ON-BOARD SYSTEM ARCHITECTURES FOR HYBRID/ALL-ELECTRIC REGIONAL AIRCRAFT

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Abstract

The need for a more environmentally friendly aircraft is driving the designer towards the aircraft electrification. In particular, new aircraft concepts with hybrid-electric and full electric propulsion system are currently proposed. The propulsion system electrification also entails novel requirements for the aircraft on-board systems. The present work is focused on the definition of an electrified on-board system architecture to be integrated with hybrid-electric or full electric aircraft. A small propeller driven regional aircraft is considered as reference for this study. Electrified environmental control system, ice protection system, actuation system are analyzed and preliminary designed. This has driven the electric system definition and sizing also considering possible synergies with the electrified propulsion system. Finally, the systems masses and their power requirements are analyzed together with new possible enhancements.

Keywords: More Electric Aircraft, All Electric Aircraft, Hybrid Electric Aircraft, Electric-Environmental Control System, High voltage electric system.

1. Introduction

Since the need for a greener aircraft with low environmental impact, the hybrid electric propulsion is having increasingly relevance in the aeronautical segment [1], [2], [3], [4] as a means to reduce the use of the thermal propulsion system, hence reducing the polluting emissions directly emitted by the aircraft. The hybrid electric propulsion is also a means to enhance the aircraft aerodynamics reducing its drag and the need of thrust. The wing tip propellers should reduce the induced lift drag as well as the tail propeller should reduce the fuselage drag [5]. New propulsive concepts have been developed with different level of electrification up to full electric propulsion [6] which relies only on battery system. The mass of the electric system of a full electric aircraft or those with a high electrification level is becoming a concern. To reduce cables and electric machines mass [7], these new propulsion systems usually adopt high voltage power supply [8].

These new propulsion architectures with their new technologies have some important effects on On-Board Systems (OBS) architecture as well. Usually, the OBS are strongly connected with the propulsion system in the standard aircraft because of their need of power supply of different types (i.e. mechanical and pneumatic) [9]. This is still true in some systems architectures of hybrid electric aircraft for which the OBS are supplied by the thermal engine and, sometime, by the battery system as well (see Figure 1).

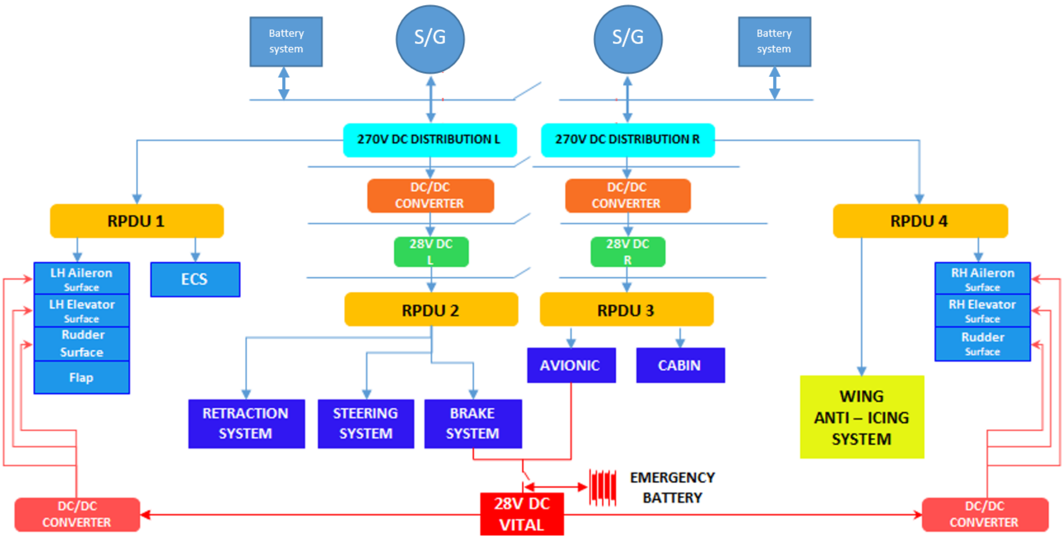

Figure 1 Example of architecture of Electric Power Generation and Distribution system for hybrid electric aircraft

For those configurations, the thermal engines are usually downsized and the electric motors, supplied by the battery systems, have to provide the remaining necessary thrust. Using such propulsive architecture, the OBS should be optimized to avoid the overload of the downsized thermal engine. To efficiently extract the power from the thermal engine, the bleedless technology should be considered. The use of the compressed air from engine compressors reduces the engine efficiency more than the same power extracted mechanically [10] [11]. This leads to the use of More Electric Aircraft (MEA) and All Electric Aircraft (AEA) architectures for the OBS.

Moreover, when the hybrid electric propulsion system has to provide the maximum thrust (e.g., during takeoff and climb) depending on its architecture, the OBS may be supplied by batteries. This is also the case of the full electric aircraft (see Figure 2) for which, the only way to provide power to the OBS is by means of batteries. Therefore, also for these propulsion architectures the use of use of MEA and AEA OBS architectures is necessary.

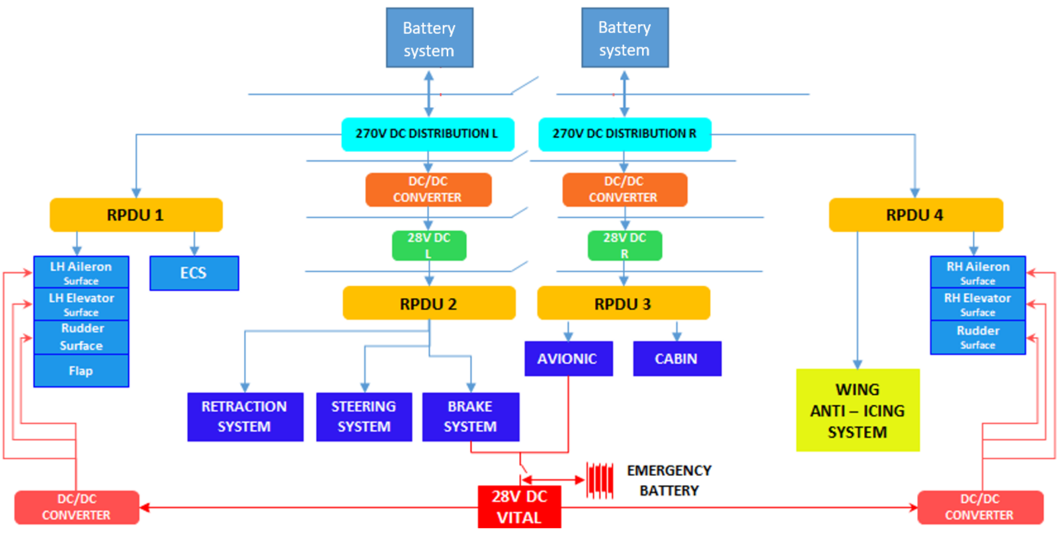

Figure 2 Example of architecture of Electric Power Generation and Distribution system for a full electric aircraft

It is worth noting that the electrification of the propulsion system leads to the electrification of the OBS. Moreover, since the OBS are supplied by downsized thermal engine and/or by battery system, their efficiency should be increased in order to reduce the power requirement [12] [13].

This paper deals with the definition of the more suitable OBS architecture according with the innovative and electrified propulsion system. The study is focused on a regional turboprop platform that could be considered the first aircraft class that can benefit from propulsion electrification. In particular, the hybrid-electric twin turboprop aircraft developed in the PROSIB (*PROpulsione e Sistemi IBridi per velivoli ad ala fissa e rotante* – Hybrid propulsion and systems for fixed and rotary wing aircraft) project is selected as test case.

The aircraft systems that are most affected by the necessary electrification are: the Electric Power and Generation System (EPGDS), the pneumatic system, the Environmental Control System (ECS), the Ice Protection System, the Flight Control System. For each of the above systems the following variables have been identified:

- EPGDS: voltage typology and level. Considering the amount of power required the increase in voltage is envisaged. For full electric propulsion aircraft, the use of direct current busses is provided to directly connect batteries and OBS.
- Pneumatic system, ECS and IPS: use of bleed air. In hybrid propulsion aircraft the use of bleed air is limited because of the smaller thermal engine. For full electric aircraft, the pneumatic system should be bleedless due to the absence of a thermal engine. The pneumatic power needed by ECS is provided through dedicated centrifugal compressors driven by electric motors (see Fig.2) [14], [15].
- FCS: use of electric actuators [16].
- Fuel System: reduced number of tanks up to its complete removal for full electric propulsion.
- APU: use and typology. The APU play an important role in hybrid propulsion aircraft. It is used both for batteries recharge and to supply power to electric motors during power demanding phases (i.e. take off, climb) [17]. For full electric propulsion, the APU can be replaced by auxiliary batteries.

After a brief description of the reference aircraft, the main important OBS are defined and sized. At the end of this section the global results are provided. Before conclusions, a further section is dedicated to the implementation of a MDO workflow for hybrid electric aircraft design within the AGILE4.0 research project as future enhancement of the present study.

2. Design of user systems for aircraft with electrified propulsion

The study is focused on the regional turboprop platform developed within the Italian national research program PROSIB (*PROpulsione e Sistemi IBridi per velivoli ad ala fissa e rotante* – Hybrid propulsion and systems for fixed and rotary wing aircraft). The hybrid aircraft mounts two gas turbine (GT) engines symmetrically located at the tip of the wing, and eight electric motor (EM) providing for the distributed propulsion (Figure 3). The thermal engines and the electric motors are connected together by means of electric motor/generators.

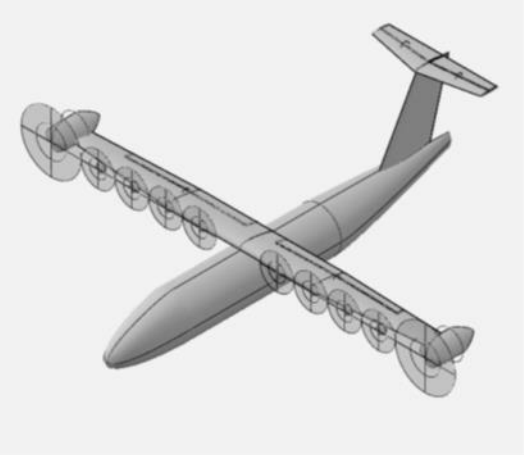

Figure 3: PROSIB Hybrid propulsion aircraft developed by University of Naples.

The main characteristics of the hybrid aircraft are reported in Table 1:

Table 1 Hybrid aircraft characteristic

Aircraft characteristic	
Number of passengers	40
Number of crew member	3
Power thermal engine (GT)	2008.2 kW
Number of thermal engine (GT)	2
Electric motor power (EM)	416 kW
Number of electric motor (EM)	8
Dimensions	
Wing surface	44.71 m^2
Wing span	24.57 m
Fuselage length	22.67 m
Fuselage diameter	2.865 m
Propeller diameter GT	3.93 m
Propeller diameter EM	1.37 m
Performance	
Mach cruise	0.4
Cruise altitude	6096 m
Ceiling OEI	4627 m
Ceiling AEO	7620 m
Take-off run	785 m
Landing run	978 m
Design masses	
MTOM	22455 kg
OEM	16598 kg
Maximum fuel capacity	2114 kg

All onboard systems are electrically powered to meet the all-electric aircraft (AEA) configuration. Figure 4 shows the general scheme of the system architecture used for this test case.

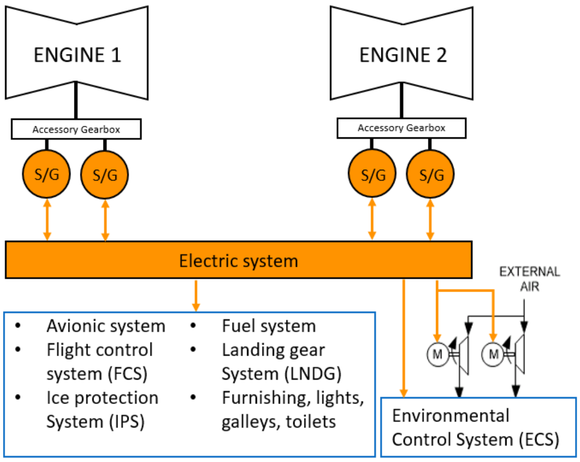

Figure 4 Onboard system scheme

The onboard systems which are affected by the hybrid-electric propulsion system are described below.

2.1 Ice Protection System (IPS)

For the test case it was decided to use Electro-Mechanical Expulsion Deicing System (EMEDS) for the wing and horizontal tail (Figure 5) in order to reduce the power required by the IPS. As an alternative of the power demanding electrothermal system, the EMEDS system uses electromechanical actuators installed on the leading edge of the surface to be de-iced. During the de-ice cycle, an electrical impulse is sent to the actuator, generating opposite electromagnetic fields that cause the shape to change abruptly. This change of shape is transmitted to the surface making it flex and vibrate at very high frequencies thus causing the detachment of the accumulated ice [1]. This system required only a small amount of the typical IPS system (i.e. electrothermal or aerothermal) and, above all, it does not require any bleed air from the propulsion system.

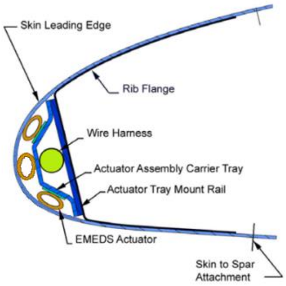

Figure 5 Electro-Mechanical Expulsion Deicing System [1]

Instead, small utilities (sensors, propellers, air intake and windshield) are protected from ice using the traditional electrothermal system. The electrical power required for the IPS system is shown in Table 2. The estimated mass of the EMEDS is 116.28 kg.

Table 2 IPS results

Surface	IPS type	Electric power [kW]
Wing + horizontal tail	EMEDS	0.25
Propeller (GT e EM)	electrothermal	9.05
Air intake	electrothermal	5.63
Sensors	electrothermal	2.2
Windshields	electrothermal	5.66
Total electric power [kW]		**22.79**

2.2 Environmental Control System (ECS)

In the AEA configuration, the system is equipped with dedicated electric compressors (e-ECS) to generate the pneumatic power. It is assumed that a two-wheel bootstrap air cycle machine (ACM) will be used (Figure 6). This type of ACM consists of the compressor and the turbine connected to a transmission shaft. Instead, the secondary flow fan receives mechanical power from a dedicated electric motor. For safety reason, the ACM is redundant.

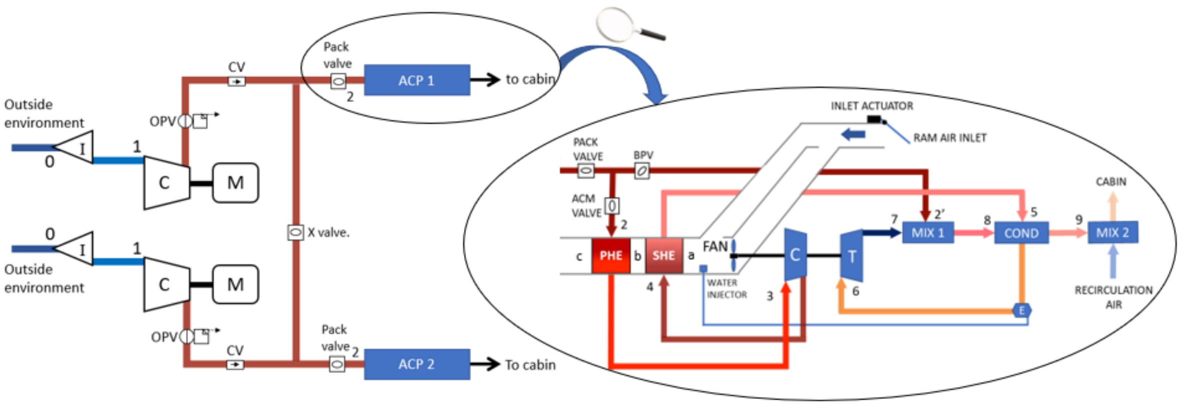

Figure 6 e-ECS schema

To evaluate the power budget of the e-ECS system it is necessary to consider the following sizing conditions:

- Case 1: hot day with maximum number of passengers and day flight at sea level;
- Case 2: cold day with minimum number of passengers and night flight at sea level;
- Case 3: hot day with the maximum number of passengers and day flight at the ceiling altitude;
- Case 4: cold day with minimum number of passengers and night flight at the ceiling altitude;

The overall results in terms of power budget and mass budget are presented in Table

Table 3 e-ECS results

	Case 1 hot day ISA+25 (ground)	Case 2 cold day ISA-35 (ground)	Case 3 hot day ISA+25 (FL250)	Case 4 cold day ISA-20 (FL250)
Total electric power [kW]	60.56	31.61	25	49.30
Total airflow [kg/s]	0.4572	0.3784	0.2048	0.3997
e-ECS mass [kg]	198			

The e-ECS is particularly suitable for hybrid electric / full electric aircraft since it does not need pneumatic power from engine compressors as for traditional ECS. The e-ECS is completely bleedless and more efficient than traditional system [10].

2.3 Flight Control System (FCS)

For the reference aircraft, a Fly-By-Wire architecture was chosen, therefore, the aircraft control is assigned to onboard computers that manage the inputs from the pilot and sensors and drive the mobile surfaces. Considering that the overall systems architecture is electrical and the additional mass of a complete hydraulic system, an electric actuation system is selected. Electromechanical actuators (EMA) with a power supply voltage of 270 V DC are used to operate the primary flight controls. The control surfaces identified for the reference aircraft are given in Table 4. Due to the presence of distributed propulsion, it has been chosen not to use the leading-edge slat.

Table 4 Control surfaces

	Aileron	Elevator	Rudder	Spoiler	Flap
Number of mobile surfaces	2	2	1	2	1
Actuator number (each surface)	2	2	3	1	2
Actuator type	EMA	EMA	EMA	EMA	e-PCU
Supply voltage	270 V DC	270 V DC	270 V DC	270 V DC	270 V DC

Table 5 shows the maximum power and weight for the single actuator for each mobile surface.

Table 5 Actuator power and mass

Surface	Actuator power [W]	Actuator mass [kg]
Aileron	1.57	12.04
Elevator	0.59	4.66
Rudder	3.37	11.91
Spoiler	1.10	5.91
Flaps	1.53	29.54

The mass of the single actuator has been statistically determined. In addition, it is necessary to consider the mass of the actuator cables and the kinematic lines of the flaps. The total mass of the FCS system is 445 kg.

2.4 Landing gear system

The landing gear is a system subjected to considerable mechanical stress. In this preliminary phase, the structure of the landing gear will not be designed in detail. Once again, the requirement that drives the system design is the all-electric configuration. It is assumed to use EMA with a power supply voltage of 270 V DC for retraction/extraction, braking and steering system. The structure of the landing gear is a tricycle with the main landing gear housed in the fuselage. The nose landing gear is equipped with a steering wheel to allow ground manoeuvres, however, only the main landing gear is equipped with a braking system. The electrical power required for the landing gear is shown in Table 6.

Table 6 landing gear power budget

	Retraction	Steering	Braking
Electric power [kW]	5.58	0.39	3.35

The weight of the landing gear has been statistically determined.

2.5 Other user systems

All other onboard systems, by their nature, are already supplied by electric power. For this study, they are not described but are considered for the design of the electrical system. In particular, the other onboard systems considered to evaluate the power budget and mass budget are:

- avionic system;
- fuel system;
- equipment & furnishing;
- fire protection system;
- light;
- oxygen;
- water/waste.

3. Electric Power Generation and Distribution System (EPGDS) and global results

The Electric Power Generation and Distribution System (EPGDS) is the essential system of the aircraft. Following the requirement of all-electric onboard system, the electrical system is the only one to supply and distributes the power. The electrical system must be sized on the power budget derived for all other onboard systems and must be able to provide the necessary power to different users depending on the phase of the mission profile. Due to the design requirement of all-electric systems, the required electrical power is high and therefore it is convenient to choose a primary generation with high voltage. This allows containing the weights, both for the equipment used to generate and to transform the electric power. A primary generation was chosen at 270 V DC. In addition, given the absence of an APU installed onboard, the electrical system has the additional task of allowing the start of thermal engines.
To size the main circuit, it is necessary to evaluate the maximum electrical power divided by supply voltage (Table 7).

Table 7 Electrical power budget

Voltage	Maximum electrical power [kW]
270 V DC	101.00
28 V DC	4.57

Being known the maximum power required by the bus at 270 V DC and the bus at 28 V DC you can calculate the weight of generators and converters. It has been chosen to use two permanent magnet generators per thermal engine. Table 8 shows the results of the sizing of generators and converters.

Table 8 EPS result - generator and converter

Electric machines	Numbers	Mass [kg]	Power [kW]
Generator, 270 V DC PM	4	24.53	33.61
DC – DC converter (270V-to-28V)	3	4.56	2.28

A further element of the electrical system that must be dimensioned is the energy storage system necessary to power the onboard systems in emergency condition and during the phases of the mission profile where the thermal engines are switched off (i.e. parking, pre-flight check). The results of the storage system are given in Table 9.

Table 9 Energy storage system

Battery packs	
Technology	Lithium-ion battery
Number of battery pack	2
Voltage	270 V DC
Capacity (each pack) [kWh]	2.5
Mass (each pack) [kg]	31.25

The length of electrical cables needed for the electrical system has been estimated. This estimate takes into account: the power of the generators, type of primary generation and geometry of the aircraft [7]. The main results are shown in Table 10.

Table 10 Electric cables estimation

Cables	
Total length [km]	28.417
Mean diameter [mm]	0.25
Total mass [kg]	54.74

Table *11* are reported the masses of the electrical system divided between generation and distribution:

Table 11 electric system results

Electric system masses [kg]	
Generation	94.14
Distribution	270.68
Total system mass	**368.83**

3.1 Global results

Table 12 shows the masses of all onboard systems.

Table 12 Onboard systems mass breakdown

Onboard systems mass breakdown [kg]	
Avionic systems	358
Flight control system -ATA 27	445
Ice protection system - ATA 30	116
Environmental control system - ATA 21	198
Fuel system - ATA 28	41
Landing gear system - ATA 32	803
Equipment & Furnishing - ATA 25	1922
Fire protection system - ATA 26	27
Lights - ATA 33	101

Oxygen - ATA 35	35
Water/Waste - ATA 38	57
Electric system - ATA 24	369
Total system mass	**4471**

Figure 7 shows the total mechanical power needed to power the onboard systems.

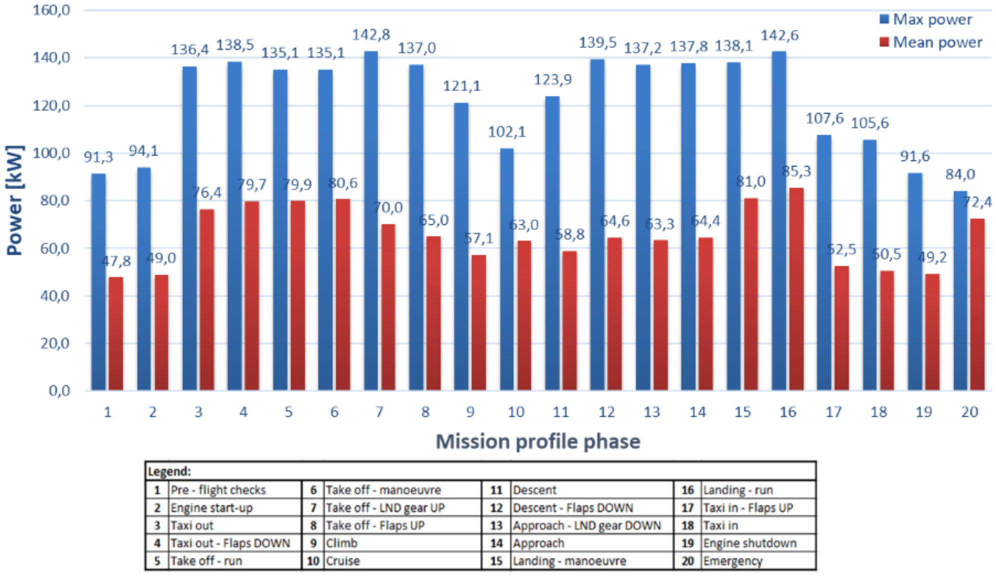

Figure 7 Mechanical power offtake

As can be seen, both the maximum and average mechanical power are reported. The maximum power is used for sizing, instead, the average power is useful to calculate the consumption of onboard systems.

4. Further improvement

The results presented in the previous sections are obtained starting from the results of the aircraft preliminary design and performing the OBS sizing. However, to fully understand the effect of OBS sizing and design choices the aircraft and the propulsion system should be redesign according with the OBS results. In the framework of AGILE4.0 project (Towards cyber-physical collaborative aircraft development) [18] a specific workflow is developing to integrate aircraft, propulsion and OBS design for hybrid electric aircraft (see Figure 8).

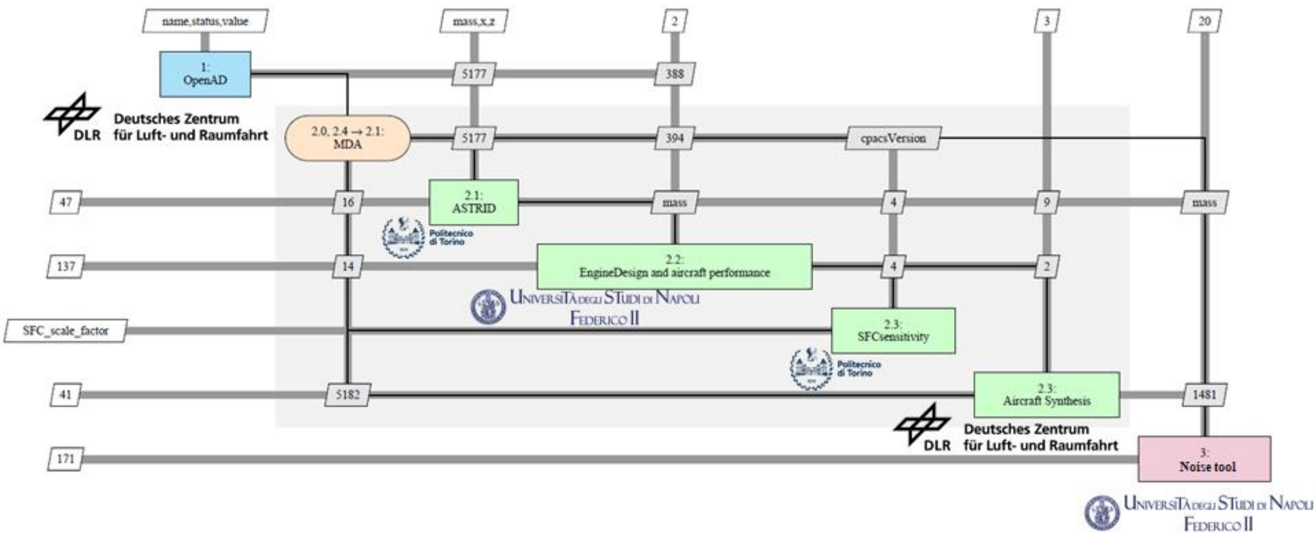

Figure 8 Future design workflow for aircraft, propulsion and OBS integrated design for hybrid electric aircraft

By means of this design workflow is possible to take into account of:

- OBS mass and power variation for different systems technologies.
- Effect on engine power and mass, in particular when the thermal engine has to supply power to the OBS during some or all mission phases.
- Influence on thermal engine efficiency of the power offtakes due to OBS and electric motors. The workflow is sensible to different quantity and typology of power offtakes for each OBS technology.
- Recalculation of aircraft performance and fuel consumption considering the new engine efficiency in all mission profile phases.
- Redesign of the aircraft after changes of OBS, fuel and engine mass. The airframe mass takes into account for concentrated load due to distribute propulsion and tip engines.

Finally, compared with the activities carried out in PROSIB project, the future workflow will allow for Multi-Disciplinary Optimization (MDO) problem. In this way, the MDO workflow will be used to define the best electrification level for both propulsion system and OBS according to the aircraft typical mission.

5. Conclusions

The selection of an OBS architecture for a hybrid electric regional aircraft is carried out in this paper. Specific OBS technologies is selected in order to better integrate the OBS with the new propulsion system. The bleedless technology is essential for full electric aircraft and beneficial for hybrid electric aircraft. This technology allows for the removal of bleed system that could not be present on full electric propulsion and could overload the downsized thermal engine of the hybrid electric propulsion. Above all, the OBS technology that allow for bleedless architectures are the e-ECS and the electrified IPS. Moreover, a general electrification of the OBS is valuable to increase OBS efficiency and to increase the compatibility and integration with the propulsion system. The removal of the hydraulic users and generation system is beneficial to reduce OBS mass and complexity avoiding the need for an additional power source.

Finally, a future enhancement of the present study is given by the integrated design of OBS, propulsion system and airframe. This will allow to better understand the influence of the different OBS technologies on engine and on the whole aircraft in order to define the optimal OBS architecture.

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7. Copyright Statement

8. Acknowledgments

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- National research PROSIB (PROpulsione e Sistemi IBridi per velivoli ad ala fissa e rotante – Hybrid propulsion and systems for fixed and rotary wing aircraft)
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