AIRCRAFT POWER ARCHITECTURE

ELECTRICAL SYSTEMS

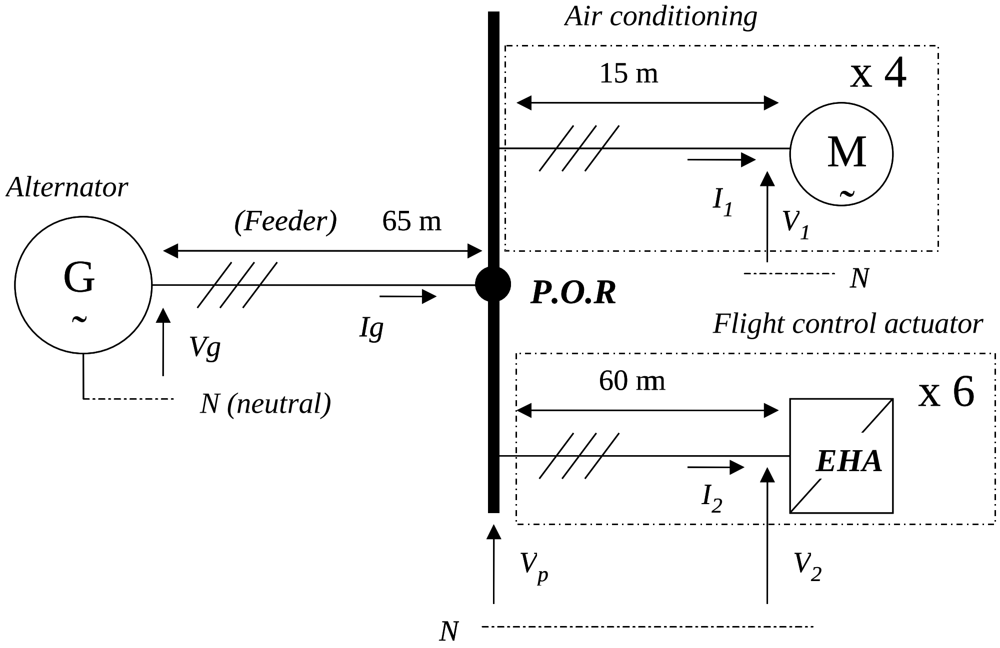
TUTORIAL

V. Budinger

Institut Supérieur de l'Aéronautique et de l'Espace

Tutorial 1 - Aircraft on board electrical supply network
Point of regulation

A 150 kVA three-phase generator supplies part of an aircraft equipment as shown in the figure below.



For this network, the voltage at P.O.R. (Point Of Regulation) is constant and the effective value is noted V_p.
V_p = 115 V

The alternator is driven directly by a reactor. The frequency f_r of the obtained voltage lies between 400 Hz et 800 Hz.

The P.O.R. supplies 4 motors for the aircraft air conditioning and 6 electro-hydraulic actuators (EHA) for the flight control.

For each air conditioning motor (f_r = 400 Hz)
V_1 = 111.6 V ; I_1 = 44.8 A ; cos φ = 0,8

Air conditioning motor cable: length:15 m ; resistor: r_{c1} = 90 mΩ/conductor & inductance: l_{c1} = 3 µH/ conductor.

For each EHA (f_r = 400 Hz)
V_2 = 111.3 V ; I_2 = 29.9 A ; cos φ = 1

EHA cable: length:60 m ; resistor: r_{c1} = 126 mΩ /conductor & inductance: l_{c1} = 12 µH/ conductor.

Feeder cable
length: 65 m ; diameter 20mm
material: copper (density: 8960kg/m^3)

Question 1: Study of the loads requirements for f_r = 400 Hz

- Compute the active power and reactive power (Pm and Qm) for each air conditioning motor.
- Compute the active power and reactive power (P_{c1} and Q_{c1}) for each supply cable of the air conditioning motor.
- Compute the active power and reactive power (P_{EHA} and Q_{EHA}) for each EHA.
- Compute the active power and reactive power (P_{c2} and Q_{c2}) for each supply cable of the EHA

Question 2: Sizing of the feeder cable

- Do a power balance and compute the effective value of the current I_g in the feeder and the power factor ($\cos \varphi_p$) at the P.O.R.
- Compute the feeder cable weight

Tutorial 2 - Analysis of electrical power architecture for a typical 130-150 PAX aircraft

The typical mission profile of aircraft is given in Figure 1.

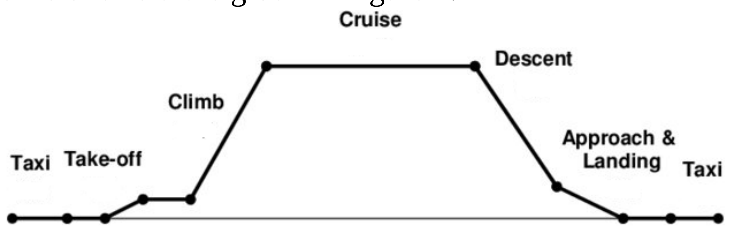


Figure 1 - Typical aircraft mission profile

During each phase of the flight, the requirement of electrical load varies, depending on the equipment in operation. We limit our study to 3 phases: taxi, cruise and landing. For each phase, Table 1 gives the required power for essential and non-essential electric loads and the kind and level of voltages. “essential loads” means that the loads must be supplied even in case of abnormal operations.

	Taxi		Cruise		Landing	
	Non-essential	essential	Non-essential	essential	Non-essential	essential
Environment Conditioning System (ECS)	105 kW 230 VAC CF = 400 Hz cos φ = 0,8	5 kW 28 VDC	105 kW 230 VAC CF = 400 Hz cos φ = 0,8	5 kW 28 VDC	10 kW 230 VAC CF = 400 Hz cos φ = 0,8	5 kW 28 VDC
Ice Protection System (IPS)	5 kW 270 VDC	5 kW 28 VDC	40 kW 270 VDC	5 kW 28 VDC	5 kW 270 VDC	5 kW 28 VDC
Navigation & communication		5 kW 28 VDC		5 kW 28 VDC		5 kW 28 VDC
Cabin equipment	2 kW 230 VAC CF = 400 Hz cos φ = 0,9		20 kW 230 VAC CF = 400 Hz cos φ = 0,9		2 kW 230 VAC CF = 400 Hz cos φ = 0,9	
APU starter	0 kW	10 kW 28 VDC	0 kW	0 kW	0 kW	0 kW
Actuation system	5 kW 230 VAC VF = 400→800 Hz cos φ = 0,95	10 kW 230 VAC VF = 400 →800 Hz cos φ = 0,95	20 kW 230 VAC VF = 400→800 Hz cos φ = 0,95	75 kW 230 VAC VF = 400→800 Hz cos φ = 0,95	10 kW 230 VAC VF = 400→800 Hz cos φ = 0,95	30 kW 230 VAC VF = 400→800 Hz cos φ = 0,95
Landing gear	0 kW	5 kW 230 VAC VF = 400→800 Hz cos φ = 0,95	0 kW	0 kW	0 kW	30 kW 230 VAC VF = 400→800 Hz cos φ = 0,95

Question 1
Compute the apparent power required for the cruise phase.
Compute the power taken during this pahse from the generators and for a transmission line with an efficiency of 0.8.

Question 2
Compute the apparent power required by essential loads for each phase.

Question 3
We consider an aircraft with the following energy sources:

- 2 generators 230V VF (400 →800 Hz), 200KVA
- 1 APU: 230V VF(400 →800 Hz), 120KVA
- emergency source: 2 battery packs

Requirement: the essential loads must be fed in case of failures of the 2 generators.
Consider the first architecture of Figure 2.
Analyze the architecture to explain the power distribution in case of:
- 1 generator failure
- 2 generator failures and AC bus failure. What is the size of the battery packs in this dual engine failure configuration with the assumptions of power energy of 300 VAh/kg and of an emergency phase that lasts 30 minutes (25 min. cruise + 5 minutes landing).

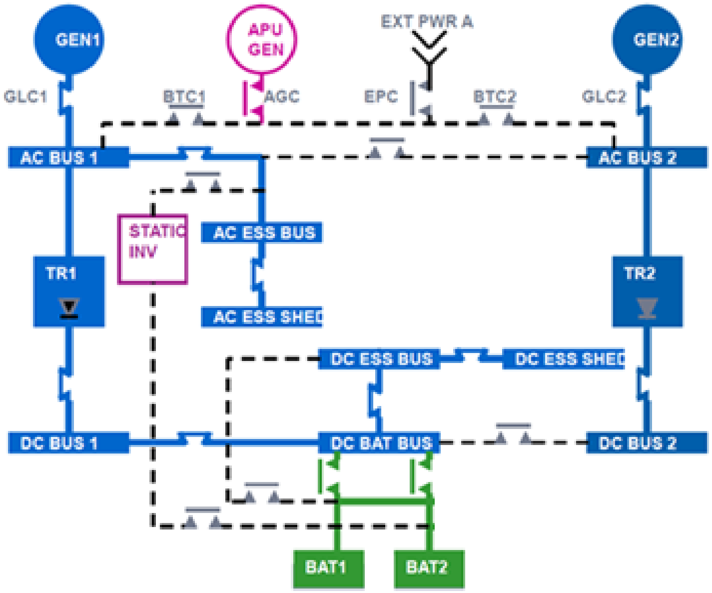
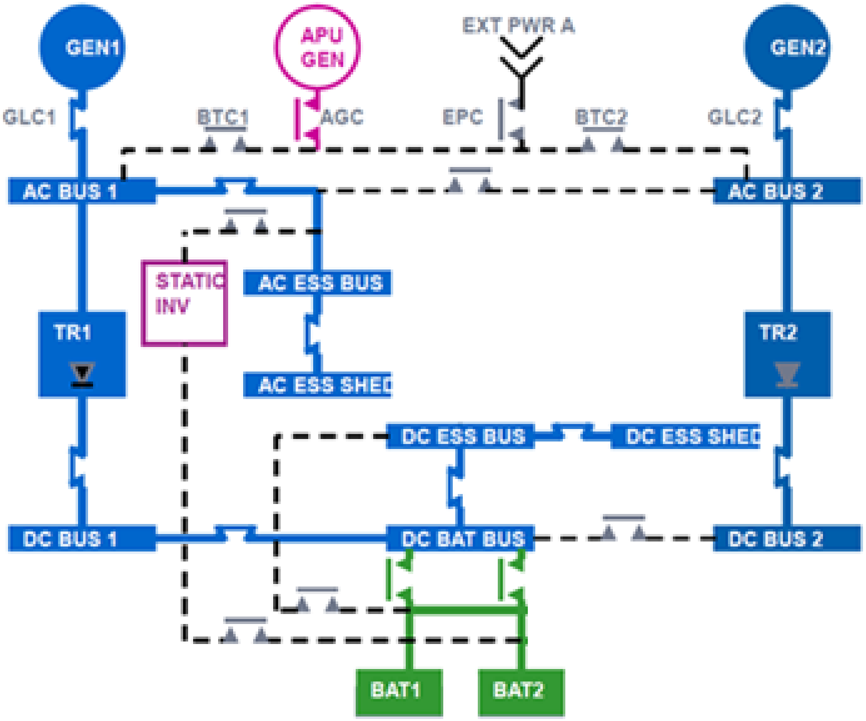


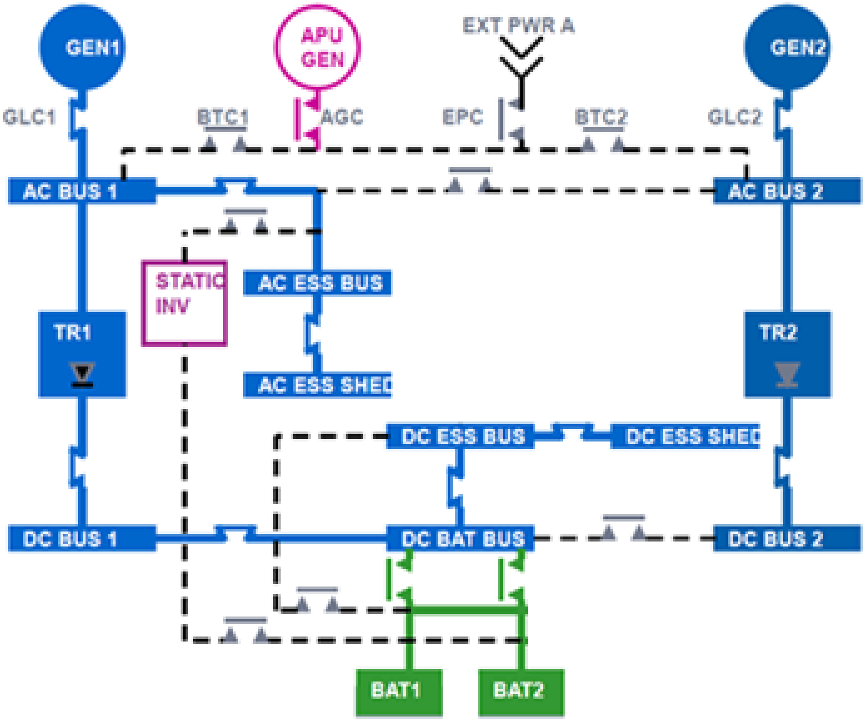
Figure 2 – Power architecture

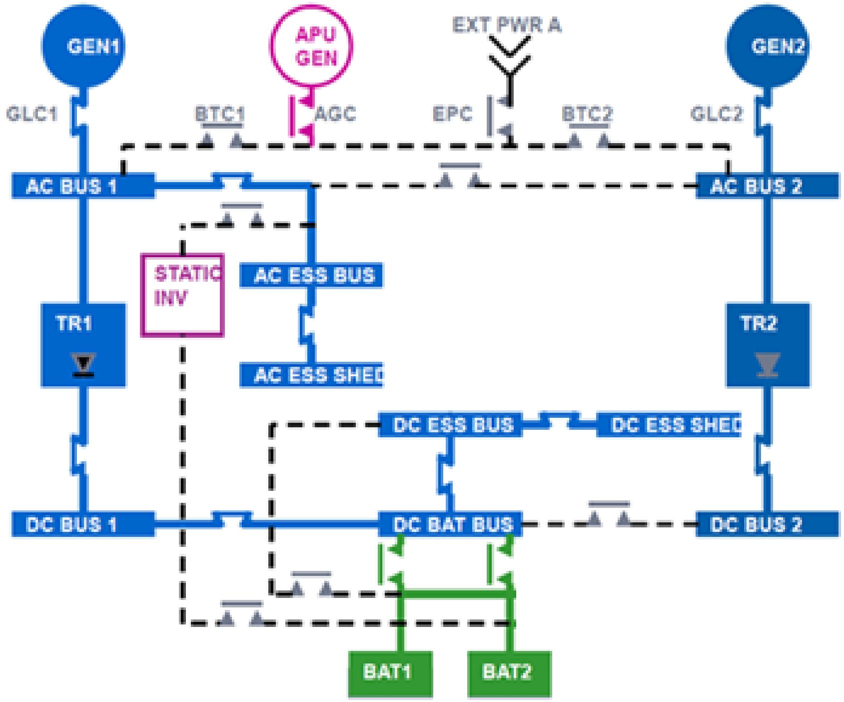
Question 4
Propose one architecture with a ram air turbine in order to limit the size of the batteries in case of dual engine failure.

Question 5
Compute the current in the feeder of the AC non-essential bus for the cruise phase in normal conditions.

Scheme for the answers






GEN1
APU GEN
EXT PWR A
GEN2
GLC1
BTC1
AGC
EPC
BTC2
GLC2
AC BUS 1
AC BUS 2
STATIC INV
AC ESS BUS
TR1
TR2
AC ESS SHED
DC ESS BUS
DC ESS SHED
DC BUS 1
DC BAT BUS
DC BUS 2
BAT1
BAT2

Tutorial 3 - Hybridization of a Ram Air Turbine for an emergency network

Note: the data of this study were extracted from the thesis of Olivier LANGLOIS
Design of an electrical emergency network for aeronautics

1 -Concept and interest of the hybridized RAT

The RAT is used to provide energy in the event of failure. The most critical case is the Total Engine Flame Out (TEFO). In this fault configuration, the RAT must provide power to:
- flight control actuators, mainly electro-hydrostatic (EHA) actuators, whose consumption is high but relatively brief with respect to the emergency mission. These consumers are said to be fluctuating as their consumption patterns vary greatly during the mission.
- equipment (electronic equipment, de-icing systems, brakes, etc. (Figure 1) which have a relatively stable consumption over time and which can simply be assumed to be constant.

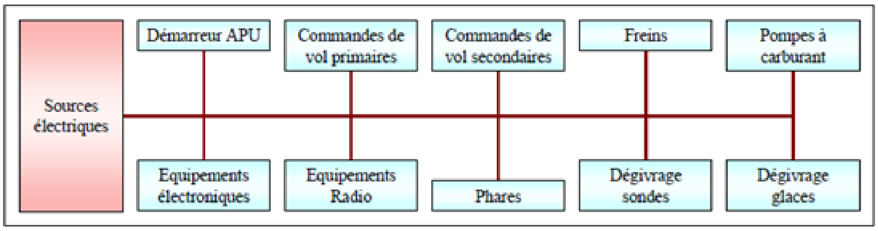


Figure 1 - "Emergency" electric loads of a "more electric" aircraft (Langlois, 2006)

To fulfill its function, the concept of hybridized RAT combines:
- a traditional source of wind turbine type, acting as an energy source and capable of supplying at least the average power absorbed by all the loads
- a storage device acting as an instant power source capable of supplying the peaks of power absorbed by the fluctuating loads

The expected benefits of hybridized RAT are:
- Structure:
The hybridization of a power source and an energy source allows making the most of each one. The interest lies in the right dimensioning of the primary source of energy. This is especially true for a RAT. An optimization of the wind turbine would reduce its dimensions, and therefore its mass, and facilitate its integration in the aircraft.
- Management of the energy flow and the load of the storage element:
The power management with a simple but simple control allows managing the state of charge of the storage system. The system, assumed to be initially charged, is discharged during power peaks consumed by the load. Between these points, the element recharges itself by taking the energy necessary for the RAT.

2 - *Data for the design of the hybridized RAT*

Definition of the aircraft mission in emergency situation

The configuration chosen among the different cases of failure is the total loss of the engines involved during a cruise flight. This complete mission of the aircraft, starting from the loss of the engines until the end of the evacuation of the passengers, can be segmented as indicated in Figure 2. The segmentation is carried out by distinguishing the different phases of operation: descent, approach to the ground until landing, braking until the aircraft stops, and finally evacuation of the passengers. For each mission segment, the requirements of the aircraft differ, which also implies different energy requirements. For our study, we will consider the segment that corresponds to a ground approach case of a low-speed aircraft (140knots).

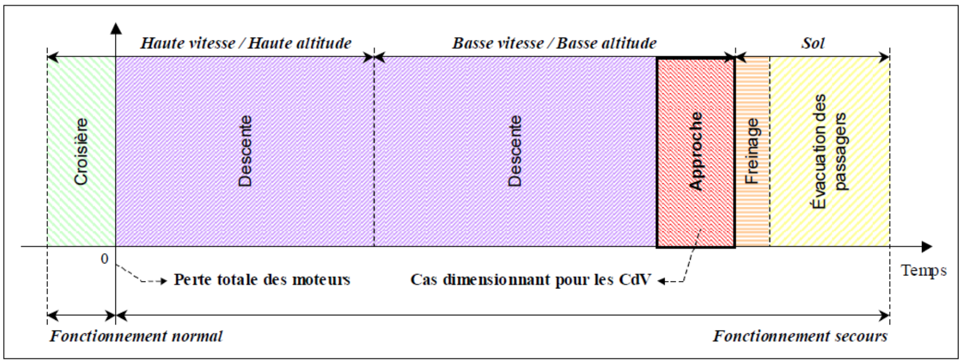


Figure 2 - Segmentation de la mission : différentes phases de fonctionnement de l'avion après une perte totale des moteurs survenant en vol de croisière (Langlois, 2006)

Power consumers

Fluctuating consumers

The power absorbed by all aircraft EHAs during the study segment is given in Figure 3. This power profile is very fluctuating; very short (mission-wide) peaks occur frequently. The mean value of the power absorbed is equal to 5.5 kW and the peaks absorbed by the actuators reach 30 kW.

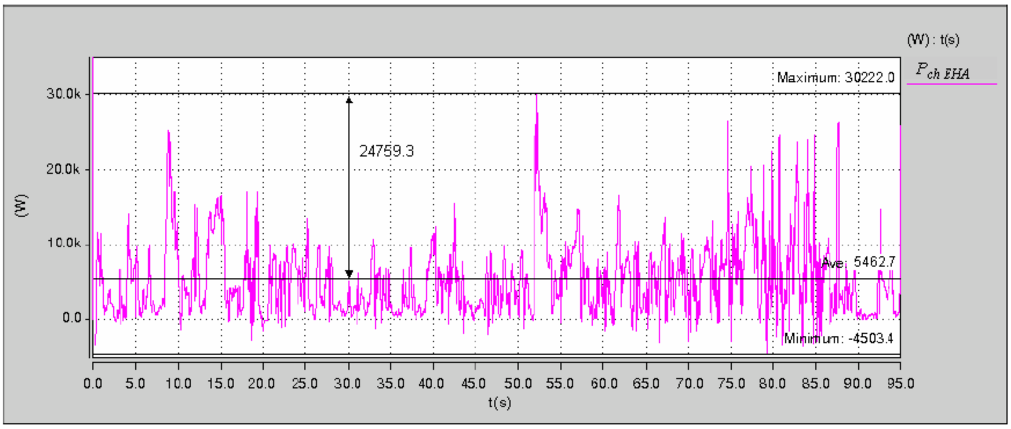


Figure 3 - Power absorbed by all aircraft EHAs as part of emergency mission and for low-speed approach (Langlois, 2006)

Constant consumers

The loads considered constant can simply be assumed to absorb a fixed power over time, over the entire segment of the mission. Overall, this fixed consumption is estimated at 20 kVA. This amounts to considering a power of 20 kW in equivalent direct current.

Question:

Draw the power profile absorbed by all consumers by highlighting the average power and fluctuating power.

3 - Structure and strategy of hybridization and associated power requirements

The hybridization structure chosen for the study is given in Figure 4.

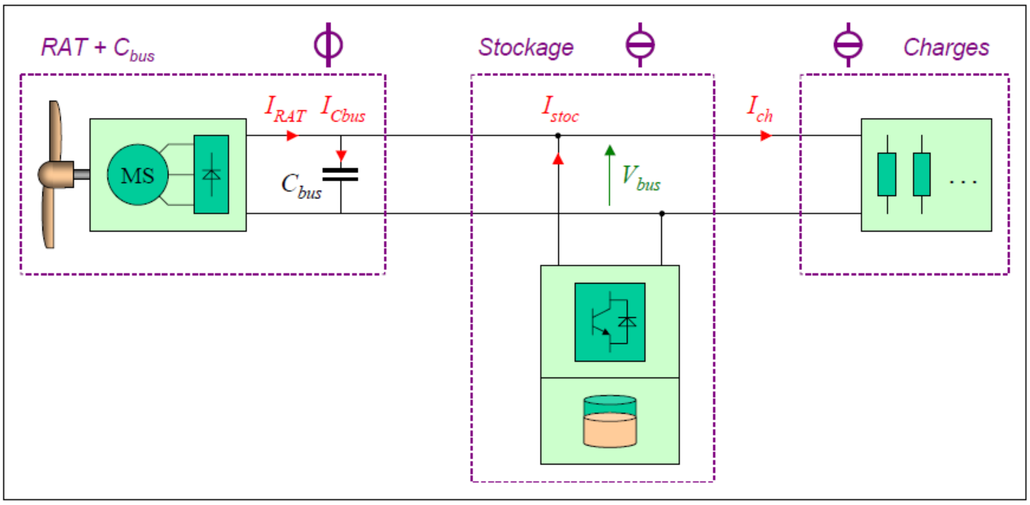


Figure 4 – Conventional hybridization structure. (Langlois, 2006)

Questions:

1 / Calculate the power to be provided by the hybridized RAT and the storage system by incorporating a design margin of 6.5 kW for the RAT.

2 / Compare the power to be provided by a hybridized RAT structure with respect to a conventional RAT.

4 - Pre-sizing of the turbine

The RAT consists of a turbine, a synchronous machine, a rectifier bridge and mechanical parts for the support. A change in power impacts all the components but we will only study the impact on the turbine (similar studies could be carried out for the other components). This study is done using similarity relationships and a simplified model of the turbine.

Simplified model of the turbine.

The mechanical wind power captured by the turbine can be written as:
$\boxed{P_T = \frac{1}{2}\rho S_T v_T^3 C_P}$ with $S_T = \pi R_T^2$ et R_T : radius of the turbine

The electrical power that can be recovered by the wind turbine is given by

$$\boxed{P_{elec} = \eta P_T}$$

with η: efficiency of the turbine.

Principle of resizing by similarity

The principle of this method relies on the study of the geometrical variations of equipment in relation to existing so-called reference equipment. The new magnitudes of a model are expressed in terms of the original quantities of the reference equipment. The characteristics of this reference equipment are given in Figure 5.

RAM AIR TURBINE MODULE

Speed and Direction of Rotation	
Direction of Rotation (looking aft)	Clockwise
Minimum Airspeed at the Turbine for Rated Output	135.5 KEAS
Governed Turbine Speed (minimum/maximum)	4,800/6,600 rpm
Turbine/Hydraulic Pump Speed Ratio	1:1.09
Environmental Conditions	
Maximum Operational Altitude	41,000 ft (12.5 km)
Ambient Temperature Range	-85°F to 194°F (-65°C to 90°C)
Weight and Overall Dimensions	
Weight (Including 6.1 lb (2.77 kg) for Stow Panel)	180.0 lb (81.65 kg)
Height	48 inch (1,220 mm)
Length	26 inch (660 mm)
Width	7 inch (178 mm)
Turbine Diameter	29.5 inch (749.3 mm)

Figure 5 – Structure d'hybridation conventionnelle (Hamilton Suntrand)

Several variation parameters are defined to write the similarity relationships. For any quantity X, the variation parameter is defined as the ratio of this quantity to the corresponding reference variable:

$$\alpha_X = \frac{X}{X_{ref}}$$

In order to resize the turbine, the parameters of the new turbine must be expressed as a function of the reference turbine by similarity relationships. We are particularly interested in the geometric resizing of the turbine as a function of its power, which leads us to introduce two parameters of similarity.

- variation parameter on the power: $\alpha_P = \frac{P_{elec}}{P_{elec-ref}}$
- variation parameter on the radius: $\alpha_R = \frac{R_T}{R_{T-ref}}$

Questions:

Constant efficiency is assumed whatever the turbine.

1/ Give the evolution of the radius of the turbine according to the required electrical power. Calculate the radius of the hybridized RAT using the reference RAT data.

2/ To select the turbine, in addition to its size, it is also necessary to recalculate its torque and its rotation speed. Calculate the rotation speed of the hybridized RAT and give the evolution of its torque as a function of the variation parameter on the radius α_R.

5 - Pre-Sizing of the storage system

The supercapacitors are well suited for the storage application as part of the hybridized RAT. The time scales of power variation are too short for the batteries to be advantageous. The mass of the storage system with supercapacitors is lower than that of an equivalent system with batteries. The frequency of cycling is also better appreciated by the supercapacitors, improving the life of the storage elements.

Two configurations are studied for integration of the storage system into the hybridized RAT structure.

First configuration

The first configuration includes supercapacitors and a "boost" type power converter which allows the voltage of the supercapacitor to be raised to match the mains voltage (Figure 6). To interconnect the two voltage sources that are the supercapacitors and the converter, a coil is added between these two components. This coil will be sized not to exceed a maximum current ripple.

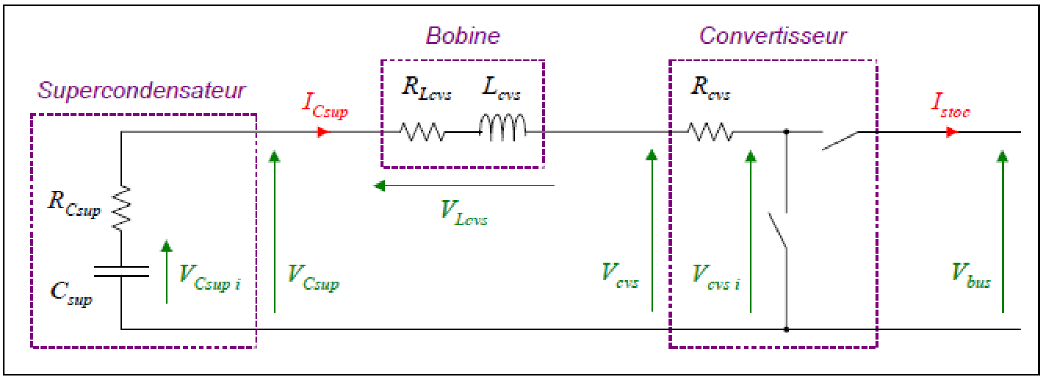


Figure 6 – Storage system with supercapacitor and converter (Langlois 2006)

Sizing the supercapacitor

The notations for calculating the supercapacitor are given in Figure 7.

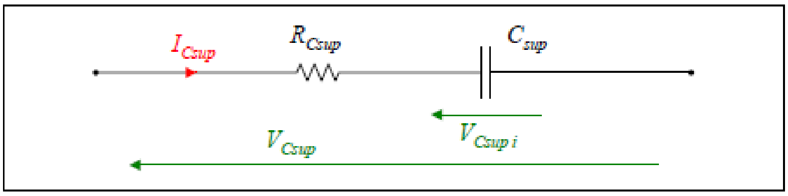


Figure 7 – Model of the supercapacitor

A simple method of pre-sizing the supercapacitor is proposed here, neglecting the losses presented by the storage system (the resistance of Figure 7 is therefore neglected). The principle consists in calculating the supercapacitor so that the energy stored in the capacitor is sufficient with respect to the fluctuation of energy required by the network. This energy fluctuation ΔW_network is calculated by integrating the fluctuating power curve of Figure 3 and is 62 226 J.

Question:

1/ Give the expression of the energy stored in a capacitor of capacitance C and subjected to a voltage V.

The discharge depth is defined as the voltage deviation from the maximum voltage (full load) with respect to this maximum voltage

discharge depth = $\frac{V_{C-sup-max}-V_{C-sup-min}}{V_{C-sup-max}}$

A discharge depth of 50% is chosen. It makes it possible to exploit 75% of the maximum storable energy while remaining in the upper half of the voltage of the supercapacitor

Question:
2/ Give, as a function of the maximum voltage $V_{C-sup-max}$, the expression of the energy stored in a supercapacitor of capacitance C with a discharge depth of 50%.

It is sought to obtain a maximum voltage of supercapacitor equal to 250 V, so as to be close but less than the DC bus voltage of 270 V. Supercapacitors of 350F and 2.5V (mass 84g, internal resistance of 3.2mΩ) are chosen.

Questions:

3/ Calculate the number and association of the supercapacitors to reach the voltage of 250V. Deduce the equivalent capacity and the total mass of the supercapacitors

4/ Calculate the required minimum value of the capacity of the supercapacitor so that the energy stored in the capacitor is sufficient with respect to the energy fluctuation demanded by the network. Verify that the value calculated in 3 / satisfies this minimum value

Converter and calculations of currents

The nomianl power to be controlled by the storage converter is known. The converter has an efficiency of 95% and a mass of 10 kg. It is now sought to calculate the nominal current flowing in the supercapacitor, at the input of the converter. In continuous operation, neglecting the voltage drops in the resistance of the coil which is low, it can be considered that the input voltage of the converter is also the voltage across the supercapacitor and that the input power of the converter is that at terminals of the supercapacitor.

Question:

1/ Calculate the input power of the converter

2/ By performing a power balance at the supercapacitor, write the relation which makes it possible to express the current I_{Csup}

3/ By solving the above equation, calculate I_{Csup}

Sizing of the inductance.

The calculation of the inductance is based on the maximum acceptable current ripple. It is set here at 10% of the maximum current value.

For the chopper used here, the peak-peak ripple of the current is expressed by the formula:
$\Delta I = \frac{V_{bus}}{4L_{cvs}f}$
with: frequency of opening and closing of switches (here 20kHz)

Question :
Calculate the value of the inductance.

Note: the current in the coil is high, the conductors are of large section and the estimated mass of the coil is 5kg.

Mass balance

Question
Evaluate the mass of this first configuration.

Second configuration

The first configuration offers a very good quality of network voltage, with variations less than a few percent. However, this quality of voltage is not indispensable in the case of the emergency electrical network. It is therefore conceivable to place the storage element directly on the DC bus, in order to avoid the storage converter.

We now study the scheme of Figure 8 in which supercapacitors we will calculate. The variation of energy in the emergency mission is always 62 226 J. The voltage V_bus varies from 234 V to 306V.

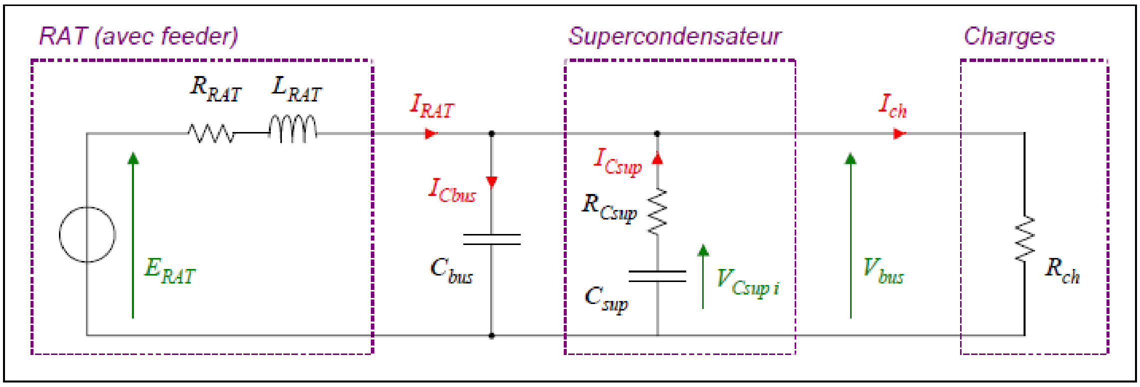


Figure 8 – Storage system with supercapacitor without converter (Langlois 2006)

Questions:

1 / Calculate the minimum capacity of the supercapacitor

2 / Propose an association of 15 V / 58 F / 19.2 mΩ / 0.5 kg supercapacitors to achieve a minimum voltage of 306V and the minimum capacity you have just calculated.

3 / Calculate the mass of supercapacitors.

4 / Make an analysis of the advantages and disadvantages of this second configuration compared to the first.

6 - Study of the implementation of the hybridized RAT in the aircraft

The implementation of the hybridized RAT closest to the implementation of the conventional RAT is to keep the RAT at its current location under the wing and to position the storage system in the backup core (
Figure **9**).

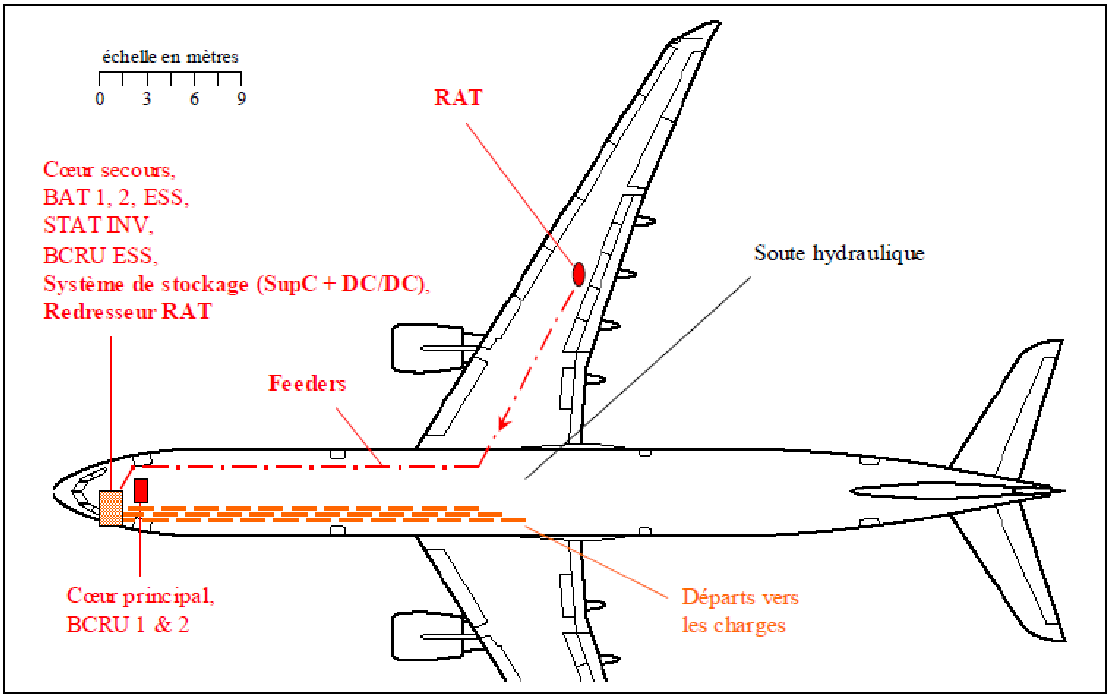


Figure 9 – Example of location of emergency sources in the aircraft with RAT under the wing and storage system in the "backup" (Langlois 2006)

The location of the RAT under the wing is the result of a compromise between available space and air supply allowing the turbine to be properly exposed to air flow in order to obtain good performance. This is why the RAT is placed under the wing or under the fuselage of Airbus aircraft. To reduce cable lengths, the RAT could be brought closer to the front tip on some regional aircraft. Thanks to the hybridization of the emergency sources, the RAT is small in size, making it possible to envisage such a location.

To go further in the mass gain, we are now studying the implementation of two storage systems instead of just one (Figure 10). The first is located in the center, closer to the central actuators (CTR) present in the wing, namely the EHAs of ailerons and spoilers, and the EMA of slats. The second is located at the rear, close to the rear actuators (AFT) present in the tail unit, namely the depth and direction EHAs, and the EMA of PHR (plan horizontal réglable - adjustable horizontal plane).

Figure 11 shows the average and fluctuating powers of each of these groups of actuators.

Question :

Analyze these curves and draw conclusions about the benefits of implementing two storage systems

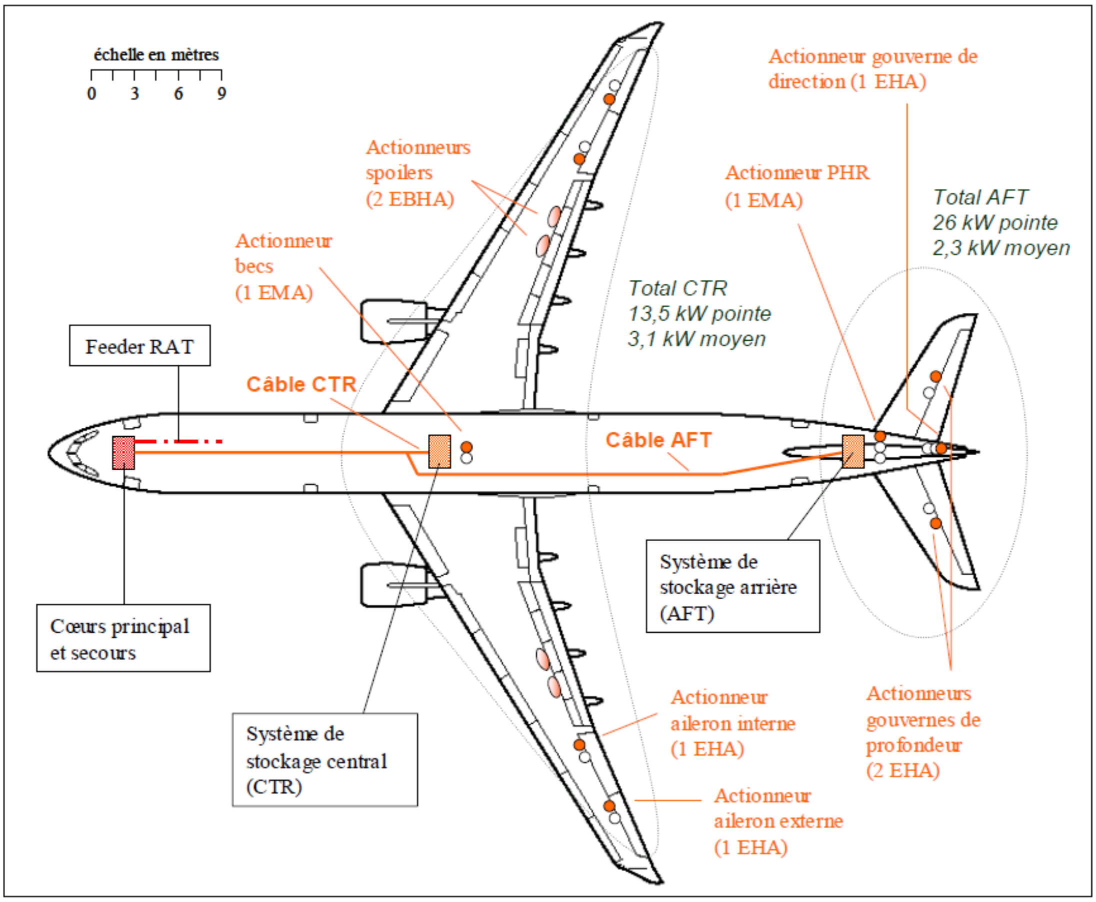
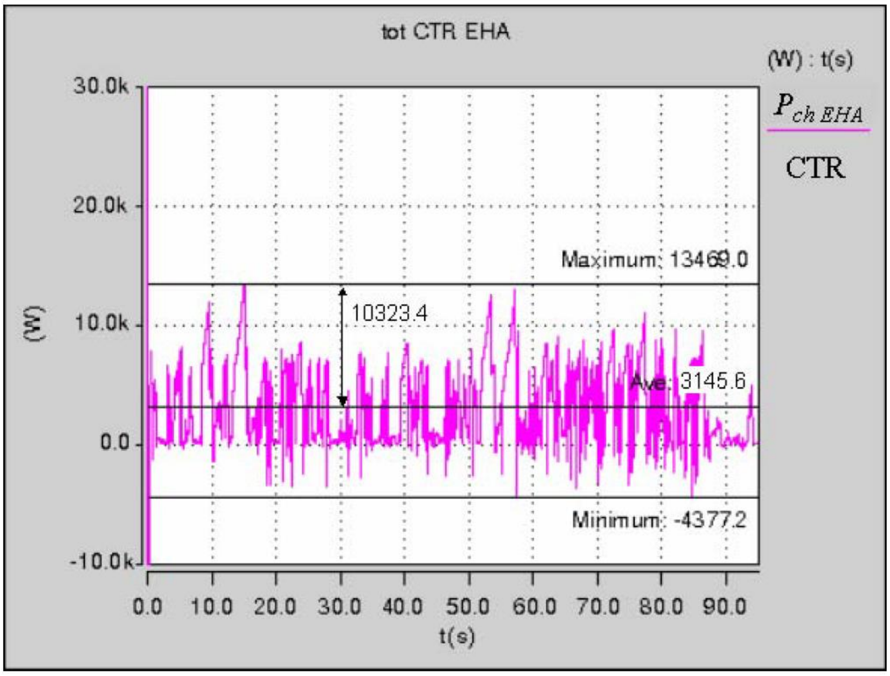
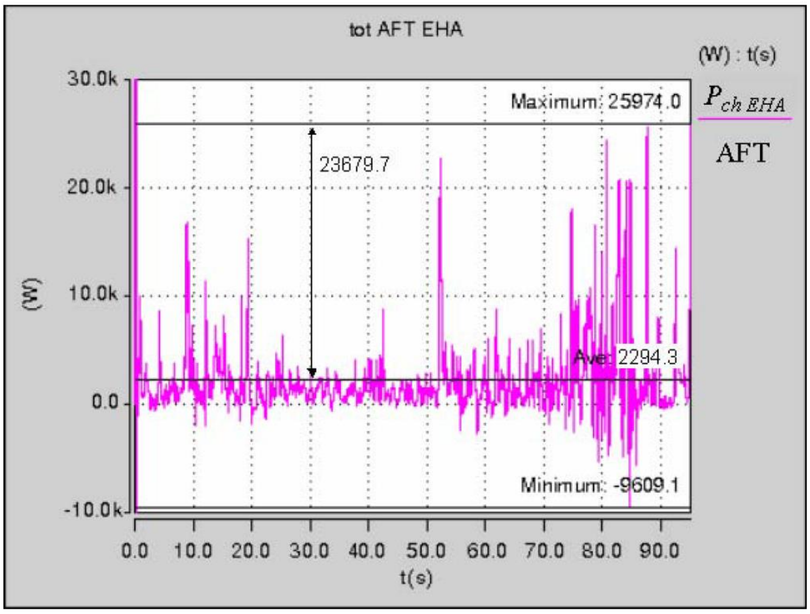


Figure 10 - Example of the location of two storage systems, in the center and at the back of the aircraft (Langlois 2006)



(a)



(b)

Figure 11 – (a) Power absorbed by the actuators in the center (b) Power absorbed by the actuators at the rear (Langlois 2006)

7 – Replacement of the RAT by fuel cell

Research on the applications of fuel cells in aviation is extensive. In our application, the RAT could be replaced by a fuel cell, knowing that the cell has a slow dynamic and is therefore more suitable for supplying consumers with constant or little fluctuating power. To size the fuel cell that could replace the RAT, we use data on mass and volume energy density and the impact of storage which is measured via the gravimetric storage capacity:

$$\text{gravimetric storage capacity in weight percent (wt\%)} = \frac{m_{H_2}}{m_{H_2} + m_{tank}}$$

Hydrogen storage options

- Compressed gas – lightweight composite cylinders
  - 300 bar – 700 bar pressure
    - Diminishing returns with increasing pressure because of non-ideality of hydrogen
  - Fibre-reinforced composite with fiberglass, aramid or carbon fibre and gas-impervious liner
    - Type III cylinder uses metal liner (typically aluminium)
    - Type IV cylinder uses thermoplastic liner
- Cryogenic storage
  - Hydrogen is liquid below −252.87 °C
  - Double-walled vessel with vacuum insulation
  - Low pressure (a few bar)
  - Need to allow for losses of hydrogen to boil-off
    - ~1 to 3 % per day
  - Benefits most from economies of scale
  - 7.5 wt% for 5 kg H_2, ~15 wt% for 50 kg

Storage type	Hydrogen (gas)	Hydrogen (liquid)
kWh/kg (MJ/kg)	33.29 (119.93)	33.29 (119.93)
kWh/l (MJ/L)	2.75 x 10^{-3} (9.9 x10^{-3})	2.36 (8.50
Volumetric capacity/ g/L	0.08	70.85

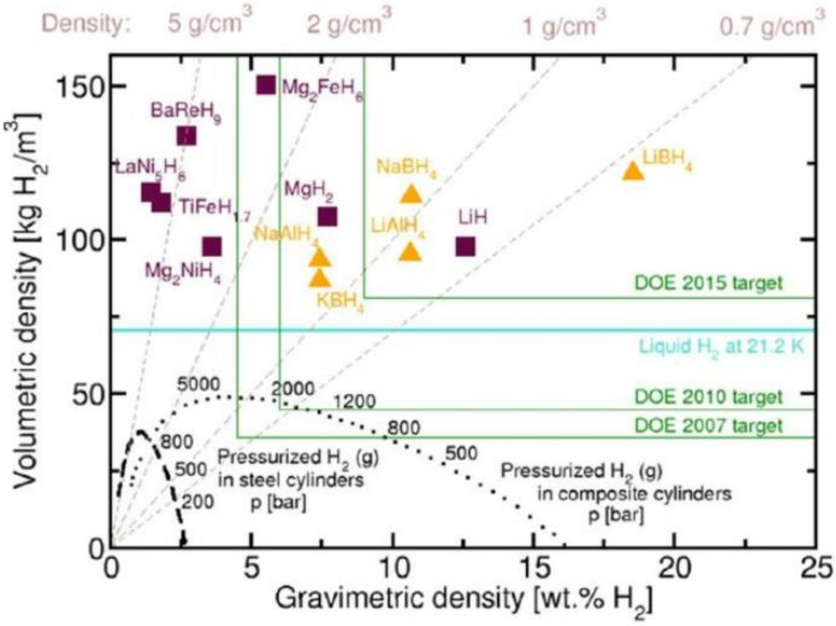


Figure 12 – **Hydrogen Storage - DOI: 10.5772/51238**

<u>8.1 – Replacement by a liquid hydrogen fuel cell</u>

Question :   1 / Calculate the mass and volume of liquid hydrogen needed to replace the RAT in the event of a 30-minute rescue mission.   2 / Calculate the total mass (hydrogen + tank).

<u>8.2 – Replacement by a gas hydrogen fuel cell</u>

Question :   1 / Calculate the mass and volume of hydrogen gas needed to replace the RAT in the event of a 30-minute rescue mission.   2 / Calculate the total mass (gaseous hydrogen at 350b + tank).

Question :   Estimate the mass of the 32 kW RAT with a radius of 281mm. Compare to the mass of the hydrogen system.