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New trends and challenges of electrical networks embedded in “more electrical aircraft”

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Abstract- This paper describes the main trends and future challenges of electrical networks embedded in “more electrical aircraft” especially in the fields of industrial electronics and energy conversion. In the first part, the current context and new standards are put forward, emphasizing the main evolutions on aircraft architectures, from AC fixed frequency networks, variable frequency to “Bleedless” architectures. The main characteristics of more electrical aircraft are discussed, especially in terms of power management rationalization, maintenance, health monitoring capacity, etc. The second part deals with the new trends and challenges of “more and more” electrical aircraft linked with power integration and new architecture with HVDC standard. Recent methodological orientations towards “Integrated Optimal Design” are discussed with representative examples. Finally, new trends towards reversible and hybrid HVDC networks including new storage devices are also emphasized.

I. CURRENT CONTEXT AND STANDARDS OF EMBEDDED NETWORKS IN THE MORE ELECTRICAL AIRCRAFT

Air traffic market growth is estimated at 5% per year until 2020, in the context of strong competition between Europe and USA, while new providers of commercial aircraft will appear in North America and Asia. The aerospace industry will have to face both economical and environmental issues: civil aviation emitted some 2% of man made CO₂ emissions into the atmosphere in 2008 [1]. It is often claimed that saving one kilogram on each flight could save roughly 1700 tons of fuel and 5400 tons of CO₂ per year for the whole air traffic. Furthermore, mass saving would also be cost profitable: a gain of one kilogram on the “systems” increases approximately the price by 1000 US\$. Thus, aircraft manufacturing industry is placing greater emphasis on the use of technologies which can influence both the overall costs (design, operation and maintenance) and the fuel burn. In addition to the aerodynamic structure and the engine optimization, equipment systems will also play a major role, especially in reducing operation costs with minimum maintenance and maximum availability.

A. More and more electrical systems and power needs

In this context, the rationalization of power sources has led engineers towards the more electrical aircraft design involving to the replacement of conventional devices by electrical systems. This trend is emphasized in Fig. 1 which displays the evolution of electrical power needs. So far, the conventional aircraft has integrated four different energy vectors (see Fig. 2):

- pneumatic power: for the air conditioning, the wing ice protection system (WIPS) and the engine start up;

- electric power: for commercial loads and avionic systems;
- hydraulic power: for pumps and flight control actuators;
- mechanical power: to drive hydraulic or fuel pumps directly from the engine gearbox.

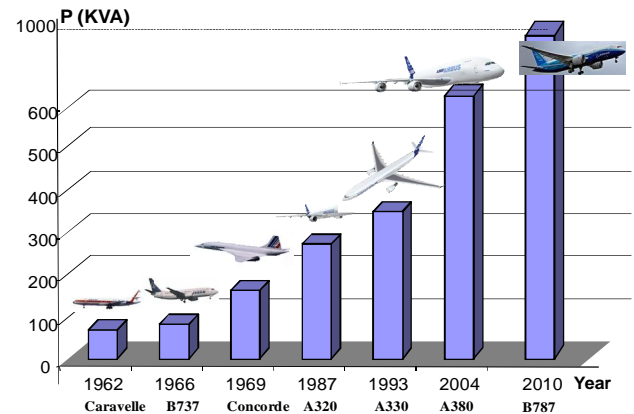


Fig. 1. Evolution of electrical power needs

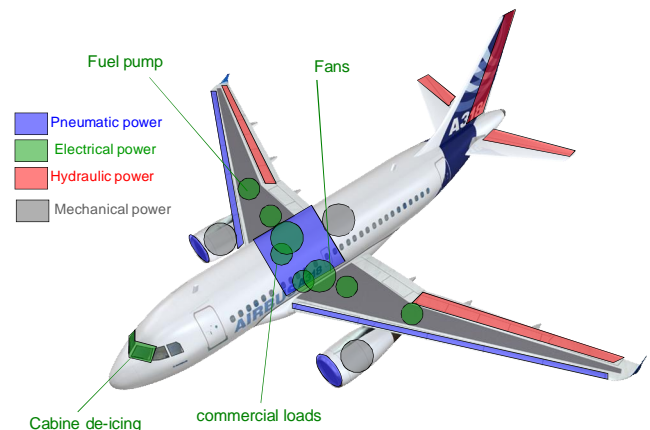


Fig. 2. Current architecture with four different energy vectors

B. From fixed to variable frequency generation: “on board power electronics”

The first generation of electrical networks was equipped with fixed frequency (115/200VAC–400Hz) Integrated Drive Generators (IDGs) as on the A320, A330, and A340. In order to simplify the Constant Speed Mechanical Gearbox (CSMG), the Variable Frequency Generators (VFGs) have been preferred as on the A380 and on the next A350 for which the voltage standard will be doubled (230/400VAC) with respect to the increase of electrical power needs. Certain prospective solutions for power generation have also been studied: in the framework of the POA EU project [2,3], Thales AES has proposed a permanent magnet generator

directly as part of the engine [4]: thermal constraints (300°C), safety (in case of stator short circuits) and high peripheral speeds were the main challenges.

Due to the introduction of variable frequency generation, several power loads supplied at fixed frequency, such as induction motor driven pumps, have been replaced with power electronic fed loads compatible with variable frequency standards (360-800Hz). For example, it was the case for flight control actuation systems (see Fig. 3) where Electro-Hydrostatic Actuators (EHAs) were embedded on the A380 for hydraulic network back up. Inside this system, the inverter feeds a high power density Permanent Magnet Synchronous Machine (PMSM) driving a volumetric pump-jack association.

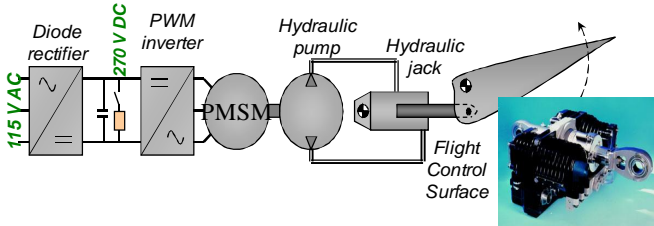


Fig. 3. An example of a power electronic fed actuator: A380 EHA

Another typical example of power electronics based aircraft systems is linked with voltage conversion for avionic (28V) systems (see Fig.4). Indeed, the Transformer Rectifier Unit (TRU) with a passive diode rectifier could be replaced by the Battery Charger Rectifier Unit (BCRU) associating an Auto-Transformer Rectifier Unit (ATRU) with a controlled DC-DC chopper. With the arrival of new High Voltage DC (HVDC) standard, this same function may be obtained from the Buck Boost Converter Unit (BBCU) consisting of 2 DC-AC stages interfaced with a high frequency transformer [5].

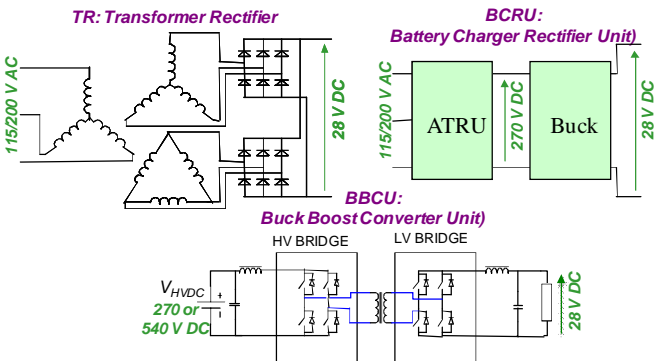


Fig. 4. An example of power electronic evolution: the 28V power conversion

These changes are typical of the current trends towards embedded power electronics which represent new challenges in terms of integration (mass decrease) and safety [4,6]. A power/mass ratio greater than 4kW/kg is currently considered as available for applications such as DC/AC converters for drive supply. However, the power density strongly depends on various factors (power rating, environmental constraints, isolated converter or not, etc): system integration in aircraft with filtering equipment (due to EMI and network quality) and cooling system may actually reduce this density up to 2kW/kg. Furthermore, some power electronic devices have to

face harsh environmental constraints in terms of temperature (-55 °C - ~200 °C), low pressure, humidity, vibrations and radiation. A wide spectrum of applications is also concerned, but with a reduced number of delivered devices. The power device range being almost compatible (voltage, power, etc), electrical and hybrid vehicles could “drive” aerospace technologies in the near future, even if environmental and safety constraints are slightly different.

C. “Bleedless” Architecture

With the B787 [7], Boeing has caused a major upset in the “aeronautical world”, by speeding up the transition towards the more electrical aircraft. While the bleed-air-based Environmental Conditioning System (ECS) is currently embedded on conventional aircraft, an electrical “bleedless” system has been proposed for air conditioning as for de-icing (WIPS). At the same time, certain loads classically powered from hydraulic network were replaced by electrical power loads (braking, pumps). The engine start up, which was carried out so far with the bleed pneumatic network, is now electrically powered thanks to torque controlled Variable Frequency Stator Generators (VFSG): the PWM voltage source inverter dedicated to the ECS is also used on the ground to power the VFSG in motor mode to start the engine [7,14].

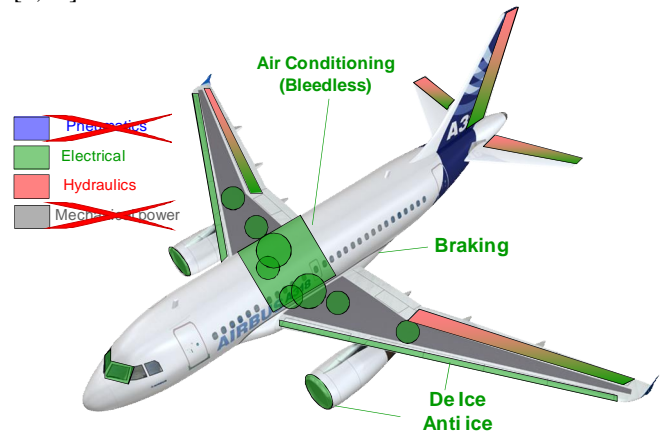


Fig. 5. Bleedless architecture (as for the B787)

For a given size of aircraft, the “bleedless effect” should multiply by four the electrical embedded power by removing mechanical and pneumatic networks and partly suppressing hydraulic loads (4x250kVA generators are embedded on the B787). In fact, the electrical power required by new loads (ECS, WIPS) is nearly the same as the power necessary for the engine start up which allows avoiding the oversizing of the starter/generator (VFSG).

D. A more electrical aircraft: why?

Beyond mass or fuel burn reduction, the advantages of the more electrical aircraft are found in power/energy rationalization and subsequent gains in terms of power management. The aircraft’s operation costs include both the direct operating costs (fuel burn, etc) but also the indirect costs linked to the maintenance and availability: “75% of late flights are due to system faults”. An electrical device will not offer better reliability but would increase availability thanks to the opportunity to isolate a sub system in case of failure.

On the contrary, a hydraulic leakage in a device leads to the isolation of the whole circuit which provokes a “No Go” fault. The failure of a hydraulic circuit is equivalent to an electrical bus bar failure for which probability is 100 times smaller. It may even become possible to anticipate faults in the near future, due to the health monitoring capacity. Anticipating failures of the electrical network would be possible through the behavioral modeling of systems coupled with fault detection algorithms [8,19]. For example, thanks to reflectometry devices, it is possible to detect and localize cabling fault within 1 meter of accuracy. Fault tolerant power electronic structures could also increase the availability of electrical systems [9].

Gains are also expected on the ground: on the one hand, an electrical ground card may replace all ground power services (air starters, aircraft hydraulic system and cabin pressure testing, etc) offering a better “power rationalization”. On the other hand, oversized ‘green’ electrical ground services could be used instead of the APU (Auxiliary Power Unit) which approximately burns 100kg/h of fuel. Furthermore, using the landing gear system during the taxi phase as a motoring system on the ground, so as to allow airplane engines to idle back during this phase, would allow replacing pushback tugs with the expected triple benefit of reducing ground noise, fuel burn and CO2 emissions [10]: the required power is almost 100kW which would be compatible with the APUs of more electrical aircrafts.

Several projects specifically dedicated to ‘the more electrical aircraft have been developed especially in the USA and in Europe [3,10,11]: the MOET (More Opened Electrical Technologies) EU project [11] has then assembled 46 industrial companies and 15 research centers between 2006 and 2009.

II. NEW CHALLENGES OF MORE ELECTRICAL AIRCRAFT

A. More integrated power systems

First of all, more electrical aircraft will signify powerful, compact and reliable electronic devices in order to facilitate power system integration. New challenges exist in this field, especially with high temperature devices (GaN, SiC) [12] which are going to allow high temperature (~250°C) operation with subsequent cooling device optimization and power integration: SiC is particularly attractive in terms of thermal conduction and technological maturity while GaN would be the future “low cost” device. Switching and conduction losses are also reduced with respect to the classical Silicon devices.

Beyond the power electronic device, several possibilities are being studied for whole system integration such as driver integration, powerful connection and passive devices (capacitances, inductances, etc), new concepts of cooling devices [13].

A 70kW ‘dual use’ inverter for an electrical ECS and the engine start up application (see section I.C) is a first example in terms of power integration (~4kW/kg). It is presented in [14] with a ‘duplex structure (2 inverters in parallel) which allows optimizing filters thus reducing the mass. It integrates

power and control components, but also input EMC filter, preload resistor and cold plate for liquid cooling.

In [15], the authors present an interesting example of integrated power converter: it corresponds to a BBCU structure allowing a 300VDC – 28VDC 12kW power conversion with galvanic insulation. A multicell (8 cells) interleaved Flyback Converter structure has been proposed using Intercell Transformers (ICT) with power MosFet for primary switching stages and SiC diodes for the secondary rectifier. Finally, a density of 4.5kW/l has been obtained to fulfill the severe requirements of the BBCU structure.

Mechatronic integration is another way to reduce system weight as emphasized with the example of the EMA (ElectroMechanical Actuator) for flight control actuation, braking or landing gear systems [16].

B. New HVDC standard and architecture

With the increasing number of power electronic loads, a more electrical aircraft with a classical AC network would include a high number of AC-DC rectifier stages (ATRU, PFC active rectifier) which would have to comply with the AC quality standard (ABD100 for Airbus). A system solution for mass reduction would be to prefer a HVDC network with an optimized association consisting of a generator – a diode rectifier (RU) – a filter – and a Generator Control Unit (GCU). If no loads are connected on the AC side, the AC standard may be released and replaced by a new HVDC standard. Several studies have recently been carried out, especially in the framework of the MOET EU project [11], emphasizing the interest of such architecture. The HVDC network would facilitate generator – load coupling with possible regenerative load acceptance. This latter issue should be interesting for certain consumers as for flight control actuators for which the current power electronic topology with a non reversible rectifier stage (RU) necessitates the use of braking resistors for regenerative transient management (see Fig.3). Other potential advantages as is the case for hybrid HVDC networks are displayed in section II.D.

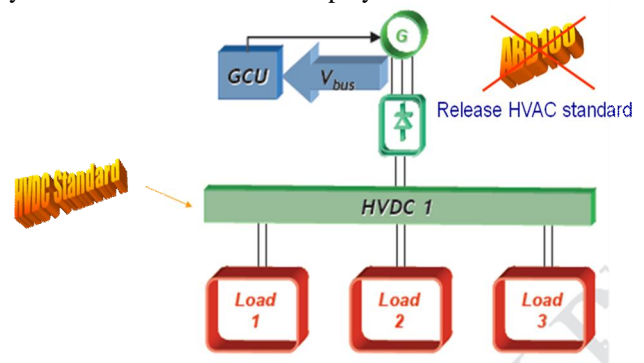


Fig. 6. Towards a HVDC (High Voltage DC) network architecture

Such architecture would impose the availability of reliable HVDC contactors and protection devices. The capacity of such devices has been recently demonstrated by Zodiac [4,11].

With this new HVDC standards, particular issues in terms of quality and stability have to be addressed. The power loads supplied with controlled power electronics (PWM inverter for

drive structures) especially involve a constant power operation which potentially makes the device unstable if a convenient filter sizing is not achieved. Several studies have been devoted to this topic [11,17,18]: for example, an analysis tool based on the Routh Hurwitz stability criteria coupled with an analytical modeling of drive structure input admittance has been proposed in [19]. Stable and unstable zones can be defined versus sizing parameters (filtering, control, load, etc). In Fig. 7, the authors have considered the stability domain of a drive versus filtering parameters (L_f , C_f) in the case of a HVDC weak grid with (L , C) impedances. On the left curve, the stability domain is obtained if the drive under study is powered alone in the network. The right curve displays the same drive stability zone with equivalent parameters, but in the case where another drive is coupled to the same HVDC bus.

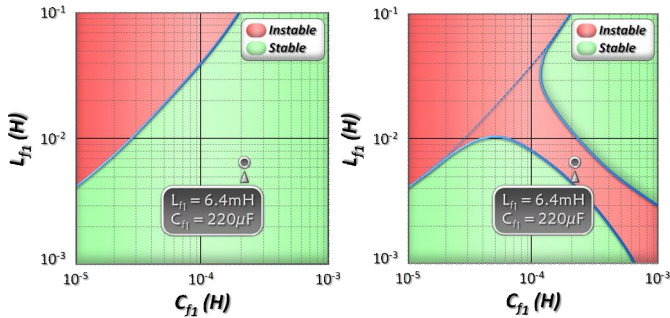


Fig. 7. Stability analysis of a drive structure placed in a HVDC network: the drive operates alone on the left side and is coupled with a second drive on the right side.

This particular example emphasizes that special attention has to be paid in order to ensure a stable operation of the whole distributed HVDC network. However, numerous theoretical studies validated with experiments [11] have shown that this issue may be addressed with a convenient sizing of filtering devices.

C. More electrical power leads to more and more optimized network design

Due to the increased complexity of electrical devices and network architecture, simulation at a system level has recently been a key issue for system analysis in order to help engineers during the preliminary design steps, but also in the V&V (Validation & Verification) process. During the MOET project [11], a Work Package managed by Aeroconseil [21] has been fully dedicated to the development of simulation platforms. Model accuracy being the key issue, at least two levels of modeling (functional, behavioral) have been required for each equipment. Each device model was firstly refined with respect to experiments. Secondly, the same model was integrated at the system level: a virtual prototyping of two rigs (a first for large aircraft, a second for small aircraft) was finally proposed to analyze a broad set of criteria (compliance with quality & stability standards, steady state / transient behavior, etc).

The Figure 8 displays an example of a network modeling and simulation corresponding to the large aircraft test rig: behavioral models were used for example to analyze the

compliance of AC/HVDC conversion (with ATRU converter) with quality standards.

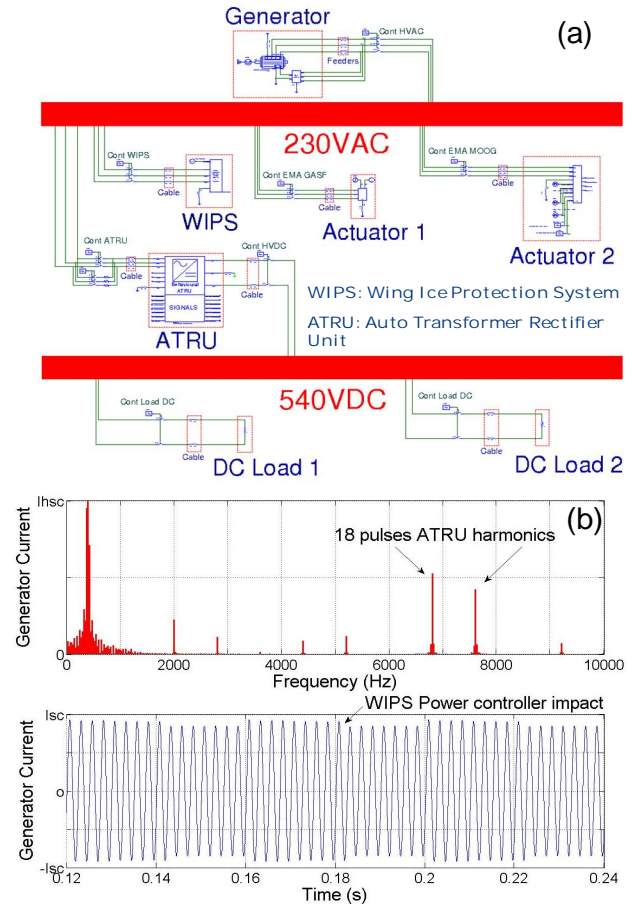


Fig. 8. a- Electrical network simulation of a “large aircraft test rig”. b- compliance analysis with quality standards for AC/HVDC conversion

“If the 2000s have been the years of network simulation, 2010-2020 could be the decade of Integrated Optimal Design”. Indeed, optimization has been achieved so far from expert choices through a “test – error” iterative process. Such an approach has proved to be efficient but designers are never sure of reaching the system optimum, especially when numerous coupling effects are involved. The Integrated Optimal Design approach consists in coupling sizing models with an optimization algorithm which automatically tunes parameters to optimize system criteria (mass, losses, etc) while satisfying technological and operating constraints (thermal, compliance with quality/stability standards, etc). Several optimization studies have recently taken place, for example in the case of a HVDC power generation system [22], or to minimize mass and losses of an ECS drive including a High Power Permanent Magnet Synchronous Machine (HPPMSM) supplied by a PWM voltage source inverter. In this case, the multi criteria optimization approach was based on the NSGA II evolutionary algorithm. 12 sizing parameters were addressed with 8 constraints and 2 criteria to obtain a Pareto front which suggests that a significant mass/loss reduction can be obtained with respect to a ‘reference solution of sizing’ (1 p.u.): -40% on mass at iso-losses.

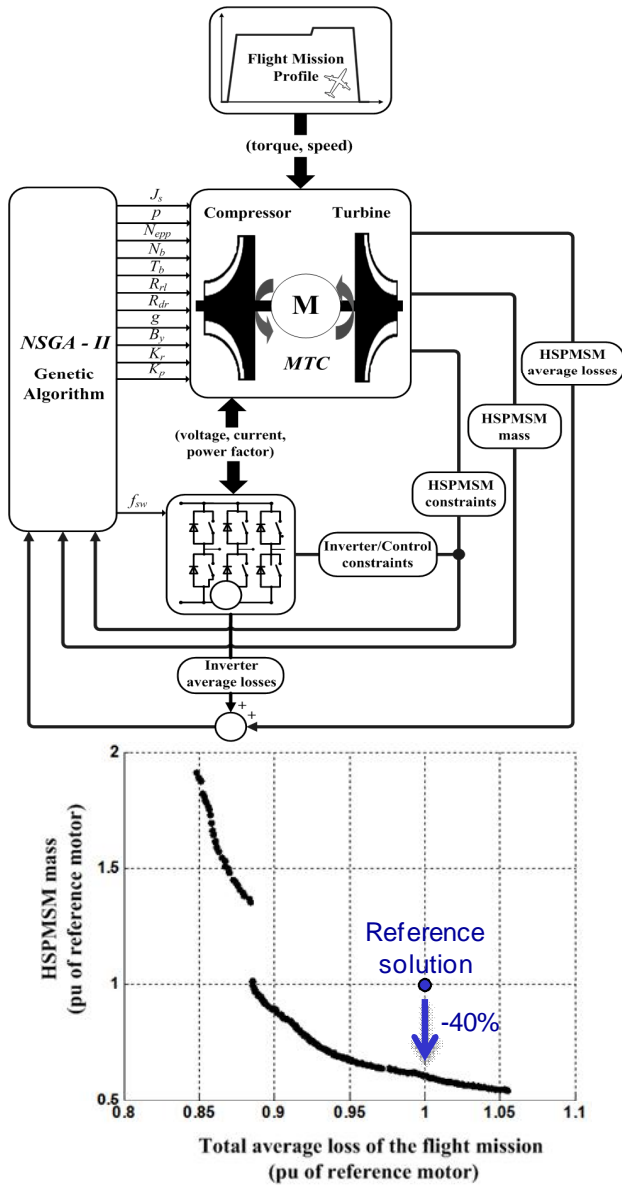


Fig. 9. Optimization process of ECS and its global Pareto-optimal front

D. More and more electrical power involves innovative architecture and energy management optimization

The increasing electrical power needs have also led engineers towards innovative architecture in order to save system mass. One solution should consist in merging several functions supplied with a similar power electronic device [14] which is used for different flight phases: a typical case proposed on the B787 bleedless aircraft [7] consists in a function merging of the ECS with the engine start up supplied from a common “dual use” PWM inverter. This functional merging is all the more interesting since ratings of both functions are almost compatible, which allows considering the electrical engine start up without any over-rating.

One step beyond, in terms of power electronic sharing, was proposed in [23]. The authors have suggested to put in parallel “base modules” consisting of 3 phase PWM inverters: for example, four 30kVA inverters can be interleaved (phase to phase) with inductors to obtain a quadruple switching

frequency with a 25% equivalent inductor on each leg, which allows obtaining a 120kVA equivalent inverter capable of feeding an air compressor for ECS.

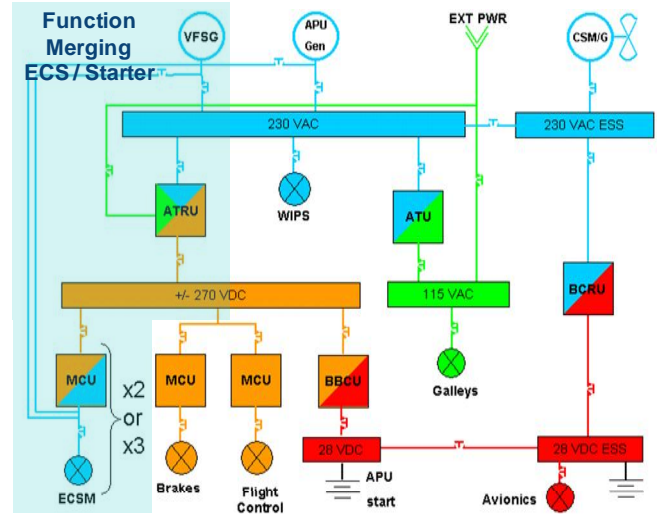


Fig. 10. An example of Bleedless architecture with the ECS / engine start up functional merging process

Other innovations in terms of architecture could be proposed with a hybridization of power sources with storage devices, as for the ground electric vehicles. The advantages of network hybridization are to under-rate power sources thanks to the storage source capacity to contribute to peak power loads. Reversible power may also be acceptable for specific operations with hybrid networks. A typical example was proposed in [24], for the particular case of the emergency electrical network. In extreme case of engine failure, a RAT (Ram Air Turbine) is classically used to power the “essential network” with flight control actuators, avionic loads, essential lightning and de-icing. The authors have proposed to hybridize the RAT with super capacitances: 30% of mass saving has been estimated through this hybrid architecture together with an original optimized energy management process in which the storage device associated to a DC-DC converter is in charge of the HVDC bus voltage management. Consequently, the RAT can be power controlled with a Maximum Power Point Tracking (MPPT) exactly as in the case of classical wind turbines.

It has been proved that storage devices are capable of handling an important part (40-50%) of peak power consumption mainly due to the operation of flight control actuators.

It should be noted that a HVDC network facilitates coupling between the main source and the storage device. In case of total engine failure, the transition between normal and emergency operation has to be safely ensured, even while the RAT becomes powered. This transient operation was previously ensured by the hydraulic network on classical aircraft but will have to be managed by the electrical storage device in the more electrical aircraft with an electrical RAT: for this purpose, other storage technologies such as Lithium Ion batteries could be used to supply energy needs [25].

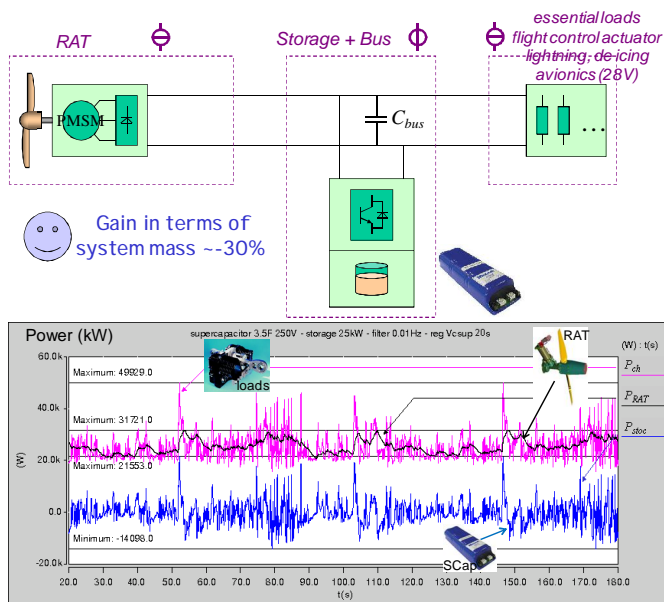


Fig. 11. An example of hybridization of the RAT with super capacitors

The replacement of the RAT with fuel cells has been studied in the CELINA EU project in the context of an emergency network [26]. Replacing the RAT by a fuel cell is technically feasible: a prototype was embedded on the A320 in 2007. Replacing the APU by a fuel cell is another prospect which would also allow progressing towards “greener aircraft during taxi”.

III. CONCLUSION

Recently, more and more electrical power needs and systems have been embedded on aircraft. The gains in terms of mass are increasing. However, the advantages of the more electrical aircraft should mainly reside in energy rationalization and management capacity that would allow increasing the availability of the systems. Maintenance costs could also be reduced from the health monitoring capacity. Electrical systems may also contribute to making aircraft “greener” for particular operations such as the ground phase. Nevertheless, the electrical systems and components have to be more mature with an increased reliability. Their power density should also be increased to save mass. This objective involves numerous areas of progress in terms of power integration at component and device level. In particular, the cooling devices have to be optimized together with new types of architecture in order to avoid recreating a new “secondary hydraulic network”. Research efforts are particularly active on these topics in the US and EU industry and also at university level. Electrical and Hybrid Electric Vehicles would give added impetus to the whole adventure of the more electrical aircraft since standards, devices and certain constraints are quite similar.

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