More Electrical Non-propulsive Architectures Integration

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ABSTRACT

This paper discusses some thoughts about aircraft integration associated with more electrical non-propulsive architectures in the context of future hybrid propulsive concepts. In order to optimize the aircraft integration outcome, the coupling between propulsive and non-propulsive power sources must be considered. Despite a general tendency to increase non propulsive energy onboard, the related energy and power consumption remains minor against propulsive need. However, the design of thermal engines is strongly affected by the non-propulsive energy off-takes altering the overall behavior of the engine due to operability considerations. In a new context of hybridization, integration strategies show synergies between a thermal engine's operability requirement, efficiency and more electrical non-propulsive architectures. This leads to new opportunities to design electrical architectures and associated power management.

KEYWORDS: *Hybrid, Architecture, Electrical, Aircraft, Non-propulsive.*

NOMENCLATURE

APU	– Auxiliary Power Unit	LPC	– Low Pressure Compressor
ECS	– Environmental Control System	PbW	– Power by Wire
ETOPS	– Extended Twin-Engine Operations	WIPS	– Wing Icing Protection System
HPC	– High Pressure Compressor	c_{gr}	– Generator redundancy coefficient
IDG	– Integrated Drive Generator	c_{cr}	– Converter redundancy coefficient

1 MORE ELECTRICAL NON-PROPULSIVE ARCHITECTURES STATE-OF-THE-ART

Many of the civil or military transport aircraft from the past few decades have been designed with several non-propulsive electrically powered systems, whereas, those respective systems were previously hydraulically or pneumatically powered. One can observe that different aircraft integrators did not introduce the same sources of energy for those same systems. These facts tend to indicate that the general evolution towards a more electrical aircraft is not a question of technical fashion but a response to specific requirements for each aircraft integrator. Each of them had their own philosophy, their own set of motivations and they all followed their own roadmap to achieve the requested technological step. Mass was a major challenge when Airbus introduced Power by Wire (PbW) actuation in the Flight Control System (FCS) of the A380, allowing the replacement of the classical "3H" (3 Hydraulic networks) architecture by their "2H2E" (2 Hydraulic, 2 Electric networks) architecture. Fortunately, the deletion of one hydraulic circuit combined with the exceptional size of the aircraft has led to mass saving, evaluated close to one ton despite the mass penalty of the PbW actuators. Furthermore, this evolution has permitted the introduction of new power distribution routes in the aircraft, facilitating the certification process relative to some particular risks (e.g. engine rotor burst). One can think that this property on top of the dissimilarity offered by the "2H2E" FCS architecture was determinant for the selection of the same architecture for the A400M thus reducing the vulnerability to military threats. In the same period of time, Boeing opted for a more conventional "3H" architecture for the B787 flight control system, but decided to make a significant technological step in selecting an electrically powered Environmental Control System (eECS) and an electrically powered Wing Ice Protection System (eWIPS) [21]. For the great majority of civil transport jets from the past and present generations, both of those systems are pneumatically powered via pressurized air off-take from the High Pressure Compressor (HPC) of the main engines (on ground, engine off, the pressurized air required for the ECS is generally supplied by an Auxiliary Power Unit (APU) or by ground facilities). As explained in the next paragraph, air off-takes have a significant impact on the engine performance and improving the aircraft energy efficiency was obviously the motivation for Boeing to select those revolutionary energy system architectures for the B787. In a logical way the classical pneumatic starter of the engines was also replaced by an electrical starter, taking the opportunity to mutualize significant pieces of hardware i.e. electrical converters, between these two systems, the Engine Start and the eECS. New functions may appear on next generation aircraft which may amplify the trends toward more electrical systems. Electrical taxiing for example could be selected by some aircraft manufacturers as an answer to ACARE Strategic Research and Innovation Agenda for 2035, aiming emission-free taxiing.

Concurrently to electrification of non-propulsive systems, the cumulated power of the different electrical generators of the last generation aircraft dramatically increased. On the B787, the primary electrical generation reaches a cumulated rated power of more than 1400 kVA shared between 4 engine driven Starter/Generators (2 per engine) and 2 APU driven Starter/Generators (2 per APU), batteries and emergency generator left aside. On civil transport aircraft, one can observe that the total amount of installed power generation is almost twice the power which can be consumed in flight by the non-propulsive systems; this over-supply of electrical power is mainly explained by the level of redundancies resulting from safety/reliability considerations.

Furthermore, for most twinjets, Extended Twin-Engine Operations (ETOPS) rules introduced supplementary requirements regarding availability of electrical generation. This lead to make the APU capable of working on the majority of the flight envelope and for a long time. However, this enhanced capability is most of the time unused during conventional, non ETOPS, flights. The management of primary electrical power generation remains up until now for various operational situations limited to pre-established logics of reconfiguration on failure detection and to human decision from the flight crew.

For non-propulsive systems, the energy optimization through appropriate management of electric power sources is not an onboard function yet.

Non-propulsive systems energy optimization, by managing the different available electrical sources is not a function onboard yet. However, current considerations about the impact of the main engines off-takes on the overall energy efficiency of an aircraft tend to indicate that such a power source management could offer more integration and quite significant energy saving over the overall mission of the aircraft.

2 MORE ELECTRICAL NON-PROPULSIVE ARCHITECTURE IMPACT ON ENGINE PERFORMANCE

2.1 Engine Performance and Operability

Aside from the starting mode, transient thermal engine performance comprises changes in power or thrust level. During an acceleration, the engine control system responds by increasing the fuel flow at a defined limiting rate until the demanded power is achieved. Due to the additional fuel flow the turbine produces more power than required by the compressor which implies a significant deviation of the compressor working lines from the steady state operating lines. During a deceleration phase the opposite phenomenon occurs. The consequence of the transient working line crossing the surge/stall line could result in damage to the engine. In addition, the transient working line deviations increase as the acceleration or deceleration times are reduced. Each engine application has its own time requirement for key transient performance. Fig. 1 shows typical transient responses (pressure ratio, corrected mass flow) of gas turbine compressors during acceleration and deceleration phases versus time.

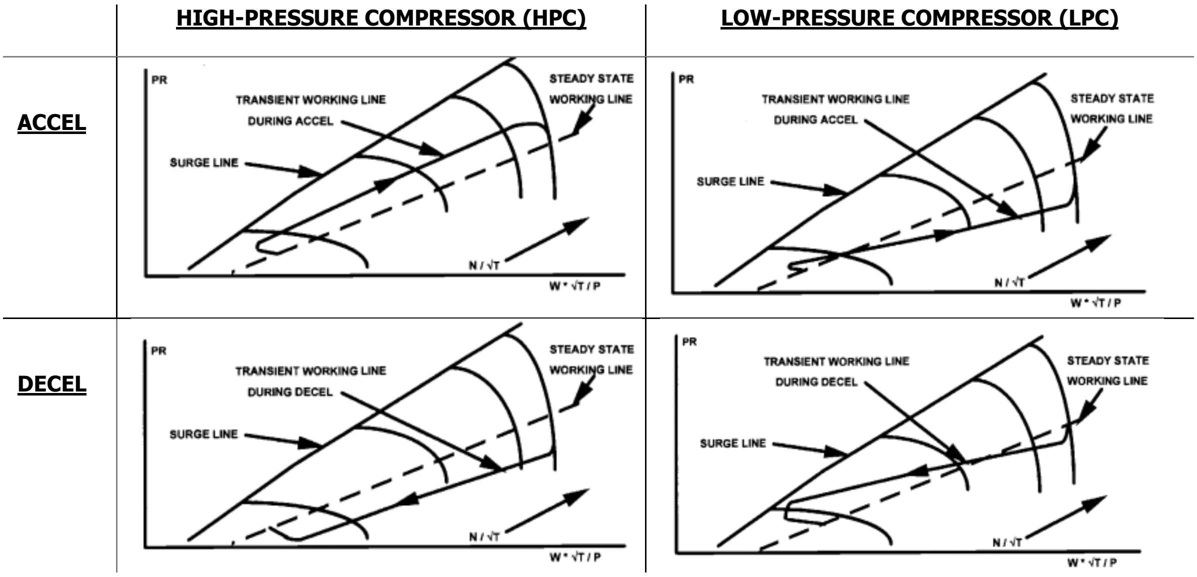

Figure 1: Typical transient working lines for gas turbine compressors [7]

For a given engine, the required surge margin (the distance of the operating point from the surge line) is evaluated from a surge margin stack up where a range of issues such as transient working line excursions (Fig. 1) must be addressed at the worst operating conditions (Fig. 2).

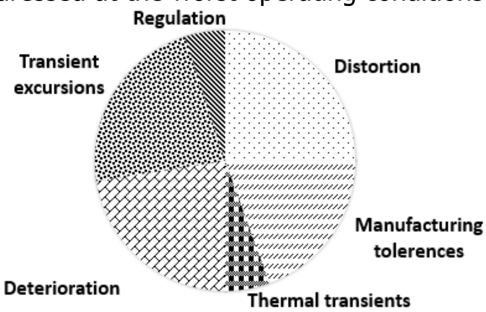

Figure 2: Typical turbofan HPC surge margin composition

Typically, the HPC surge margin amounts to roughly 20% of safety margin in terms of Pressure Ratio on the HPC map and a large proportion is reserved to the transient issues. Otherwise, one should know that the surge margin usually excludes the operating point positioning on the most efficient compression area. Thus, a trade-off between engine performance and operability is considered for the engine design.

2.2 Steady state engine Off-takes impact on Performance and Operability

More electrical non-propulsive architectures are not without impact on engine performance. Off-takes affect the performance of the engine by altering the work balance between compressors and turbines. Traditionally, electrical power is extracted from the High Pressure (HP) engine spool. Its high operating speed makes it an ideal source of mechanical power to drive the electrical generators connected to the engine. However, the turbine then needs to produce a greater amount of work to cover the mechanical power extraction. The HPC acts as a blockage for the Low Pressure Compressor (LPC) pushing it towards the surge. The power requirement may remain at a high level when the engine is operating at low power. In this case, the HPC operating line is displaced towards surge over the whole running range (Fig. 3). Thus, power extraction must always be considered in establishing surge margin.

The opposite occurs for bleed extraction. The turbine has to operate with a reduced mass flow to produce the work required by the HPC. This results in a higher turbine inlet temperature with a reduced mass flow so that the HPC pressure ratio decreases. Thus, the HPC operating line is lowered (Fig. 3). The lack of extraction equilibrium due to bleed reduction and mechanical off-takes increase implies the compressors surge margin becomes much more critical to ensure operability which impacts engine efficiency.

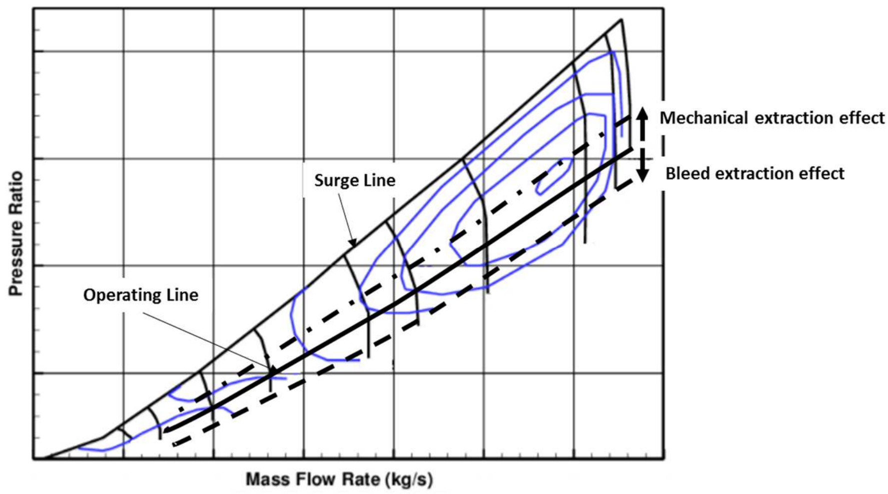

Figure 3: Off-takes effect on HPC steady-state working line

In addition to the loss of performance, this extraction power unbalance produces operational constraints, especially for descent in idle and for taxi operations. Through descent phases, it is essential to increase the engine speed to satisfy important mechanical off-take requirements for icing conditions. This will result in an undesirable thrust being countered with airbrakes deployment and implying comfort issues due to vibration and buffeting on top of energy waste.

2.3 Technical Solutions to Meet the Increase of Mechanical Off-takes

The need here is a solution extracting electrical power from the engine during a low power operating mode without reducing the engine operability. With most modern compressors, surge is likely to happen at low speeds and is less of an issue at high rotational speeds. To overcome the problem it is necessary to lower the operating line in dangerous operating zones. One common method is to bleed air from an adequate compressor stage (Fig. 3). However, bleed involves a waste of turbine work. As an alternative, variable areas could be used to adapt the surge line. Both methods produce a temporary reduction in pressure ratio lowering the operating line. In addition, engine manufacturers are investigating the Low Pressure (LP) engine spool power extraction as an alternate source, or, as an additional source. However, the lower speed of the LP spool requires the use of a gearbox, to ensure appropriate electrical generators speed and thus suitable integration volume [8-12].

3 MICRO/MILD-HYBRID PROPULSION ARCHITECTURES

3.1 Hybrid Electric Architectures Definition and Requirements

Hybrid-electric propulsion system consumes power from electric sources additionally to the thermal engines. The electric source can either be a dedicated turbo-generator or electrical storage. The latter can either be exchanged during aircraft turn-around or recharged during operations via generators coupled to the thermal engine and/or through some form of energy recovery. Hybrid electric architectures can be elaborated according to strategies arising out of series and parallel combinatorial arrangements (Fig. 4).

The distinctions are tied to the nature of the power node between the system constituents: in a series hybrid arrangement, the node is electrical, whereas, in a parallel hybrid, it is mechanical [3].

In more electric aircraft, the availability of high power electrical machines integrated to the engine is a step towards engine hybridization. First, the engine can improve its operability and performance based on starting strategies, on a real-time power sharing management for the off-takes within all available shafts and/or by using additional energy storage. This is the so called micro-hybrid architectures [12-15].

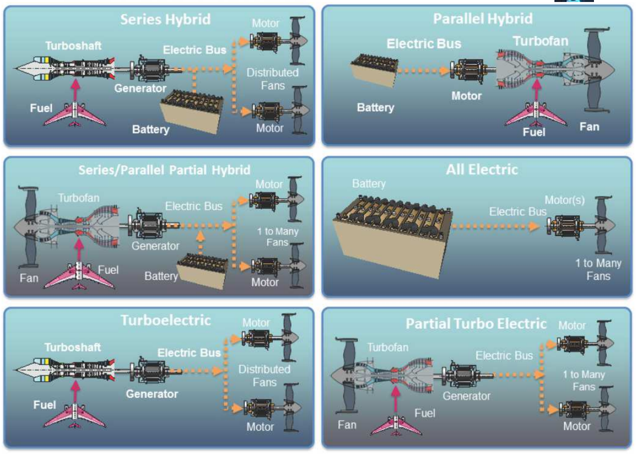

Figure 4: Hybrid-electric propulsion architecture classifications [22]

If the installed electrical power is increased further, referred to as mild-hybrid architectures, some engine design constraints can also be removed or relaxed by injecting or subtracting power from the two shafts, in a continuous or transient mode. In addition to managing the off-takes and assisting the engine with electrical machines:

- A traditional engine is sized to overcome the most demanding conditions and must operate at partial power during large periods of time, resulting in lower thermal efficiency. With an assistance in a continuous mode, one should understand optimization of the gas turbine performance throughout the flight mission profile using an additional energy storage. For example, the injection of shaft power at the key cycle sizing conditions (Take-Off and Climb) reduces the thermal power demand, and thus, the gas turbine core temperatures at these conditions. Hence a degree of decoupling is achieved between the core sizing and the thrust delivery requirement, providing opportunity to optimize the core in terms of thermal efficiency and component life [6][16]. Another option for mission energy saving could be driving the turbofan on electric power during the descent phase.
- By assistance in a transient mode, one should understand power injection on the HP shaft during accelerations and power off-take from the LP shaft during decelerations. By injecting power on the HP shaft during an engine acceleration, the operating point excursion towards the surge line of the HPC can be reduced or eliminated (Fig. 1). Similarly, by subtracting power from the LP shaft during a deceleration, the LP compressor can be operated further away from the surge line. This improvement in the operation of the two compressors can be seen as beneficial either by decreasing the response time of the engine during transients or by reducing the compressors stall margin need in the steady state conditions. Both enable the engine to operate closer to its maximum efficiency [17-19].

Table 1 shows typical power levels of electrical loads for short-medium range commercial and large business jet aircraft.

Table 1: Electrical power and energy requirement

Electrical Power use	Power level (kW)	Duration	Energy
Non-propulsive systems	300 - 500	Descent phase = 20-30 min Taxiing phase = 10-25 min	Max for descent X00kWh Max for taxiing X00kWh
Engine starting	50 - 200	30 s	XkWh
Engine transient electrical assistance	500 - 2000	10 s	XkWh
Engine Take-Off and Climb assistance	2000 - 4000	Take-Off phase = 2-3 min Climb phase = 20-30 min	Max for take-Off X00kWh Max for climb XMWh

(X depends on power management strategy)

3.2 Electrical Power and Energy Sources

Supplementary engine needs for energy and power imposes additional electrical sources into the aircraft. These sources have to provide enough power during some flight phases but not during the whole flight.

To ensure such a supply, other power generators such as an APU, may be used. However, APUs are not adequate for all the conditions described in Tab 1. Indeed, the time response is not always compatible in the case where the APU is not turned on throughout the flight. Moreover, restarting the APU would erase the fuel saving due to hybridization. Nonetheless, chemical storage is time response compliant with hybridization needs. This storage may consist of batteries such as Li-Ion batteries and super capacitors for short duration uses.

The composition of storage systems is completed by considering the hybridization requirements and by considering super-capacitors are appropriate for high power spike and batteries for longer time power needs. Considering a Ragone diagram [20], mapping chemical technology versus power and energy, a trade off shall be completed using required values from table 1.

4 MORE ELECTRICAL NON-PROPULSIVE ARCHITECTURES INTEGRATION AND SYNERGIES

4.1 Engine Performance and Operability Opportunities

One option for mild-hybrid architectures would be to recover the HPC transient surge margin. Consequently, electrical machines should provide assistance to the engine during acceleration by injecting mechanical power into the HP engine spool from another energy source. On the other hand, providing non-propulsive energy by other means during transient phases can lower the HPC operating line. In the interest of not oversizing electrical machines, synergy is found between the HPC operability requirement and more electric non-propulsive energy architecture (Table 1 shows the same power levels for both functions). One strategy could be to design the HPC so that the steady-state operating line would be the closest possible to the best HPC efficiency area, and to partially allow the line to lower during the transient phase by providing non-propulsive energy using electrical storage. The excursion can be further limited by injecting mechanical power into the HP engine spool from the electrical machines (operating in motor mode). A similar strategy can be conducted to assist the LP compressor during deceleration phases when electrical machines are coupled to the LP engine spool.

4.2 A New Deal for New Architectures

Including new power and energy sources in an aircraft offers the opportunity to optimize their use. Hybridization benefits can be improved using available energy to supply functions that are not already electrified. Indeed, weight saving may be achieved with more electric functions using these new embedded energy sources.

A global electrical architecture may be split into three main parts (Fig. 5):

- Power and energy sources
- Distribution system
- Loads

A control system is used to manage the whole electrical system and to ensure that the power required for loads is provided by the sources through distribution.

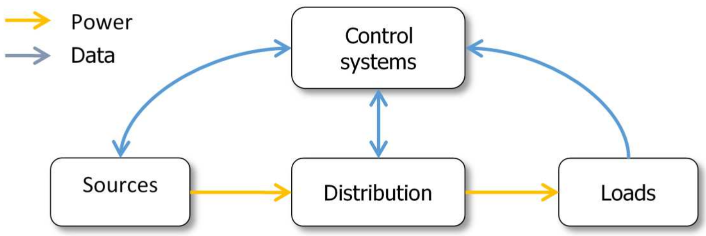

Figure 5: Global electrical architecture view

As supplying electrical boost to the thermal engine is critical for hybrid propulsive system, the number of sources (for redundancy) and power levels must be increased. The complexity of the distribution architecture is also adapted to new safety/reliability requirements.

The control system should supply the loads with an adequate amount of power, control the sources and the distribution system, considering their respective states and current failures. As a result, hybridization gets to use more complex electrical architecture including more energy sources and more loads. However, this complexity can also result in new power management opportunities.

4.3 Power Management Opportunities

Regarding the different electrical sources, there are many possibilities to supply loads. Each source has a different impact on fuel consumption and aircraft performance. Therefore, the power management function needs to ensure a configuration of power network supplying loads all flight long in a safe and efficient way.

The main types of electrical sources are:

- Electrical storage sources
- Engine generator
- APU generator
- Ground chart

For each power source, performance and availability vary during the aircraft mission, i.e. during the flight phases. For each hybrid solution, it is possible to set up a synthesis table. For example, Table 2 shows an operating strategy for a mild-hybrid architecture.

Table 2: Source availability

<table>
<tr><th rowspan="2">Flight phase</th><th colspan="2">Engine off-take</th><th colspan="2">Park plug</th><th colspan="2">Electrical storage</th><th colspan="2">APU</th></tr>
<tr><th>Available</th><th>Efficiency</th><th>Available</th><th>Efficiency</th><th>Available</th><th>Efficiency*</th><th>Available</th><th>Efficiency</th></tr>
<tr><td>Gate</td><td>No</td><td>N/A</td><td>Yes</td><td>High</td><td rowspan="9">Capacity defined by design</td><td rowspan="9">High</td><td rowspan="9">Yes</td><td rowspan="4">Medium</td></tr>
<tr><td>Taxi</td><td rowspan="2">Optional</td><td>Low</td><td rowspan="7">No</td><td rowspan="7">N/A</td></tr>
<tr><td>Take off</td><td rowspan="3">High</td></tr>
<tr><td>Climb</td><td rowspan="4">Yes</td></tr>
<tr><td>Cruise</td><td>Low</td></tr>
<tr><td>Descent</td><td rowspan="3">Low</td><td rowspan="4">Medium</td></tr>
<tr><td>Landing</td></tr>
<tr><td>Taxi</td><td>Optional</td></tr>
<tr><td>Gate</td><td>No</td><td>N/A</td><td>Yes</td><td>High</td></tr>
</table>

* Charge efficiency depends on the energy source

In an equivalent manner, the electrical loads can be listed regarding the power level requirement:

- Engine start and assistance
- Electrical Taxiing (eGTS)
- Flight Control Actuators (FCA)
- Environmental Control System (ECS)
- Wing Icing Protection System (WIPS)
- Main or Nose Landing Gears Systems (MLGS or NLGS)
- Other electrical systems (galley, avionics, In-Flight Entertainment…)

Two power management strategies can be performed: pre-configured strategy or real-time strategy (Fig. 6).

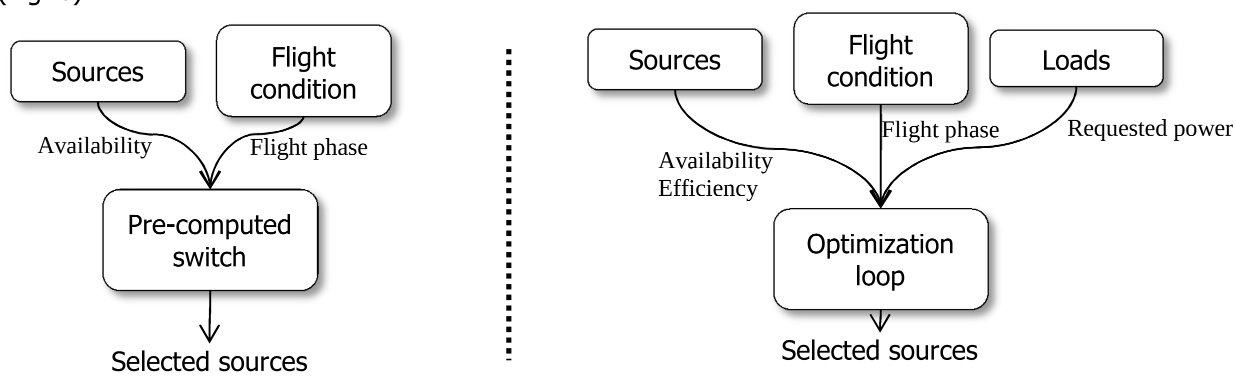

Figure 6: Source algorithm selection

Pre-configured power management strategy depends on flight phases and available power sources. Power requirements for loads are considered by sequence and not measured. This kind of management is robust as no specific measurement is needed.

A real time management computes the whole aircraft system power needs and the configuration of all power sources to select the best energy paths for fuel consumption or other criteria. This power management is more efficient than the first one but much more complex.

Power management opportunities are not specific to hybrid propulsive architectures as far as they are already performed for some non-propulsive functions. However, hybridization increases synergy between electrical power use and fuel flow. Moreover, power management is more complex due to the reversibility of the sources: in normal mode, the thermal engine is the main electrical power supply while the electrical storage is a load. In engine assistance mode, e.g. during an acceleration, electrical storage is the main electrical power source and the thermal engine is considered as a load. Fig. 7 shows an example of power management strategy for a mild-hybrid architecture. Electrical storage is used to provide energy for engine start and boost. This embedded energy is mutualized with landing gear function for landing gear extraction and retraction. APU is used to provide non-propulsive energy during descent and to supply eGTS, NLGS and MLGS (braking) during taxing.

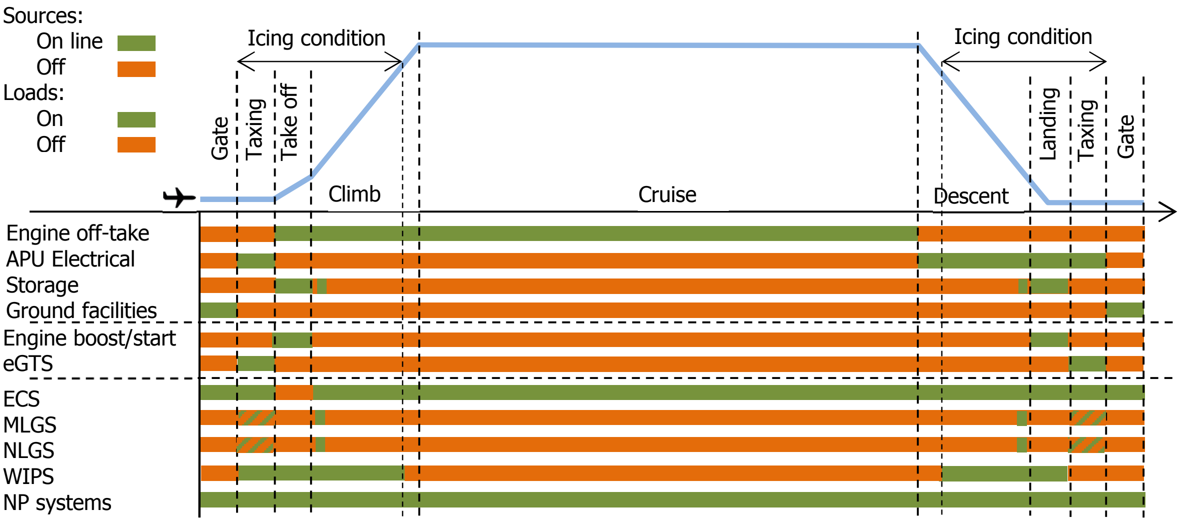

Figure 7: Aircraft mission example

4.4 Electrical Architectures Impact

The electrical architecture shall ensure power supply to loads respecting a defined failure rate. This leads to added redundancies that increase system weight. Main objective is to limit this increase by adjusting redundancies to the lower possible limit.

Criteria c_{gr} and c_{cr} defining generators and converters installation factors are defined as follow:

$$c_{gr} = \frac{P_{generators}}{P_{loads}} \quad (1)$$

$$c_{cr} = \frac{P_{converters}}{P_{loads}} \quad (2)$$

Where $P_{generators}$ is the generator installed power (sum of nominal powers), $P_{converters}$ is the converter installed power (sum of nominal powers),

P_{loads} is the power required by the loads.

For a classical Short-to-Medium Range (SMR) aircraft such as A320 or B737, c_{gr} = 2 as only one generator should be able to supply the entire electrical network. Any additional generators allow reducing this factor, but the availability of all generators shall reach safety requirements.

As engine failure is considered for the electrical network sizing, adding a generator to the same engine does not allow reducing significantly c_{gr} factor. As a result, the number of generators that are installed in the aircraft is nowadays linked to the aircraft engine number. Adding an independent power source for engine hybridization is an opportunity to reduce the need for redundancy in terms of generators (Fig. 8).

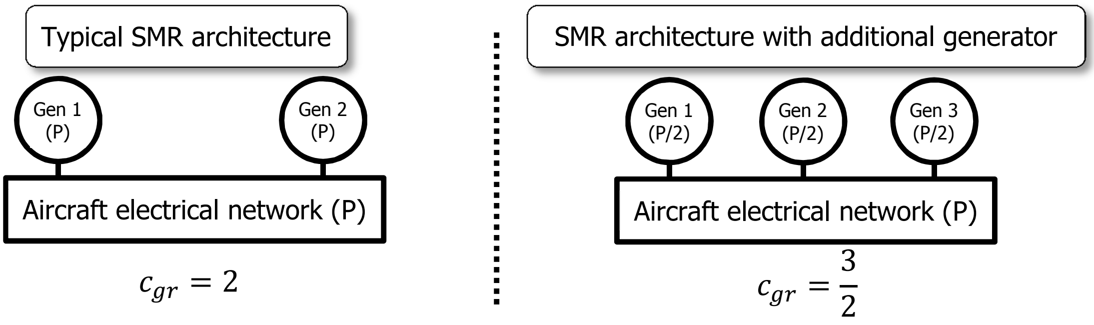

Figure 8: Source sharing redundancy

Another optimization opportunity is linked to the main electrical converter included in the electrical network. Two methods are possible for architectural design (Fig. 9):

- Local function design: redundancies are applied for each function. Each converter is dedicated to a single function, if the reliability of this converter is not sufficient regarding a functional requirement, it shall be duplicated.
- Global design: redundancies are shared between functions allowing weight rationalization. This design uses generic converters that may be used to supply different functions during different flight phase. Switching from one load to another one is performed through a contactor matrix.

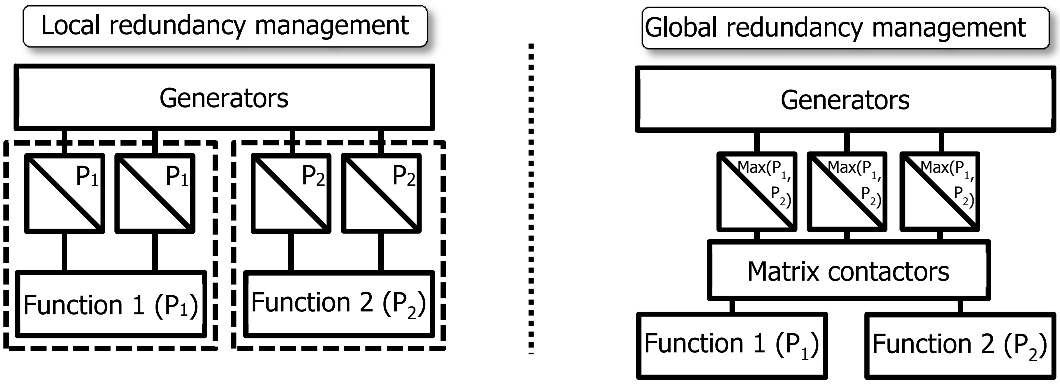

Figure 9: Local and global electrical architecture view

In this example, with a local redundancy management the c_{cr} factor is equal to 2 while managing redundancy globally leads to a $c_{cr} = \frac{3\max(P_1,P_2)}{P_1+P_2}$. Even if the global design may lead to a lighter architecture by reducing the converter number, it is not always the best solution. For example if:

$P_1=10kW$ and $P_2=8kW \rightarrow c_{cr}=1{,}7$

$P_1=10kW$ and $P_2=4kW \rightarrow c_{cr}=2{,}1$

Moreover, a generic converter is heavier than a specific one, as it is not optimized for a specific function. Engine hybridization leads to use of high power electric converters that shall be duplicated to ensure sufficient availability. Optimizing electrical redundancy management, using generic converters for other aircraft functions (that are not used at the same time) with similar power levels, may limit the extent of weight reduction due to safety requirements. However, to rationalize electrical equipment, aircraft electrical network architecture has to be changed.

5 CONCLUSION AND PERSPECTIVES

Progress in electrical technologies permits an opportunity to consider hybrid propulsive architecture concepts revealing synergies between thermal engine performance, operability and increasing electrical power requirements for new generation aircraft. Furthermore, the use of new onboard electrical energy source implies new energy suppling approach of non-propulsive systems allowing better redundancies management and rationalization, reducing system weight and maintenance cost. However, one should be aware that such opportunities cannot be reached without more control and power management complexity.

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