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Optimal design of the Integrated Modular Power Electronics Cabinet

X. Giraud [a,b,c], M. Budinger [b,*], X. Roboam [c], H. Piquet [c], M. Sartor [b], J. Faucher [a]

[a] Airbus Operations SAS, 316 route de Bayonne, 31060 Toulouse Cedex 9, France
[b] Université de Toulouse, ICA (INSA, UPS, Mines Albi, ISAE), 135 av. de Rangueil, 31077 Toulouse, France
[c] Université de Toulouse, LAPLACE (CNRS/INPT/UPS), 2 Rue Camichel, 31071, Toulouse, France

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ABSTRACT

This paper deals with a new concept of electrical power distribution system called IMPEC for Integrated Modular Power Electronics Cabinet. The paper defines methods aiming at carrying out an optimal design of IMPEC, the main variables being, on the one hand, the number and size of power electronics module. On the other hand, reconfigurations between these modules and electrical loads are also optimized. The formalization of the problem highlights that designers must deal simultaneously with a combinatorial explosion and a multi-physical system sizing. The main objective of the study is to propose a methodological framework for solving this original optimal design problem. A heuristic-based algorithm is developed to solve this combinatorial optimization problem. A particular attention is paid to develop a weight estimation procedure using generic sizing models. Finally a mapping is performed to identify the best solutions and to highlight the technological components having the most significant sensitivity on the complete system weight.

1. Introduction and context

1.1. More electrical aircraft

On traditional aircraft such as A320 or A330, systems are powered by 3 different energy vectors: pneumatic, hydraulic and electric (Fig. 1 and Fig. 2). These 3 power vectors are extracted from primary power sources such as the engines or the auxiliary power unit (APU) that are today all supplied by fuel (kerosene) [1].

In terms of power levels, the pneumatic vector is the most demanding one. During some flight phases, it represents around 80% of the power taken off the engines (Fig. 1). This energy vector supplies the engine starting system, the wing anti-ice protection system (WIPS) as well as the environment control system (ECS) by extracting pressurized air taken from the engines (bleed air).

Systems requiring high force at low speed such as flight control surface actuation, landing gear actuation and aircraft breaking are traditionally powered by the hydraulic vector.

Eventually, the electrical power system (EPS) provides power to numerous and various systems (also called electrical loads). Onboard an Airbus A330, around 700 electrical loads are embedded. Some of them are essential such as: the fuel pumps, the electro-hydraulic pumps, the fans, the processing blades; others are installed in order to provide comfort to the passengers: the galleys and the flight-entertainment systems.

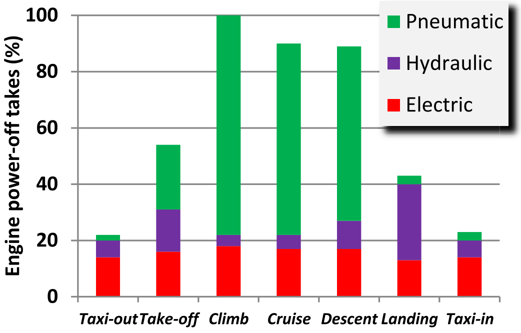

Fig. 1. Sharing of the power-off take extracted from the engines (Airbus A330) [2].

For the last decade, the use of electricity is rapidly increasing in commercial aircraft. This trend illustrated in the paradigm of the More Electrical Aircraft (MEA) consists in replacing hydraulic and/or pneumatic powered systems by electrical ones [3–5]. As a consequence, the realization of the “all-electrical” aircraft aims at completing simultaneously 2 types of configurations: Bleedless [6] and Hydraulicless [7,8] (Fig. 3). By embedding only 2 hydraulic circuits instead of 3 traditionally, the Airbus A380 and A350 are seen as an intermediate configuration towards hydraulicless aircraft [9].

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* Corresponding author.
E-mail address: marc.budinger@insa-toulouse.fr (M. Budinger).

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Nomenclature

APU	Auxiliary Power Unit
DOE	Design Of Experiments
DSM	Design Structure Matrix
ECS	Environmental Control System
EPS	Electrical Power System
HVDC	High Voltage Direct Current
IMA	Integrated Modular Avionics
IMPEC	Integrated Modular Power Electronics Cabinet
MEA	More Electrical Aircraft
N2D	N-square Diagram
PEM	Power Electronics Module
WIPS	Wing Ice Protection System
$\mathcal{C}$	Total number of loading cases to analyze
$I_{PEM,max}$	Maximum PEM current
$\mathcal{L}$	Total number of IMPEC electrical loads to supply
MAT_{min}	Minimal Contactor Matrix
N_{Sol}	Number of possible reconfiguration solution of the contactor matrix
n_x	Number of x (see below to have the values)
θ	Organic solution
$\tilde{p}_l^c$	Power demand of the load "l" in the loading case "c"
W_S	Total weight of the system IMPEC
W_x	Weight of x (see below to have the values)
$z_{l,m}^c$	Connexion of the PEM "m" to the load "l" in the loading case "c"
Z	Reconfiguration solution

Possible values of the indice x:

PEM	Power Electronics Module
L	Inductance
C	Capacitor
hx	Heat exchanger
ct	Contactor
cha	Power center chassis
cp	Cold plate

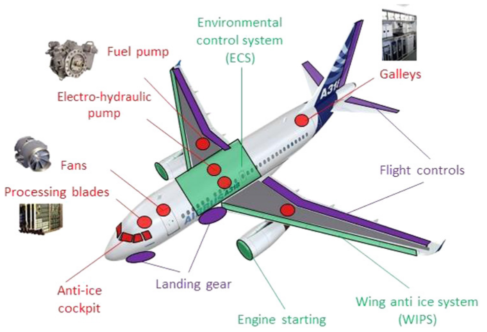

Fig. 2. Physical implementation of main power consuming systems on traditional aircraft.

On the other side, the Boeing 787 is a complete bleedless aircraft by supplying electrically: the ECS, the WIPS and the engine starting [6].

Today, the MEA is seen as a major axis of improvement for the aviation industry to achieve increasingly ambitious objectives: decrease of weight, rationalization of costs, reducing environmental impact, etc. In this frame, several research projects are today launched in order to progress on architecture and technology axis [10,11].

1.2. High demanding loads requiring power electronics in bleedless configuration

In terms of power demand, the bleedless aircraft configuration is the most challenging one. It is often said that the bleedless effect leads to multiply by 4 the electrical power generation [4]. For instance, the Boeing 787 comprises 4 generators of 250 kVA whereas a bigger aircraft such as the Airbus A380 "only" embeds 4 generators of 150 kVA.

The ECS is the main contributor of the power step change. The ECS electrification requires installing electrical air compressors consisting of permanent magnet synchronous motors driven by power electronics modules (i.e. inverter). The compressors can consume up to 100 kW during some operational cases. As the consequence, the bleedless effect will lead to a significant increase of the power amount transmitted by the power electronics modules (PEM).

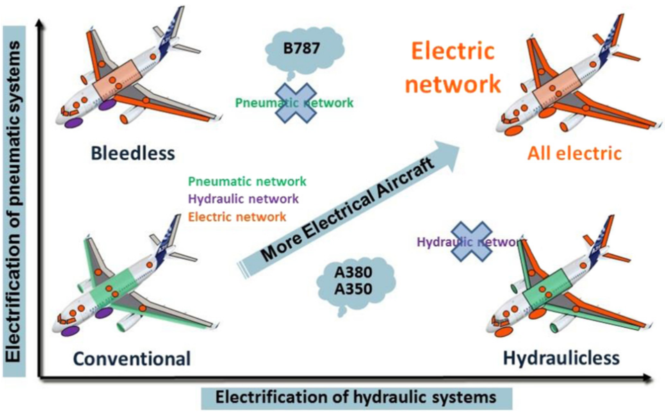

Fig. 3. The 2 axis of the more electrical aircraft (MEA).

1.3. Classical use of power electronics in aeronautics

On today aircraft, an electrical machine is supplied by a dedicated PEM often located close to the actuator. Depending on the voltage levels provided by the EPS, two structures appear (Fig. 4):

- When the load is allocated to an AC busbar (Fig. 4-A), a rectifying stage is required to create a local HVDC bus (+/−270 VDC).
- When HVDC busbars are provided by the EPS (Fig. 4-B), the rectifier stage is removed and the PEM is directly connected to a HVDC busbar.

These two structures where each load has its dedicated PEM have 3 major drawbacks:

- **Reliability aspect.** The PEM loss leads inevitably to the load loss. This aspects can have an impact on the availability/reliability of the aircraft function carried out by the load.
- **Cost aspect.** Each PEM is sized by its load. In Fig. 4 example, two different PEM sizes are required: 40 kW and 75 kW. This leads to an increase of the amount of equipment references also called *part numbers*. This list of equipment shall be as low as possible in order to increase standardization and reduce costs. Of course, it would be possible to have only one