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POWER MANAGEMENT AND FAULT ANALYSIS HYBRID PROPULSION AIRCRAFT SYSTEM

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Abstract

Power Management is the central process for an optimal management of hybrid-electric aircraft distributed propulsion system.

A Power Management system deals with Loads Management and Source Management in a coordinated mode. Indeed, it controls:

- The electrical loads which can at least be cut off or reconnected (on/off). There are also loads (EM) that are continuously regulated.
- The generators that can work above their nominal power for a short time. Such an overload capacity can be managed.
- The energy flow distribution that splits the power demand of a set of loads on several sources if parallel sources are available.
- The configuration of the electrical network that can be properly managed (i.e., which generator is connected to which sub-network or bus bar).
- The storage devices that can take or provide prescribed power, when available.
- The thermal overload management according to the flight phases.

The optimization of the energy system strictly depends on the complexity and dimension of the distribution system and on the generators system. Thus, this optimization process requires sufficient redundancy to undersize relevant failure cases and the power management enables the delivery of the required power to sustain safe operation. In normal operation, the power source management can be used to select the most efficient available energy source in order to minimize the environmental impact of the aircraft.
This paper will present the propulsion system's control architecture defining the logic to manage the propulsion aircraft system. Such algorithms shall ensure peak-load reduction, optimal energy use and the integration of all power sources with the power delivery from thermal engines.

The definition of the overall power management shall also integrate additional aspects, such as the criticality and hazardous consequences of potential failures in the electrical architecture system. This paper will also present the fail-safe strategies adopted to ensure safety and flightworthiness of the aircraft and eliminate hazardous scenarios.

Last, the power management strategies, which constitute the interface between the power control system and the aircraft design and missions, will be detailed. Such strategies shall ensure an optimal use of the different energy sources over the whole mission and of additional energy storages for emergency situations.

Since peak-power capability and cooling authority are tightly interrelated, interaction exists with thermal management. This interaction enables the potential use of waste heat recovery in terms of power management and overall aircraft efficiency.

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1.0 - INTRODUCTION

The social awareness for climate change call for a more environment-friendly aircraft putting significant emphasis on the study of disruptive greener aircraft concepts and viable alternatives for gas turbine powered aircraft [1][2]. One of the options, hybrid-electric propulsion is currently being investigated for its merits to reduce fuel consumption within the European project IMOTHEP, an acronym for "*Investigation and Maturation Of Technologies for Hybrid-Electric Propulsion*".
Hybrid-electric power-trains for aviation are gaining more and more interest in research and industry, for they feature of greater flexibility compared to more widespread propulsive solutions, and are henceforth capable of meeting various design needs. Considering an electric component in a hybrid-electric power-train allows to mitigate the pollutant emissions for part of the mission with respect to a conventionally propelled aircraft.
In the present study, a generic approach is pursued to identify the specific involved power management challenges and to provide a methodology for analysing the fault tolerance in different critical scenario.
Within this framework, we limit ourselves to study the power management system of turboelectric propulsion drive trains for a conservative Short-to-Medium Range aircraft configuration (SMR-con).
The document provides the top-level power management requirements for the preliminary design phase of the IMOTHEP project. The requirements are derived from current technology considering next generation products.

The advantages of Hybrid Electric Propulsion aircraft are:

- Electrical systems usually have a higher efficiency.
- Simultaneous usage can be exploited since power is distributed through one and not three physical domains.
- Power just needs to be produced when it is used and not throughout the flight, thus resulting in higher energy efficiency.

A typical power management function shall ensure that the generated power at any flight instant is equal to the consumed power and the minimum required for that flight instant.
The term load management (LM) is often used for aircraft since those functions can only control electrical loads and not generators.
The term source management (SM) can be used if power sources are available and controllable. Those functions often control multiple sources so that optimal energy efficiency of the entire system is reached.

A Power Management System (PMS) controls the LM and SM in a coordinate mode managing:

- The electrical loads: can at least be cut off or reconnected (on/off). There are also loads (EM) that are regulated continuously.
- The motors: can operate above their nominal power for a short time. This overload capacity can be managed.
- The energy distribution flow: which can split the power demand of a set of loads on several sources if parallel sources are available.
- The configuration of the power network: can be managed which generator is connected to which sub-network or bus.

Storage devices are also considered. . They can take or provide prescribed power, if available on the network. The optimization of energy system strictly depends on the complexity and dimension of the distribution and generators system.

1.1 TOP LEVEL PMS REQUIREMENTS & RECOMMENDATIONS

The PMS shall be an electronic control system that is designed to integrate, control, and monitor all the electrical machines, distributed throughout the aircraft propulsion and generating plants, from a single control position.
The main purpose of the PMS will be to:

- Control power generation in normal situations and managing degraded configurations of the controlled plants
- Manage electrical generation and AC and DC busbars feeders and bus ties
- Integrate the EM and AC/DC DC/AC converter local controllers
- Control and monitor all auxiliaries dedicated to propulsion and generation systems
- Control and monitor damage situations of aircraft power plant

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- Perform all control and monitoring functions in safe manner
- Overall, the PMS shall be designed with the following levels of access.

The PMS architecture will be defined to provide access to overall control functions, or to some of its functional sub-systems, through a dedicated interface. The number and location of PMS electronic system will be defined considering the generation and propulsion plant layout that will be established by the aircraft framer.

The PM system will be designed to allow full operation of propulsion and generators machineries and related auxiliaries from the pilot control positions.

The distributed system architecture will be organized on a two-level structure:

- **Machinery controllers.** This lower level will provide the hardware for interfacing field sensors and actuators, front-end intelligence for all interfaced systems/machinery for the local control and monitoring of the interfaced machineries. This level is normally demanded at local controller as the EEC (Electronic Engine Controller) for the gas turbine and at the electronics control for the AC/DC converter and for the Electrical Motor Unit (EMU).
- **PMS controller station.** This higher supervision level will be configured with the hardware for interfacing the machineries controller plus other plant common field sensors and actuators not interfaced to the local controllers. The allocated intelligence will be that for the overall coordination of the power generation and thrust system. Interface capabilities with avionics and cockpit system will be designed to have a complete visibility of all connected PMS related elements.

The communication among the PMS controller and the various local controllers will be provided through redundant network. Redundant dedicated interface will be provided to the avionics electronics.

The PMS shall provide continuous control and surveillance of the aircraft power plant machineries and the main parameters of the controllers.

Diagnostic capability shall also be provided such that the Built In Test Equipment (BITE) will run at the power up of the system and in run time (CBIT). The results of the diagnostics will be recorded and send to avionics system.

1.2 - Hierarchy of Control & Control Modes

In normal conditions, while all the systems are running with the designed efficiency, all automated and remote controlled, the systems shall be operated from PMS hardware.

PMS will enable control and monitoring of the plant machineries in the following control modes:

1. Automatic operation: at PMS controller, after pre-setting activities by the pilot, the system will be ready for automatic operations. The station will start / control / stop the different functions and elements in a pre-programmed sequence.
2. Remote operation open loop: at PMS Controller, a function will be carried out by the pilot in a step-by-step manner; the pilot will be in charge to activate from the console each element separately.

Operation hierarchy order will be from 2 to 1. The control system will be designed in such a way that degraded operation modes will not be interfered by higher operation modes.

Control modes which are lower in the hierarchy will be able to take over the control from the modes above them.

It shall be possible to simultaneously perform different procedures and actions in different modes of operation.

1.2.1 - PMS Controlled Machineries

The main Power Management System package sub-systems monitored /controlled by the PMS will be in SMR case:

1. 2 Gas Turbine Gen Set
2. 24 EMU
3. 24 DC/AC converters
4. 4 Front Bus Breaker
5. 4 Back Bus Breaker
6. 4 A/C generators
7. 4 AC / DC converter
8. 2 set of Cooling system auxiliaries

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1.2.2 - PMS System Architecture

PM System architecture will be of the type shown in the following figure:

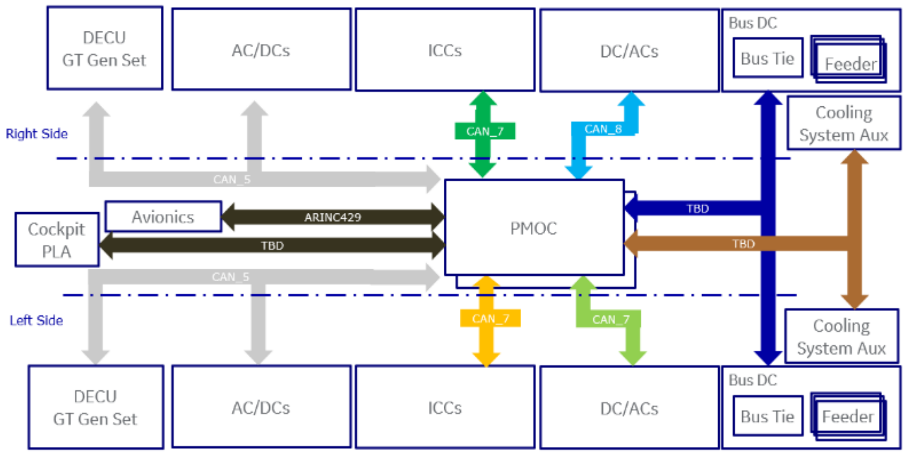

Figure 1 : PMS Architecture

1.2.4 - PMS main functions

PMS will be developed to perform the following functions:

- start / stop sequences management
- normal shut-down sequences in safe mode
- blackout prevention
- max power available calculation
- asymmetric load sharing between generators
- load demand management
- optimization of Power system performance
- safety functions for afore mentioned items

The PMS shall be developed to manage the power plant to prevent unnecessary generator trip and to meet the Aircraft thrust demand.

1.1.4 - PMS Interface to Power Plant System

The PMS controller will interface the following external machinery and relevant controllers:

- HVMSB (High Voltage Main Switchboard)
- Avionics System
- Electric Propulsion Units
- EPU Breakers System
- Generators Controllers and Gas Turbine
- AC/DC Converters
- Cooling System
- On board Power Supply System external to propulsion system
- Battery monitor systems

All hardwired signals to / from the power plant machinery and auxiliaries will be collected in the PMS Interface Control Documents, in format of I/O list, populated with all signals' characteristics and operational requirements (such as thresholds, interventions, delay to intervention, etc.).

The PMS system will be configured with the H/W necessary to interface the external systems for typical channels as:

- Analogue input / Output signals (strain gage, thermo-resistors, thermocouple)
- Digital input / Output signals (0-28Vdc, free voltage contacts)
- Serial link RS422 – RS485

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- Ethernet link
- Can Bus link (ARINC 825)
- ARINC 429

2.0 Description of hybrid model and working hypothesis

The main goals of the propulsion system model are:

- To reproduce the reference architecture and simulate the expected functionalities.
- Test the identified functionalities in different failures scenario and verified the correctness of the power flow redistribution.
- To analyze the propulsion system dynamic response in the different flight phases and the corresponding demand of thrust
- To analyze the overall failures time response of propulsion system in the different phases of flight envelope
- To investigate the overall power propulsion system efficiency

From the high-level power management system requirements and form control system level requirements, a high-level system blocks according to a model-based design approach is inferred. The main functionalities are grouped as follows:

1. **Stimulus generator composed by a supervisor and a simplified aircraft model**: the main objective of the stimulus generator is to create the failures scenario of interest and feed all the models with available raw data. Based on this data, the main dynamics of the aircraft are estimated.
2. **EPUs power train**: the power train “block” shall be able to emulate the behavior of the reference single EPU power train architecture [1].
3. **BUS breakers management and power redistribution logic**: the bus “block” shall be able to simulate the classic behavior of an electrical transmission line using electrical system modelling buses and to act according to a power flow redistribution logic.
4. **Power generation**: the power generation “block” shall be able to emulate the behavior of the loop between the turbine and generators – which are the main power sources.
5. **Power management system**: the power management system is the main functionality of the model and shall be able to correctly generate commands to all the other systems to adequately balance the overall power flow.

It is notable to observe that:

- The commands of the PMS to the EPUs power train block have the aim of mapping the overall thrust over the various flight phases.
- The commands of the PMS to BUS breakers management and power redistribution logic block have the aim of overall power generation and power load connection in a proper mode according to failure conditions.
- The commands of the PMS to the power generation block have the aim of voltage regulation and blackout prevention.

Finally, from a more general point of view, the main goals of the implemented PMS model is to analyze the high-level behavior of the PMS in different fault scenario.
All the model was implemented following a control-oriented approach using “MATLAB & Simulink” toolchain.

2.1.1 – EPU’s Model

In the EPU model, the following main subsystems are considered:

- Since a wide variety of models are available and since each of it depends on several electric characteristics, the electrical motor is simply modeled with a first-order lag and controlled by a classic PID. The main output is the required power shaft which fed the PMS and the fan / aircraft model.
- The inverter model is implemented only considering the EPU’s power which is the feedback generated by the PMS and considering the front bus voltage. Moreover, it was implemented also the two main protection function: the minimum voltage protection and the crowbar one.

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In such a way, the model of a single EPU is controlled only using the power flow directly from the PMS.
However, a more details EPU model will be consider (following [1]), in which also a fan model which correspond to the load on the electrical motor will be present.
Currently, only a simplified fan model is considered, which includes the thrust estimation model based on the ~~classic~~ fundamental theory of the propeller. It describes the relation between the aerodynamic conditions of aircraft and the distribution of forces on the propeller with the following fundamental equations [4]:

$$T = n_b \int_0^R dT = n_b \int_0^{D/2} dT = \rho n^2 D^4 C_T(\beta, \gamma) \tag{1}$$

$$P = n_b \int_0^R dP = n_b \int_0^{D/2} dP = \rho n^3 D^5 C_P(\beta, \gamma) \tag{2}$$

Where n_b is the number of blades, n is the rotational speed of the propeller in RPM, γ is the advance ratio, D is the propeller's diameter, β is the reference keying and C_T and C_P are the thrust and power coefficient function of β and γ. From these equations, it is possible to derive the classic Renard's formula:

$$T = C_T \rho n^2 D^4 \tag{3}$$

$$P = C_P \rho n^3 D^5 \tag{4}$$

In this model, a more simplified formula was used:

$$T = K_T \rho n^2 \tag{5}$$

$$P = K_P \rho n^3 \tag{6}$$

where K_T and K_P are adjustable parameters use to estimate power and thrust of the propeller based on the available data throughout flight envelope.
It is important to observe that the described functions have been implemented with some simplifying assumptions:

- It is present a control of the bus between the inverter and the electrical machine.
- The considered dynamics response of each model is not based on any properly real estimation due to data unavailability but deduced from the expected overall behaviour of an EPU system.

Each EPU also includes the safety functions necessary to ensure a correct operational life to the motor and to the power converter and manage the breaker that separate the inverter form the EM in case of fail.

2.1.2 – Generator Model

The instantaneous terminal voltage v of any winding is in the form:

$$v = \pm \sum Ri + \sum \dot{\lambda} \tag{7}$$

Where λ is the flux linkage, R is the winding resistance, and i is the current, with positive direction of stator currents flowing out of the generator terminals.
For the purposes of our analysis, this model was simplified considering a Taylor approximation of the two current and mechanical mesh to obtain an equivalent and consistent model to a classic DC machine with permanent magnets. The simplified model equations are the following one:

$$T_m = K_a \omega_T \tag{8}$$

$$v = K_v \omega_T \sin(\theta) \tag{9}$$

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$$\theta = \langle \omega t | \omega t - 2/3\pi | \omega t - 4/3\pi \rangle \quad (10)$$

$$\omega = K_p \omega_T \quad (11)$$

$$E = i_r K_i K_v \omega_T \eta_g \quad (12)$$

$$Q = i_r K_i \omega_T \eta_q \quad (13)$$

Where T_m is the mechanical torque, E is the electrical power generated, Q is the thermal power, θ is the classic phase displacement of a three-phase generator, ω is the angular frequency and ω_T the turbine shaft speed in RPM.
Instead, the droop or adjustable parameter K_p, K_v, K_i are used to modulate the dynamic of the generators consistently with the flight envelop. Finally, the η_g and η_q are the efficiencies of the generators.

2.1.3 – Turbine Model

It was implemented the simplest form of linear model based on a first-order lag where the torque on the engine shaft is cast as a function of speed and fuel flow. The torque generated on the generator rotor can be expressed as[5][6]:

$$Q = f(w_{fe}, N_{set}) \quad (14)$$

Expanding this function using a Taylor Series, neglecting higher order terms and considering the rotor shaft speed dynamic as an integrator we obtain the simple first-order lag relating fuel flow and speed in the form:

$$\frac{\Delta N}{\Delta w_{fe}} = \frac{K_e}{(1 + \tau_e s)} \quad (15)$$

In the equation above, K_e is commonly referred to as the engine gain and τ_e as the engine time constant. K_e is a measure of the sensitivity of the engine, in terms of shaft speed, to changes in fuel flow and it has a low value at high power and increases as power is reduced to idle. The engine speed response is dominated by the rotor inertia which must be accelerated by the excess torque generated by the turbine above that required by the compressor until a new steady state is reached and the torques are again in balance. A time constant τ_e of the order 0.3–0.5s is typical for the high-power condition. Moreover, the fuel metering valve can be represented by a linear lag. To also consider the dynamic of the combustion chamber it is possible to consider another first order lag τ_c. But being very small compared to the primary engine time constant τ_e, it was neglected. This formulation provides the response of the rotor to changes in fuel flow without considering the dynamic response of combustion chamber pressure. The model can readily be extended to include a pressure term by recognizing the possible contribution of combustion pressure to the generation of engine torque and the balance of flows into and out of the combustion chamber.
As the last dynamics of the free-turbine necessary to obtain a sufficiently representative control-oriented model, that of the mechanical mesh was considered. For this purpose, the gas generator was considered as a torque "provider" which act on the shaft and puts the mechanical load in motion.
The mechanical shaft dynamics – or the load dynamics - considers at the same time the of moment of inertia and friction or bumping coefficient of generators and turbine. Again, a simple first order transfer function is used to represents the mechanical dynamics and it is defined as follow:

$$\frac{\Delta \omega}{\Delta T} = \frac{1}{(B + Js)} \quad (16)$$

Where J and B are the equivalent moment of the inertia and the equivalent friction coefficient respectively.
Instead, to consider the gas generator as a gas torque producer at the power turbine, in general it is necessary to consider two contributions to the overall dynamics: the fast response resulting from the change in fuel flow and the slow one which follows as gas generator speed changes to the new steady-state condition. This dynamic can be reduced to a gain and a lead term described by the following transfer function:

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$$\frac{\Delta q}{\Delta w_{fe}} = \left[\frac{q_f}{K_e} + q_s\right]\left(1 + \frac{\tau_e}{\left(1 + K_e q_s/q_f\right)}\right) \quad \textbf{(17)}$$

Which can be simplified as follows: $K_q(1+\tau_q)$ where $K_q = q_f/K_e + q_s$ and $\tau_q = \tau_e/(1+K_e q_s/q_f)$, in which q_f, q_s are, respectively, the required speed and the fuel consumption.

The chosen control architecture is a classic cascade control. The first internal loop controller, the so-called speed governor, is a classic PI able to track the gas generator speed reference provide by the external loop and manage the FMU dynamics in series with the engine one. Instead, the second external loop is the so-called power governor, which considering the speed reference in rpm defined by the PMS, to control the shaft dynamics and so the torque load coming from the generators. It is important to observe that, a more accurate model should also consider a speed selection logic based on the variation of aerodynamics loads and acceleration and deceleration limits to provide a realistic response of the required fuel flow dynamic.

Moreover, a simple overspeed and under speed protection logic is implemented. It is a state flow machine which can detect and over-/under-speed condition and accordingly change the speed limit giving rise to the under-/over turbine speed. A more accurate model should consider the closing and the opening of the fuel metering unit valve.

2.1.4 - Controlled AC/DC (Rectifier) Model

The model of the rectifier is based on the single-phase bridge C-R-Load configuration and the control logic is like the linear firing control strategy [8].

The diode bridge rectifier with capacitance-resistance load is show in following fig. 2:

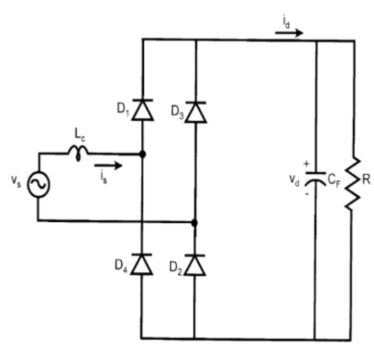

Figure 2 - Rectifier electrical scheme

The capacitor C_F filters the rectifier voltage to make the DC output voltage smooth. The equivalent R represents the load. The DC voltage may be used for a voltage-fed inverter or DC-to-DC converter. The capacitor v_d behaves as a back electromotive force of the rectifier. The capacitor will charge with a pulse current every half-cycle, when $v_d < v_s$ near peak voltage V_m, and the current becomes limited by the line inductance L_c. The capacitor then discharges exponentially with the load constant R. The load current is always proportional to the capacitor voltage. The discontinuous load current pulse causes pulsating line current. It is important to note that the initial charging of the capacitor should be done through a series resistor. Otherwise, the diodes will be overloaded with large in-rush current. The ripple in the capacitor voltage will be reduced with higher capacitance value, causing narrow current pulses, but the pulses will widen with higher line inductance.

An approximate analysis of the converter operation can be made if the ripple in the capacitor voltage is neglected, that is, the capacitor size is very large. With large energy storage, the load current will be smooth, although the capacitor charging is pulsating. The capacitor will start charging at angle θ_1 when:

$$V_m \sin(\theta_1) = V_d \quad \textbf{(18)}$$

Where $v_d = V_d$. During conduction, the equation for charging current i_d is given as:

$$L_c \frac{di_d}{dt} = V_m \sin(\omega t) - V_d \quad \textbf{(19)}$$

Which can be expressed as:

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$$i_d = \frac{1}{\omega L_c}\int_{\theta_1}^{\theta}(V_m \sin(\omega t) - V_d)d\omega t \quad (20)$$

The current will reach the peak value at angle θ_2 when $V_d = v_s$ again.
For the discontinuous conduction $i_d = 0$ at $\omega t = \theta_3$ from which it is obtained the average current I_d:

$$0 = \frac{1}{\omega L_c}\int_{\theta_1}^{\theta}(V_m \sin(\omega t) - V_d)d\omega t \rightarrow I_d = \frac{1}{\pi}\int_{\theta_1}^{\theta_3} i_d d\omega t \quad (21)$$

The previous equations can be combined to derive relation between the current I_d and the voltage V_d. It is possible to show that with higher load current I_d, the level V_d will be adjusted so that the average capacitor charging current is the same as I_d.
The presence of the capacitor also causes the voltage V_d on the load to follow the different trend of the theoretical rectified voltage. When the voltage on the capacitor is greater than the voltage V_m, all the diodes are in the lock state and the capacitor remains disconnected from the power supply line. Therefore, the trend of V_d will be that typical of transient of an RC circuit. The higher the RC time constant, the lower the ripple of the load voltage.
Based on these theoretical considerations for each phase of the rectifier a simplified model is implemented. Indeed, the model emulates the controlled rectifier emulate that of and RC-circuit, posing the main assumptions to have L_c equal to zero. It was considered also the circuit loss and the diode loss.
The function of a controller is to control the firing angle α of a converter symmetrically in response to a demand of output DC voltage or current. The simplest controller is the so call linear firing angle control method applied for each of the single-phase bridge convert. In that case, the implemented control function works in a similar way to this classic control technique. The main difference is related to the way in which the firing angle is generated. Namely, it is a simplified version of the original one in which the firing angle control is generated by the crossover point of control voltage V_c and a cosine wave - which in our case corresponds to one of the input generators three phase request – at every half-cycles as:

$$\cos(\alpha) = \frac{V_c}{V_a} \quad (22)$$

Where V_a is the peak value of the cosine wave. From this last equation it is derived the following linear relation:

$$V_d = \frac{V_{d0}}{V_p}V_c = KV_c \quad (23)$$

In this way, the converter looks like a switching-mode linear amplifier.
For the purposes of our simplifying analysis, a simpler control logic is implemented, preserving the macroscopic behavior of the logic described above. The main control mechanism is based on the comparison of the V_d generated and the three-phase input voltage of the generators. A command signal fed each phase of the rectifier which is engender based on the requested current and reference voltage and it works analogously to a gain which modulate the amplitude of the three-phase input voltage. When the V_d and the modulated voltage are equal, the desired voltage value in steady state conditions has been reached, namely the desired value of the V_d which fed bus and the EPUs inverters.

2.1.5 – Back Bus and Front Bus Model

The bus line design is based on the classic model of electric transmission for power system. The considered concentrated parameters are:

- Series resistance R
- Series inductance L
- Series capacitance C

Thus R, L, and C are also referred to as resistance, inductance, and capacitance per unit length. In the metric system we use ohms per meter [Ω /m], Henries per meter [H/m], and Farads per meter [F/m], respectively. The values of R, L, and C are affected by the geometry of the transmission line and by the electrical properties of the dielectrics and conductors. R and C are almost entirely due to the properties of the dielectric and R is due to loss in the metal more

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than anything else. L is mostly a function of geometry, as most materials used with transmission lines have μ_r = 1. In most transmission lines the effects due to L and C tend to dominate because of the relatively low series resistance and conductance. The propagation characteristics of the line are described by its loss-free, or lossless, equivalent line, although in practice some information about R is necessary to determine actual power losses.
For the purposes of our analysis the propagation characteristics are not considered.
These three fundamental parameters are estimated using the available data.
Assuming the cable used for back bus and front bus have the following geometrical and electrical characteristics derived by the "*Glenair Turboflex ultra-flexible power distribution cable*".
It is possible to estimate the resistance of the cable per unit length using the following empirical approximated formula: $R = \frac{\rho l}{A}$ where ρ is the conductor resistivity at a given temperature, l is the bus length, A is the bus cross-section area.
For the self-inductance it was used the following empirical approximated formula:

$$L = [4.6060 \log\left(4\frac{l}{d}\right) - 1 + \frac{\mu_r}{4} + (\frac{d}{2l})] \quad \textbf{(24)}$$

Derived from the more complete following one:

$$L = 2l\left\{ln\left[\left(\frac{2l}{d}\right)\left(1 + \sqrt{1 + \left(\frac{d}{l}\right)^2}\right)\right] - \left(\sqrt{1 + \left(\frac{d}{l}\right)^2}\right) + \frac{\mu_r}{4} + \left(\frac{d}{2l}\right)\right\} \quad \textbf{(25)}$$

Where l is the length of bus cable, d is the diameter and μ_r is the permeability.
For the capacitance the following empirical formula is used:

$$C = 2K_0K_r(\frac{d\pi l}{D - d_r}) \quad \textbf{(26)}$$

Where K_0 is vacuum permittivity, K_r tubular capacity, l is the length of bus, d is the diameter and D is the distance between two conductors.
In this way Power Management Switching logic for the bus architecture according to the Onera's reference one is obtained. Overall, from the interconnection of the front bus and back bus model it is obtained the power distribution logic model, whose main function are:

1. to manage and to react to any fault condition.
2. to correctly redistribute the flow of power to balancing it accordingly to the fault scenario, generating the adequate profile of the requested current and power to the generators.

2.1.6 – Battery's Model

For the regional radical architecture, the model of battery is implemented.

Thevenin-based electrical models and impedance-based electrical models are two main categories of electrical models for batteries. It is possible to count on a trustworthy model to replace the battery with something that behaves like a battery, such as an equivalent circuit model. An equivalent circuit model is the most straightforward and conventional method for characterization of the dynamic behaviour of a battery [7].

Based on the application characteristics of the PMS, the lumped parameter equivalent circuit models with circuit elements such as resistance and capacitance as the core have unique advantages in structure and precision.

The series resistance R_s shows internal DC resistance. This resistance is responsible for the immediate voltage decrease when a current is applied to the battery cell and accounts for contact resistance among parts such as electrode material, the diaphragm resistance, the electrolyte. A DC voltage source or controlled voltage source demonstrates the model open circuit voltage of a battery cell. Note that this voltage is dependent on the state of the charge (or SOC) and it can represent also the power of the battery.

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To determine the transient response of terminal voltage, two RC parallel networks were employed. The prime RC network (R_1 and C_1) demonstrated the small-time constant of the battery cell feedback and was employed to model the double layer capacitance and the charge transfer procedures. The secondary RC network (R_2 and C_2) demonstrated the lengthy-time constant of the battery cell feedback and was employed to model the diffusion procedures. These parameters generally are dependent on current, SOC, and temperature. By changing the number of the considered RC networks a battery equivalent circuit model of different orders can be constructed.

Current and initial SOC were considered as inputs to the model. Capacity was considered as function of current. A lookup table was employed to determine the effect of the capacity of the battery cell. The following equation was used to calculate the SOC:

$$SOC = E = SOC_0 - \int_0^t \frac{I_b}{C_c} dt \qquad \textbf{(27)}$$

Where C_c is capacity, I_b is the current and SOC_0 is the initial SOC.

The Thevenin model does not consider the case where the battery V_{ctrl} varies with SOC and temperature T. It can only represent the transient response of the battery voltage precisely under a certain SOC value. Therefore, it is necessary to additionally consider the following equation:

$$U_{oc} = f(SOC, T) \qquad \textbf{(28)}$$

To characterize the steady-state change of the battery. That equation needs to model the V_{ctrl}-SOC relationship through the V_{ctrl} using a test battery or available data, and the relationship is to be obtained by a curve fitting procedure. U_{oc} is the open circuit voltage of the battery model, which is obtained by fitting the variable in $f(SOC, T)$ and its parameters. Overall, the following main parameter were considered:

- Rs defines the equivalent ohmic internal resistance of the power battery.
- R_p defines the polarization internal resistance.
- U_p defines the resulting voltage drop on the polarization resistance R_p.
- C_p is the battery polarization capacitance.
- I_l is the operation current.
- U_t is the battery nominal voltage.

A specific calculation analysis of the determined model si required, which can be derived from Kirchhoff's law as:

$$\begin{cases} U_t = U_{OC} - U_p - I_l R_s \\ I_l = \dfrac{U_p}{R_p} + C_p U_p \\ U_{OC} = f(SOC, T) \end{cases} \qquad \textbf{(29)}$$

The mathematical relationship between the output voltage and the input current of the battery model can be deduced through the Laplace transform, and the resulting is show in the following equation:

$$U_t(s) = U_{OC}(s) - I_l(s)\left(R_s + \frac{R_p}{1 + R_p C_p s}\right) \qquad \textbf{(30)}$$

Then the transfer function model is:

$$G(s) = (U_t(s) - U_{OC}(s))/I_l(s) = -\left(R_s + \frac{R_p}{1 + R_p C_p s}\right) = \left(\frac{R_s + R_p + R_p C_p}{1 + R_p C_p s}\right) \qquad \textbf{(31)}$$

2.1.7 - Heat Exchanger model

The aim of a heat exchanger is to transfer heat from a hot equipment to a cold one, without a direct contact. There exist different type and configurations of exchanger depending on the geometrical configuration and on the flow direction of the fluids.

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For the purposes of our analysis, now no specific thermal dynamic is considered but only a static evaluation of the thermal power or heat fluxes for each subcomponent of the PS derived from a classic power thermal power balance:

$$c\frac{dT}{dt} = P + \sum Q_{in} + \sum Q_{out} = 0 \tag{32}$$

2.1.7 – Power Management System optimization strategy

In the power management system model are considered the two PLA levers. In the PMS is included a prevention logic to avoid the over-speed and under-speed conditions of the two turbines. To prevent an under-speed condition, the logic is to immediately disconnect the corresponding rectifiers to the turbine which is entitled to that condition.

To introduce an optimal strategy of the power management system is necessary to change perspective and to describe the key relationship in the model in a more power-oriented way. Thus, each component will be described as an input-output map in terms of power. Indeed, compared to a control-oriented representation used previously – best suited to Simulink model definition - in this section it is adopted a more analytical and tailorized description of the main models, to obtain a representation of the models suitable to implement a classic model predictive control strategy. To simplify our analysis will be considered only a single powertrain (EPU) system in which is considered also the presence of the battery and a simplify aircraft model to have a more correct formal formulation of the control problem. The resulting optimal strategy will be extendable also to the reference Onera's architecture. Moreover, a simplify mechanical model of aircraft will be considered.

To implement an optimized control strategy, it is possible to determine the characteristic input-output maps in terms of power for each subsystem. Which, in turn, allow to define the balance equation or the dynamics of the total power of the entire system. This power dynamic can be used to define an MPC controller.

The main objective of the PMS is to find real-time optimal power flow between the gas turbine and electric motor and guaranteed through the thermal management the best efficiency of the entire system reducing the gas turbine fuel consumption. Thus, the optimization problem will consist in minimizing the following cost function:

$$J = \int_0^T f(P_{gt}(t), \omega_{gt}(t), \eta_{gt})\, dt \tag{33}$$

Where η_{gt} is the efficiency of the gas turbine directly dependent by entire thermal management system, P_{gt} is the power turbine and ω_{gt} is turbine speed. In the Simulink model, to date, this function is implemented using a state flow machine that in addition to generating the main stimuli to the entire model, it has the capability to manage the splitting and the balance of the power according to the flight phase and to the presence of a possible fault condition. The overall PMS control strategy will be a hybridization of a classic discrete MPC control and a supervisory fault tolerant control.

3.0 - Implemented Simulink Model

The main implemented Simulink models to simulate the identified major functionalities are the following:

- Power train propulsion which corresponds to the EPU model, which is composed by the sub-models of the inverter, of the electrical motors and the fan models.
- Generators.
- Power line distribution and circuit breakers.
- The free gas turbine.
- Input Pilot levers (2 PLAs one for each wing).
- Cooling system will be implemented in the future but in the model are already considered the thermal power as output of each implemented model
- The Batteries

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- The supervisor of simulation to generate failure and inputs to the overall model

The general controls architecture is composed by a local controller for each component and a by a combined action of the supervisor PMS which regulate the overall dynamic.

3.1 Simulation in nominal condition

In this section will be analyzed some preliminary results deduced from the simulation of the implemented model. The mission profile is deduced from the available data and it is imposed by the supervisor. There is a power up in which the main dynamics are started to reach steady state. Then the simulation of each phase of flight starts. The descent phase is longer than the other to show the dynamics of the system due the very slow thrust variation requiring.
In nominal case all the power train breakers related to each single EPU are set to ‘On’ (active, no fault).

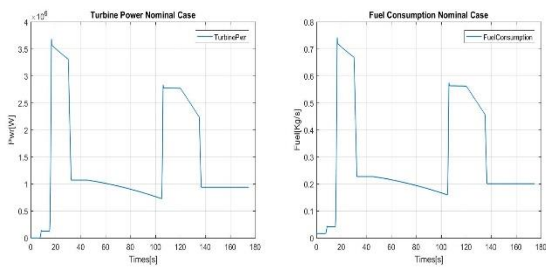

Figure 3 - Turbine power and fuel consumption

Fig. 3 shows the profile for each phase of flight of the turbine power and fuel consumption. At the time, it is possible to observe that those profiles are like that show by the reference design data, validating the model.
Fig. 4 shows the requested power to EPUs in percentage (*left*) and the corresponding EPUs shaft power (*right*). It can be seen how the shaft power correctly follow the requested power profile and how there is a sufficient match with the available reference data.

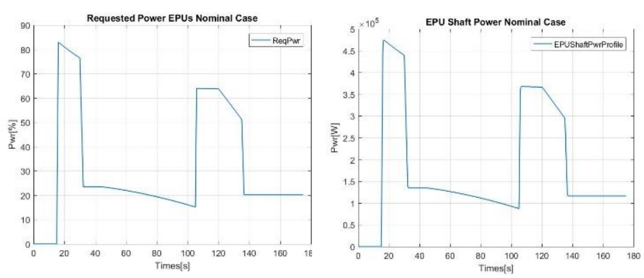

Figure 4 - EPU profiles

Finally, in fig. 5 there are the generators power profile (*left*) and the requested generators power (*right*).

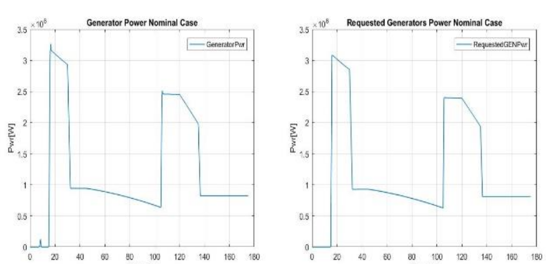

Figure 5 - Generator Profile

In the next section will be discuss how, the main power profile, varies in case of one fault condition.

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3.2 - Simulation of fault conditions

The simulated fault condition remains active for only 15 seconds and then the system returns to the nominal state. This failure is replicated for each phase of the flight envelope to investigate the system behavior reaction in a single diagram.
The main considered failures are the following:

- **One power train inoperative**: this case corresponds to a total loss of one or an entire group of interconnected EPUs. Thus, using the power train bus command it is possible to induce this fault condition.
- **One power leg inoperative**: this case corresponds to the total loss of an electrical generator, which, in turn, corresponds to a loss of back bus node. Thus, using the health bus command to switch off a back bus node will result in the loss of the connected generator.
- **One turbine or gas generator inoperative**: this case corresponds to the total loss of a gas generator or, in the model, to one turbine.

These fault conditions are deduced from the fault analysis as reported in [9]
In this article is show, as an example, only the first fault condition. Indeed, only the power train bus commands of the supervisor respect to the nominal condition are used to induce the fault condition of an EPU or a group of EPUs. Especially, only the first power train command will be switch to 'On' and 'Off' to simulate the fault of a single EPU of the first group.
In that case, moreover, the reaction of the PMS will be an automatic increase of the requested power to the other EPUs which are interconnected with that induced in the fault state.
The following power profile are obtained:

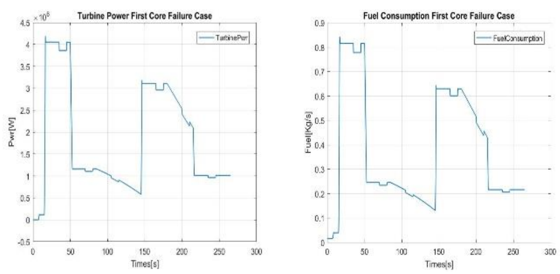

Figure 6 - Turbine power & fuel consumption profile

Fig. 6 shows the turbine power profile and the fuel consumption profile. Please note how, in presence of the fault conditions of single power train implicated in the corresponding loop of the turbine, there is a reduction of the power and of the fuel consumption. This is true in any phase of flight for each induced fault.
Similarly, fig. 7 (left) shows the profile of the power of the two generators. It is noted how the power of the first generator depends on the EPU in the fault state. Indeed, when the fault is active, the generator power is reduced. Instead, that of the second generator increases to compensate for the fault condition. In fig. 7 (right) is reported the requested power to the remaining healthy EPU.

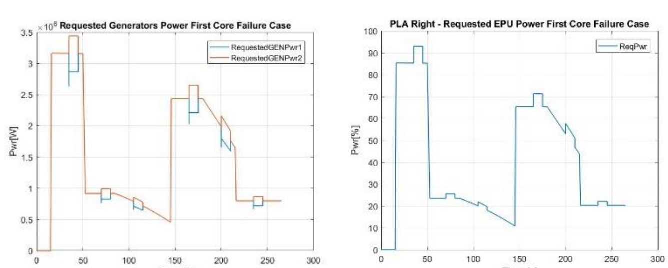

Figure 7 - Fault EPU Profiles

Finally, in fig. 8 is show the EPU power shaft profile in case of fault (left) and that one of the health remaining EPUs (right). This is clear a good balance of the power flow in case of fault.

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Similar results are showable for the other listed cases.

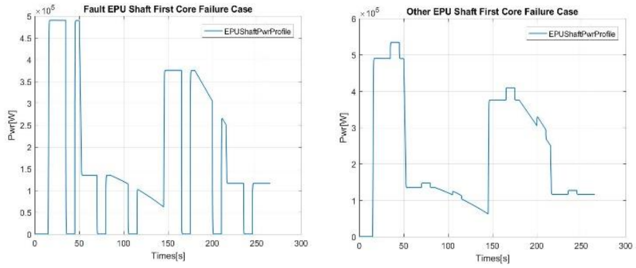

Figure 8 - Requested EPU power

4.0 – Conclusion and future improvements

In the previous section are described the main dynamics of the implemented model of the PMS. The model behaves correctly and coherently with high-level requirements and with available data – it is obtained a good approximation of raw data.

Some future improvements will be implemented:

- Introduction of a more representative model of the EPUs, with the implementation of a more detail dynamical model of the electrical motor and of the ducted fan.
- Introduction of a more representative dynamic model of the turbine or gas generator considering also a more detail model of the environmental flight conditions
- Introduction of the cooling and thermal power management system

Such more detail model will be able to represents in a more consistent way all the transient of the dynamics of interest, making them less impulsive a more representative.

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