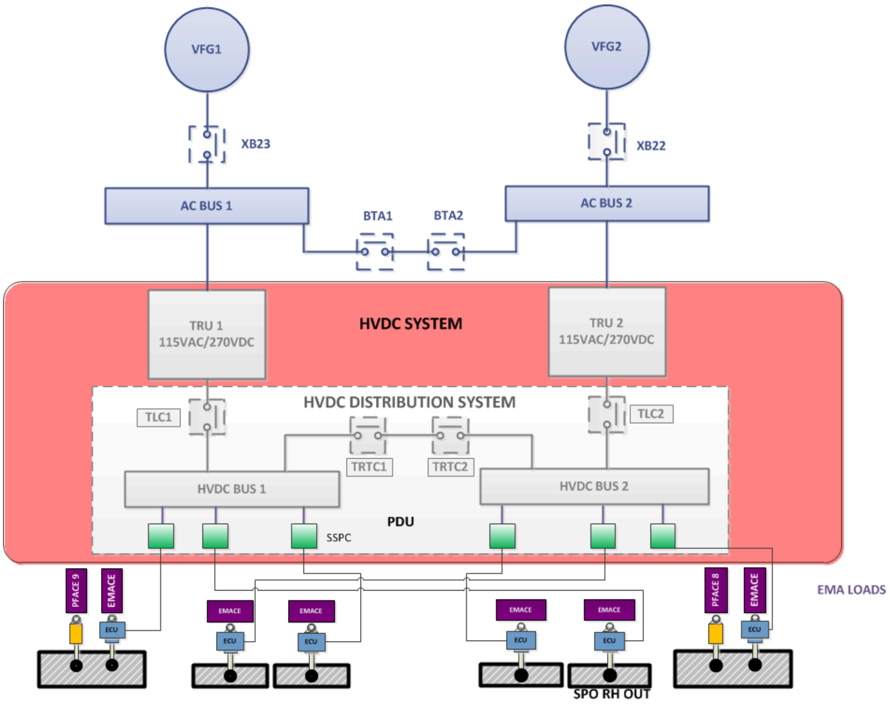

Figure 2. High Voltage System in FTB2 demonstrator (C295 platform)

2. Advantages of increasing the working voltage level

First of all, the increasing of aircraft capabilities in terms of more missions and more efficient way of aircraft utilization have led to the increasing of the electrical power demands by the on board systems. In this context wiring has become an important parameter from the aircraft weight analysis point of view. The trend in the aeronautical industry is to go to a More Electrical Aircraft and All Electric Aircraft in order to get driving more power with less weight substituting pneumatics and hydraulics systems by a more efficient systems based on electrical power. In this sense the tendency is to increase the working voltage level of the aircrafts' electrical system so that it could be possible to drive such high levels of power and to enable the reduction in wiring weight. Additionally it will lead to more efficient power distribution and more integrated systems (equipment could avoid transformation stages) which contribute to the target of using the most power possible with less weight possible.

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The main criteria for the selection of the wiring gauge are: voltage drop and temperature in the live wiring. This establish limitations in the power driven on board, so reducing the losses goes in favour of reducing the voltage drop and the temperature that it is reached in the live wiring during its operation. This means that it is could drive the same level of electrical power with less wiring diameter (higher gauge) so less weight. In order to analyse the losses reduction it is found two sources of this reduction: type of electrical power (AC or DC) and the voltage level.

2.1. Comparison between 115 VAC network and 270 VDC network.

On one hand, the nature of the electrical power used impacts in the electrical losses that it is found in the electrical network. There are two kind of electrical network available in the aircraft: Alternate Current (AC) and Direct Current (DC). On the other hand, the current is the most impacting parameter considering the power losses in wiring, so with the same power driven, increasing the voltage level leads to reducing the current and so the losses. In this section it is compared the mass saving between the two solutions for feeding the EMAs: 115VAC network vs 270 VDC network.

In order to perform this theoretical study between those two electrical networks, it is assumed:

1. Identical power driven

$$P_{AC} = P_{DC} \qquad (1)$$

2. Identical insulation level

$$U_d/_{d1} = U_m/_{d2} \qquad (2)$$

3. Identical electrical density in the live wiring

$$J_{AC} = \frac{I_{AC}}{A_{AC}} = J_{DC} = \frac{I_{DC}}{A_{DC}} \qquad (3)$$

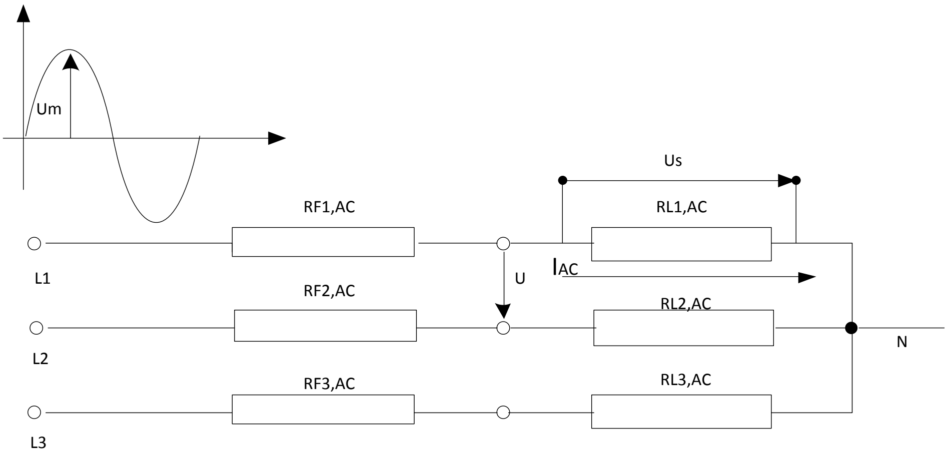

Figure 3. Parameters involved in AC network.

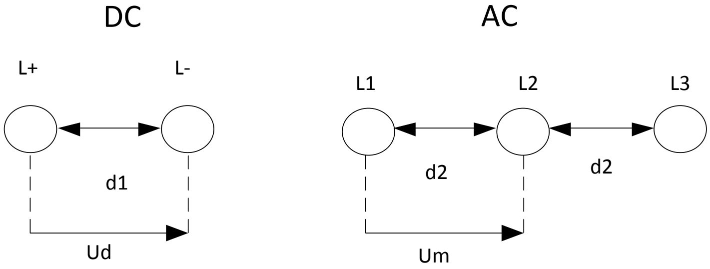

Figure 4. Insulation in AC and DC network.

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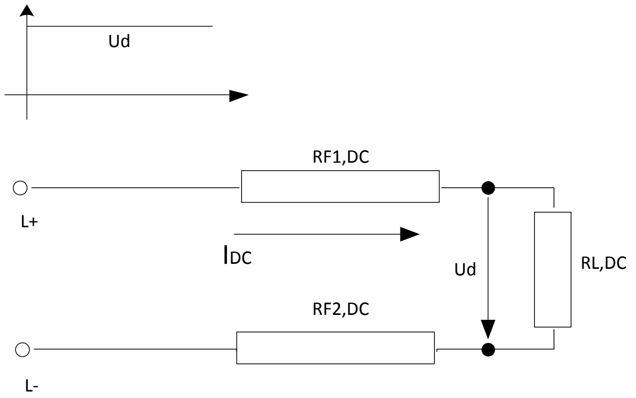

Figure 5. Parameters involved in DC network.

We are also assuming:

$$R_{F,AC} = R_{F1,AC} = R_{F2,AC} = R_{F3,AC} \tag{ 4}$$

$$R_{F,DC} = R_{F1,DC} = R_{F2,DC} \tag{ 5}$$

$$R_{F,AC} = \frac{1}{K \times A_{AC}} \tag{ 6}$$

$$R_{F,DC} = \frac{1}{K \times A_{DC}} \tag{ 7}$$

$$R_{F,AC} \ll R_{L,AC} \tag{ 8}$$

Regarding the first hypothesis (1) and taking into account the parameters shown in Figure 3 and Figure 5Figure 4 it is found:

$$3 \times I_{AC} \times U_S = I_{DC} \times U_d \rightarrow I_{DC} = \frac{3 \times U_S}{U_d} \times I_{AC} \tag{ 9}$$

Which, combined with hypothesis 3 (equation (3)) and considering $U_d = 270$ *VDC* and $U_S = 115$ *VAC*

$$I_{AC} = 0.78 \times I_{DC} \tag{ 10}$$

$$A_{AC} = 0.78 \times A_{DC} \tag{ 11}$$

Assuming the same material in both situations and the same length,

$$\rho_{AC} = \frac{m_{AC}}{A_{AC} \times l_{AC}} = \rho_{DC} = \frac{m_{DC}}{A_{DC} \times l_{DC}} \tag{ 12}$$

$$\frac{m_{AC}}{m_{DC}} = \frac{A_{AC}}{A_{DC}} = 0.78 \tag{ 13}$$

This figures (10), (11) and (13) are applicable to one wire in the network. Identifying AC as 115 VAC and DC as 2710 VDC and considering that in AC network of the aircraft it is found 3 wires (phase A, B, C being N the Aircraft metallic structure) and in 270VDC network has designed with only one wire (the return is directly the aircraft metallic structure):

$$m_{t,115AC} = 3 \times m_{115AC} \tag{ 14}$$

$$m_{t270DC} = m_{270DC} \tag{ 15}$$

$$m_{t,115AC} = 2.34 \times m_{t,270,DC} \tag{ 16)}$$

Then the delta in mass,

$$\Delta \mathrm{m}_t = \frac{(m_{t,115} - m_{t,270})}{m_{t,115}} \times 100 \cong 57\% \tag{ 17}$$

The Hypothesis (2) (see also Figure 4) is directly impacting the installation issues and requirements and it is affecting the routing of the wire in the aircraft so its contribution is difficult to be estimated. All in all and as soon as this study is theoretical using several hypothesis and regarding that there are some uncertainties as the final installation on the aircraft, it is stablished as target for the project to obtain a total mass reduction in wiring of 55%:

$$\Delta \mathrm{m}_t \cong 55\% \tag{ 18}$$

If it is compared 270VDC network and 28VDC network the reduction is more important reaching the 90% in mass. This study is considering only the reduction in wiring and to evaluate the entire system it is needed to take into account the mass of the equipment needed to develop the HVDC system.

3. Power Distribution Unit for 270 VDC

As already said, the electrical network of the C-295 demonstrator, includes two kind of network: 28 VDC and 115 VAC network. The better option to obtain a 0-270VDC network is to transform from 115 VAC to 270 VDC so for this project it is developed a high voltage transformer-rectifier unit for getting 270 VDC electrical power and a Power distribution Unit (PDU) that gathers electrical power from HVTRUs and manages it to supply electrical power to essential loads: aileron and spoilers EMAs.

The main functions of the PDU are:

- Management and control function, that shall allow:
    - To distribute electrical power by connecting/disconnecting it to main bus bars
    - To reconfigure network through managing and configuring HVDC network by controlling commutation and commutation-protection devices.
    - To manage the different A/C system’s power supply
    - Energy recovery system will be implemented for laboratory specimen and it will be able to recirculate to an storage equipment the energy generated in the loads when they go into regenerative mode
    - Energy management system will be implemented for laboratory and it will be able to connect/disconnect loads depending of the maximum power that can be demanded to the HVTRU
- The electrical load distribution and protection function:
    - To distribute electrical power to connected loads
    - To protect wires or bus bars against short-circuit and overload
    - To protect wires against arc fault (AFD), if necessary
    - To provide switching on/off capabilities for each supplied loads
    - Overcurrent and I2t protections
    - Protection against short-circuit for all the loads
    - Soft start for capacitive loads (under 220 µF). Loads with 220 µF or higher are detected as short-circuit
    - Protection for inductive loads opening
    - EMI-EMC protections
- The monitoring-indicating function:
    - To monitor the electrical distribution network in order to provide the information necessary to perform the appropriate functions.

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  - Status monitoring,
  - Maintenance information
  - Warnings and displays on cockpit

PDU designer and manufacturer is TEMAI ingenieros that is partner with Airbus DS in CS2-ITD airframe project with the sub-project HEPODIS. Airbus DS is topic manager in this demonstrator in front of Joint Undertaking from European Union.

HEPODIS PDU is being developed for managing 2x 270VDC power inputs with 15 kW per input and delivering electrical power to 6x 270VDC loads with 2,5 kW per load. This Power Distribution Unit is a hybrid design due to mix two technologies for the switching devices, electromechanical contactors and SSPCs (Solid State Power Controller) devices. Currently PDU development is in CDR status. For the PDU design it is considered the V&V process taking into account the specific requirements of the aircraft demonstrator (C-295): safety, environmental, electrical, vibrations, EMI/EMC, etc. The voltage level of the electrical power that drives the equipment shall be 270 VDC nominally but accepting excursions according to MIL-STD-704F. Additionally it is required for the equipment development a design according to EUROCAE ED-14/RTCA D0-160G regarding environmental qualification, EUROCAE ED-12C/RTCA D0-178C regarding Software development and EUROCAE ED-80/RTCA DO-254A regarding Hardware assurance. As mentioned before the electrical requirements are set according to MIL-STD-704F and MIL-HBK-704 but there are other electrical requirements not included in these standards that need to be included to assure a proper performance and a safe operation as dielectric strength, insulation resistance, bonding and grounding that needs to be considered. The design assurance level of the equipment is DAL B. On the other hand so that it is compliant also with weight reduction requirements, it is imposed to PDU the requirement to reach a weight such that complies with 1.15 kW/kg target. All these requirements are imposed in order to be able to reach TRL 6 at the end of the project (flight test).

Internally the PDU have the main busses of the HVDC network and the sensor busses for the correct operation of the equipment. It permits the reconfiguration of the network in case of failure by means the TRTCs contactors. In case of loss of one side of the aircraft it is possible to fed the EMAs from the other side of the AC HVDC network.

The main components of the PDU are:

- TRLCs contactors. Line contactors that connect with HVTRU 1 and 2 respectively. Also isolate the system from AC network. Electromechanical contactors.
- TRTCs contactors. They permit reconfigurations and BUS TIE in case of failure Electromechanical contactors.
- 270 HVDC Bus 1 and 2. Electrical distribution BUS Bars for electrical power distribution. Both sides of the aircraft are segregated and isolated in normal operation.
- Solid State Power Controllers. Connect the distribution bus bar with the loads and perform protection functionalities of the equipment.
- Power stage. Feeding the control and monitoring functions of the equipment.
- PDU Control logic: 2 CPLDs and one microcontroller
- Sensor Bus. Measure for internal controls are done in this bar.

4. Solid State Power Controller for 270 VDC

As explained before, to rise the operational voltage allows to reduce weight and volume in the wiring part. Other step in this direction of weight and volume reduction can be performed by replacing the classic electromechanical contactor (heavy and bulky) used traditionally in the commutation of electrical loads by Solid State Power Controller (SSPC) devices.

This is a very challenging issue due to the development of the semiconductor technology is not so fast as will be desirable for this application. Traditional Silicon MOSFET presents very good R_{DSON}, almost comparable to an electromechanical contactor, but a low V_{DS} blocking capability, this characteristic delimits the use of SSPCs based on Si MOSFETs to low voltage applications. In the other hand, IGBTs devices presents a very good V_{DS} blocking capability but a poor R_{DSON}, which generates a very high conduction losses.

The introduction of the Silicon Carbide technology for MOSFET application connects the two worlds (low R_{DSON} and high V_{DS}), and allows to develop SSPCs based on SiC MOSFETs with a very good relationship R_{DSON} - V_{DS}. Also with SiC MOSFETs is easier to control its ohmic zone by means of the V_{GS} which provides better control over capacitive loads, inductive loads and short-circuits as will be explained below.

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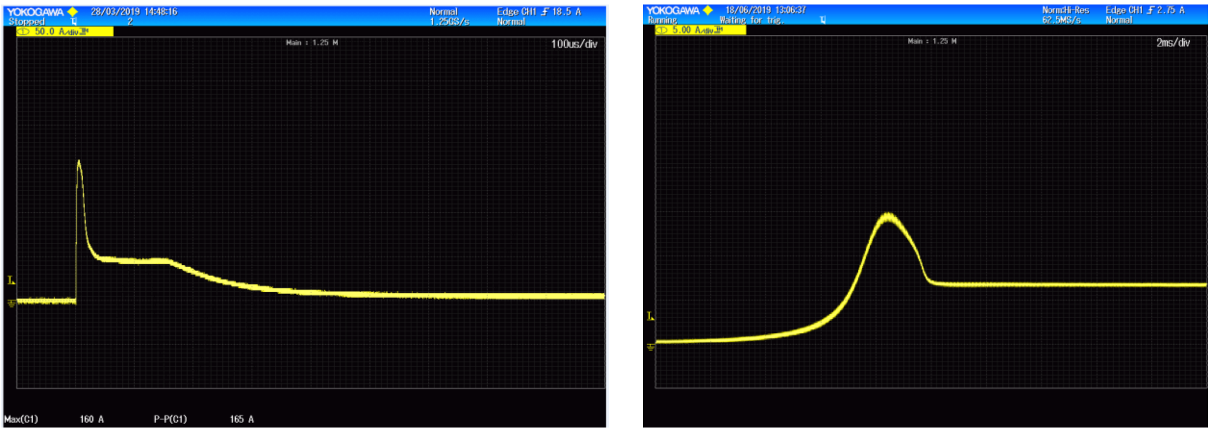
SSPCs based on SiC MOSFETs present the following advantages respect classic contactors:

- Soft start of capacitive load (100 µF @ 270VDC). If a classic contactor close against a capacitive load the initial current demanded by the capacitor is very high, see Figure 6-A. This peak of current, over 150A, could be dangerous for the elements in the path of the current so it would be desirable to reduce this peak. Using a SSPC with the soft start function implemented this peak can be reduced, see Figure 6-B, where the current is around 15 A (instead of the 150 A observed before)



A) Electromechanic Contactor (Current over 150 A) B) SSPC with soft start (Current under 15 A)

Figure 6. I_{DS} current for Switching on 100 µF capacitive load

- Protection against High capacitive loads. If a high capacitive load is connected (over 220 µF) the current peak generated could be dangerous for the MOSFET due to its SOA (Safety Operation Area) could be surpassed, so the SSPC has been set up to cut when a high capacitive load is detected (see Figure 7). Around 20 A has been measured for this case

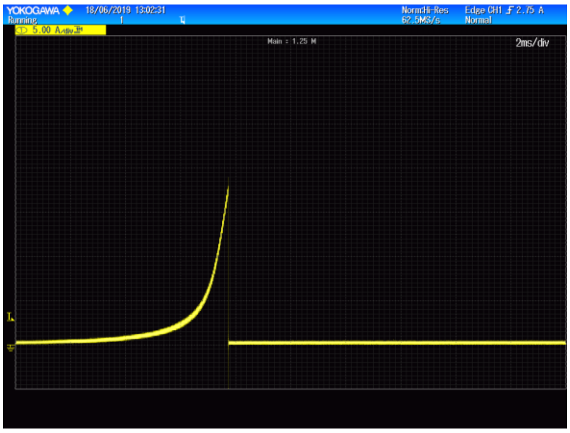


Figure 7 I_{DS} current for Switching on 220 µF capacitive load

- Protection against short-circuit at start-up. This case is very similar to High capacitive load one, in fact, a short-circuit can be considered as a capacitor of infinite capacitance (see Figure 8). Current measured in this case is similar to case before, around 20 A

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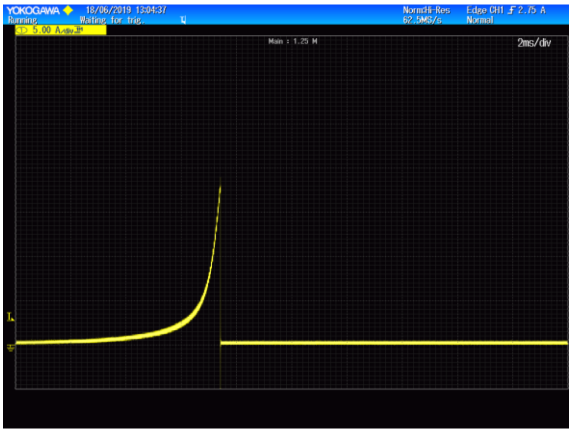

Figure 8 I_{DS} current for Switching on a short-circuit

- Protection against short-circuit when the SSPC is closed and delivering power to loads. In this case is critical the short-circuit time detection due to the SSPC is closed, in its minimum resistance zone, and when a short-circuit happens in this configuration, I_{DS} grows almost at 100 A/µs rate. Figure 9 shows how the SSPC is delivering 5 A when a short-circuits happens, then I_{DS} grows to around 175 A in 3 µs, when the SSPC detects the short-circuit and opens the fault

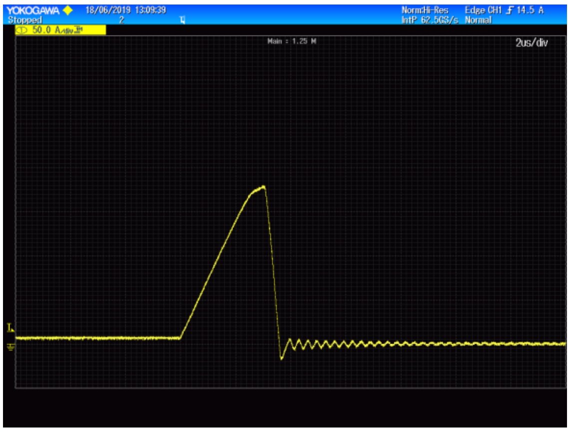

Figure 9 I_{DS} current for short-circuit when the SSPC is closed and delivering power

After any of this protection trips, SSPC can be rearmed and it works again due to the control implemented avoids permanent damage to MOSFET. But for airborne applications is not only valid to get this functionality working for a few times, it is necessary to perform an endurance test covering the life cycle of the equipment. Following cycles have been performed to the SSPC in order to probe its reliability:

- Resistive load (6,5 A): 10.000 open/close operations
- Capacitive Load 100µF: 10.000 open/close operations
- Capacitive Load 220µF: 3.919 open/close operations
- Short-circuit at start-up: 3.919 open/close operations
- Short-circuit when the SSPC is closed and delivering power: 3.000 open/close operations

These endurance test cover the whole life cycle of the SSPC when installed in the aircraft.

Next steps in the development process:

- SSPC integration in the PDU equipment
- Airbus DS Laboratory functional tests
- DO-160 Qualification tests

5. Energy Recovery

In certain operation modes, the EMAs operation results in generating electrical power instead of being only consumers. Reference [1] defines regeneration as *“electrical energy returned to the supply from loads”*. In the case of the EMAs operation the energy returned come from the aerodynamics forces acting in the actuators. The classic approach to this situation is to burn this energy generated in the EMA operation in the electronic control unit itself. In order to optimize the energy generated and used on board during the aircraft operation other options different from burning are considered currently. As it is found in ref. [1] other electrical architectures could be possible in order to reuse all this kind of energy recovered. For this project it is selected an architecture similar to the architecture named local energy storage in reference [1] but with a common energy storage device for each side of the aircraft. It is not allowed to regenerated energy going to the aircraft main busses. It could be completed with a separate buss for this regenerative power connecting the this storage devices to different loads, but this would be the next step in this topic.

Anyhow, in CS2 project as a result of the interface agreed with the EMAs, this function is not included in the flying prototype of the PDU. Nevertheless this function will be tested in the laboratory specimen. In this case it is faced the situation in two ways:

1. Classic approach in flight: Local Energy Dissipation which do not allow regeneration onto the aircraft bus and the energy recovered is dissipated in the proper control unit of the EMA. In spite of that it is foresee to include means of measuring the electrical power regenerated during the flight.
2. Energy recovery in laboratory testing. It is not permitted to drive back this electrical power to the distribution bus bars and it is driven through separate braches in the PDU to store it in storage devices as 270VDC batteries or ultra capacitors.

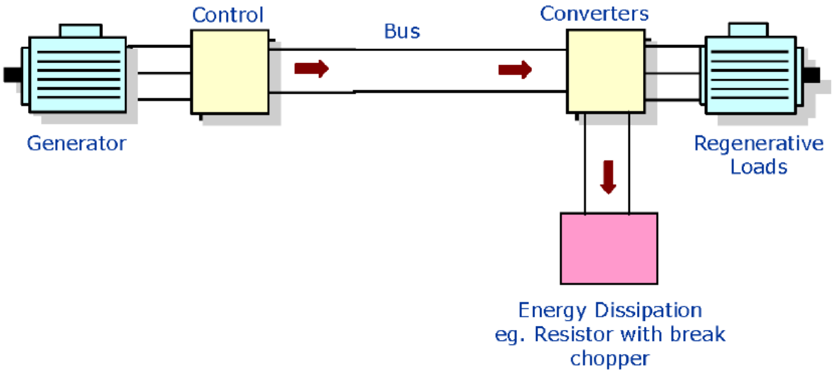

Figure 10. Local Energy Dissipation architecture (from reference [1¡Error! No se encuentra el origen de la referencia.**])**

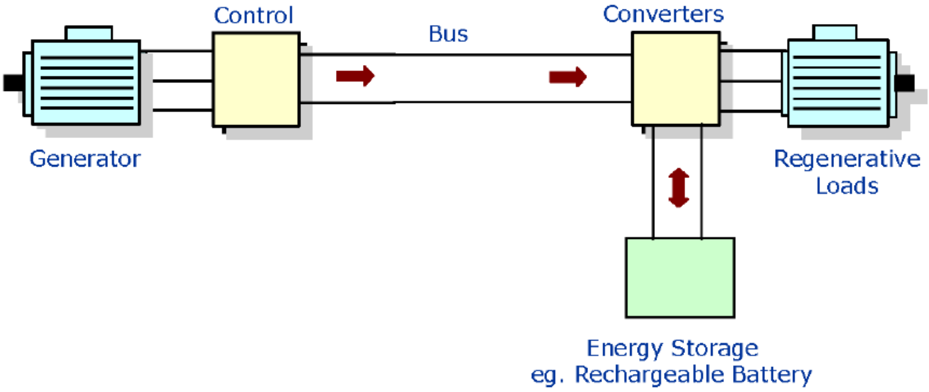

Figure 11. Local Energy Storage architecture (from reference [1])

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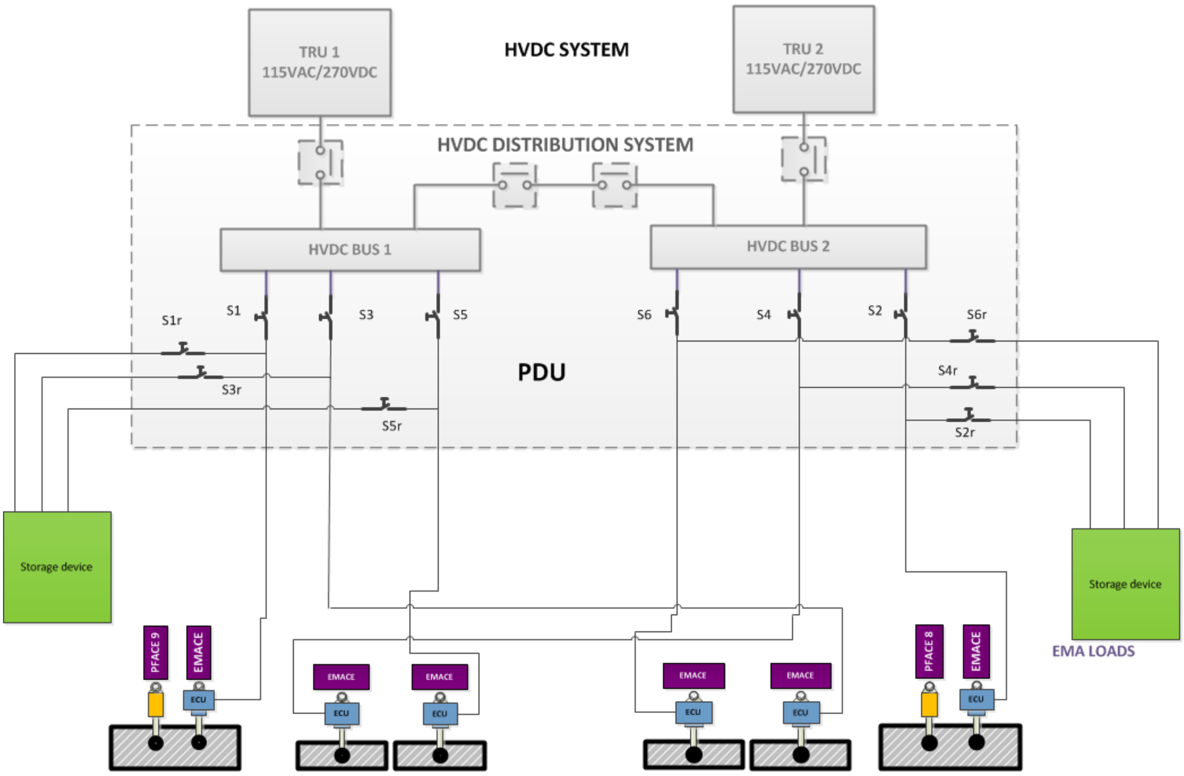

Figure 12. PDU architecture including the energy recovery branches.

In order to avoid to regenerative power go into the HVDC buss bars but going to the storage device it is needed to perform a reconfiguration of the switching devices in PDU (SSPCs) showed in Figure 12 as S_i that can be achieved by a close/open logic. The SSPCs are under the command of the control units (1x microcontroller, 2x CPLDs) installed in the PDU which are programmed with the reconfiguration logic and allow a more flexible control than the wiring logic implemented in the classic Power Distribution Units. Also, SSPCs provides more control capability than a simply on/off state as explained before

6. Challenge for HVDC system : The Arc Fault situation

Increasing the voltage operational level of the aircraft electrical system brings several consequences that could represent an important drawback for the HVDC systems development. One of the main problems of the increasing in the number of arc fault events during aircraft operation.

It is understood as arc fault a dielectric rupture induced because a high voltage drop between two live parts or between a live part and ground. In this phenomenon the air suffers an ionization that is the process by which electrons are lost or transferred from neutral molecules or atoms from positively or negatively particles. In this context it is found different manifestations of this phenomenon:

- **Partial discharge (corona)**: an electrical discharge that only partially bridges the insulation between conductors.
- **Corona**: visible partial discharges in gases adjacent to a conductor.
- **Continuous partial discharges (continuous corona)**: discharges that occur at rather regular intervals.

Aircraft wiring is exposed to a severe environment: high altitude, extreme temperatures, vibrations, dust and debris, etc (ref [3]). This may cause a degradation in the wiring insulation and so being easier to suffer an arc fault. This situation id worse with the increasing of working voltage. **Partial discharge (corona) inception voltage (PDIV [CIV])** is the lowest voltage at which continuous partial discharges occurs. This voltage is shown in the Paschen Law curve and is dependent on the ambient pressure and the distance between live parts. It is well known that at 1 atm pressure an arc fault occurs with a voltage drop of 327V between live parts distance of 7.5 µm. The higher the altitude of operation of the aircraft, the lower is the pressure of the surroundings and with the increasing of the voltage level the risk of having arc fault during aircraft operation is higher.

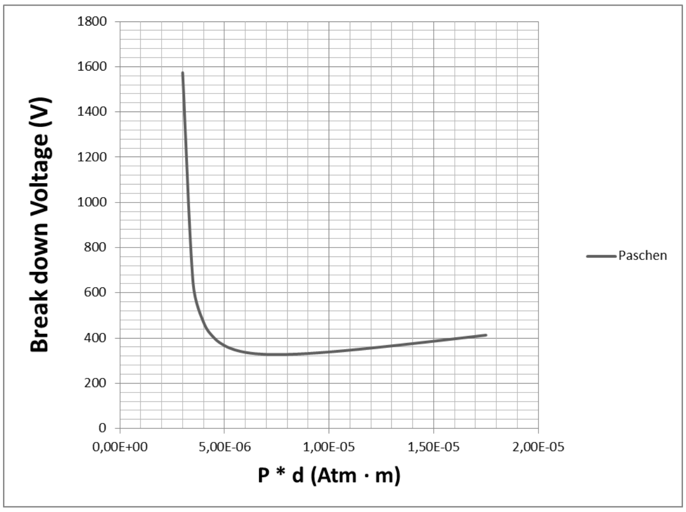

Figure 13. Paschen law curve

It is needed to protect the systems, aircraft and crew from this potential events when it is willing to increase the working voltage level. Passive measures for this protection are already taken in the industry that mainly are increasing the distance between live parts but those does not guarantee that this events don't occur. It is needed to go one step further and develop an arc fault detection system. Currently this kind of detection systems are in low TRL (3) and are not installed on the aircraft.

Typically it is found two kind of arc faults: serial arc fault and parallel arc fault. Parallel arc fault is normally low impedance arc that could lead to a short circuit. This is a hig energy phenomenon and measures for protecting against this low impedance arc are already installed on the aircraft and also in PDU with the traditional protection devices (implementing I2t curve or any other mean). High impedance arc faults are more difficult to detect and so to protect against. This type could be serial or parallel being more "invisible" the serial one. For that kind of arc fault events it is more important to implement an arc fault detection system. Many detections methods have been tested, some of them are:

- Impedance spectroscopy
- Wave reflectometry SWR
- Time Domain Reflectometry TDR
- High Voltage Inert Gas
- Resistance Measurements
- Sequence Time domain Reflectometry (STDR)
- Spread Spectrum Time Domain Reflectometry (SSTDR) (ref [2] and [9])

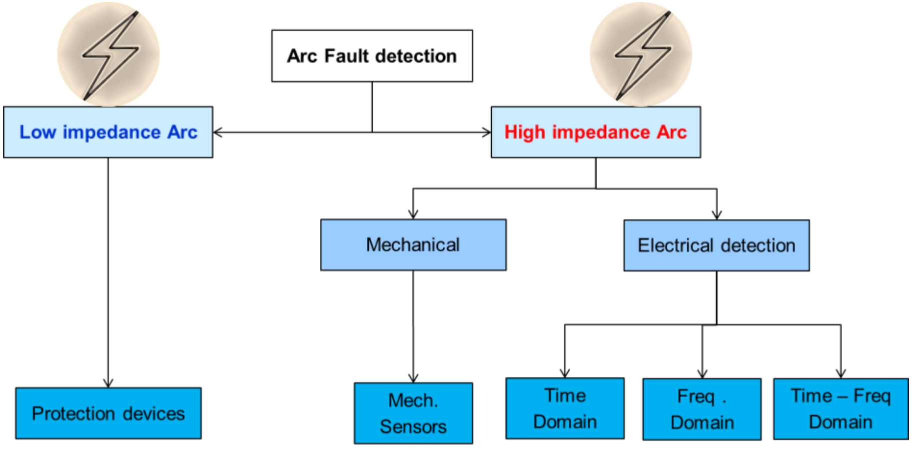

Figure 14. Arc fault detection methods.

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Combination of detection methods seems to be the better solution for facing the arc fault situation as it is needed to discriminate false arc faults events which would reduce the operability of the electrical system cutting the electrical power to the consumers when it is not necessary.

In CS2 – HEPODIS project it is reserve a provision hardware and software for developing this kind of systems in further steps. Currently the scope of the project covers TRL4 technologies to develop them up to TRL6. As currently this technology has a TRL3 is out of the scope but it is taken provisions for its inclusion in PDU. More precisely it is pointed to use Spread Spectrum Time Domain Reflectometry (SSTDR) (ref [2]) in combination with Arc Fault Circuit Breakers and SSPC (ref. [6]) which would need accurate sensors.

7. Conclusion

The tendency of the aeronautical industry is to use more and more electrical power for new missions and aircraft capabilities as well as enhance the ones already deployed on the aircraft. For that reason it is need to find solutions which permit all these improvements without weight penalty. One solution for electrical system for More electrical aircrafts and All electrical aircrafts is increasing the voltage level of the electrical network on the aircraft. This leads several problems. The using of new materials as SiC is enabling to solve the problematic of using SSPCs with high levels of voltage as 270 VDC and so go for a high voltage network with enhance capabilities with a negligible impact in aircraft weight even saving weight in total considering the wiring weight reduction that represents the increasing of voltage level. However there are still challenges to be solved as arc fault detection and some others points of optimization as energy recovery issue.

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