A WEIGHT PREDICTION MODEL FOR ELECTRIC PROPULSION SYSTEM APPLIED ON LIGHT HELICOPTERS (CS.27)

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Abstract

Aim of this work is to present a possible high-level conceptual method of weight prediction to manage configurations where an electric propulsion system is able to support the thermal engine failure to guarantee a complete safe landing and not only an emergency one like autorotation. Boundary conditions for this analysis are a starting failure event at an altitude of 6000ft associate with a descending/landing time of 6' ca.

1. NOTATION

To let the reader better understand the content of this paper, symbols and acronyms are listed as per below:

Symbols	
m	Mass of the component, kg
τ	Rotor torque, Nm
I_{max}	Electric motor maximum current, A
Q	Heat rejection, kW
DT	Difference of temperature between cooling liquid and air, °C
P	Power, kW
t	Time lapse required, sec
ρ_P	Power density, kW/kg
ρ_E	Energy density, kWh/kg
l	Cable length, m

Acronyms:	
EM	Electric Motor
EPS	Electric Propulsion System
ES	Electric System
HC	Helicopter
EV	Electric Vehicle
CABL	Cable
BATT	Battery
MR	Main Rotor
INV	Inverter
VTOL	Vertical Take Off and Landing

2. INTRODUCTION

Nowadays, new kinds of propulsion system are applied in automotive field, using electric energy, considered as purer and cleaner than fossil fuel. In this field there are mainly 3 different electric propulsion architectures: mild hybrid EV, full hybrid EV, plug-in hybrid EV. In the VTOL aeronautical field there is a strong and increasing interest to study a possible application of these technologies, taking into accounts all the differences, as high powers requested, no recharge during flight, and trying to satisfy the European targets about safety, noise reduction and CO_2 emissions limits [1][2]. In this new scenario, aim of this work is to present a possible high-level conceptual method of weight prediction to manage configurations where an electric propulsion system can support the thermal engine failure to guarantee a complete safe landing and not only an emergency one like autorotation. Boundary conditions for this analysis are a starting failure event at an altitude of 6000ft associate with a descending/landing time of 6' ca.

Purpose of this new hybrid propulsion system is to guarantee a Cat. A operations to all the single helicopters under CS27.

3. WEIGHT PREDICTION FORMULAE

3.1. Electric System Architecture

The high-level hybrid architecture evaluated for this analysis is presented in Figure *1*: a battery, an inverter with the associated cooling system, electric motor(s) and power cables. Actually, other components, such as Power Module Unit, are not considered because this analysis is high-level, so the aim is to present results that give an idea of the possible order of weight in case of electric propulsion system installation. These elements are added to the normal mechanical-thermal existing components.

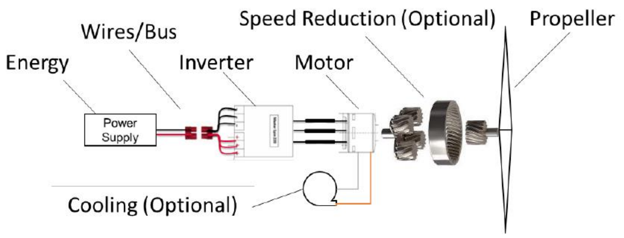

Figure 1 – Electric System (ES) Architecture example

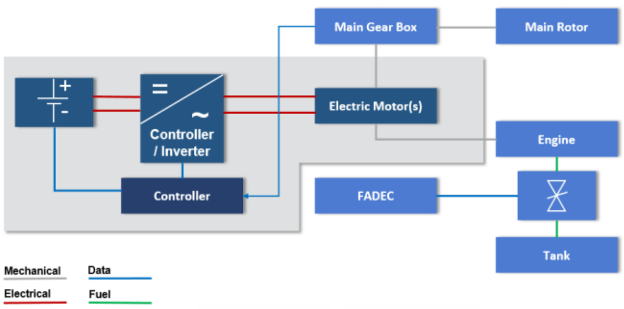

Figure 2 – Electric System (ES) Architecture scheme

This kind of hybrid architecture will be called *engine backup*, that it means that the electric motors are designed to guarantee the power required for a safe landing, that usually could happen with thermal engine in normal landing phases. This is the most demanding case for the engine backup and it can be size with the power required in safe landing phase. The EMs should pay catastrophic, so in case it is not possible that one EM can guarantee it by itself redundancies have to be considered. For instance, adoptions of a high number of EMs installed can imply an increasing of weight and failure combination to be evaluated coping with the mast torque requirement.

In the next paragraphs, prediction formulae for each component are presented.

3.2. Electric Motor

There are different kinds of electric motors nowadays: brushless, synchronous with permanent magnets, axial flex, AC. Actually, some of them have the cooling system integrated, air or liquid kind, depending on the application. In fact, air ones are best suited for aeronautical applications, meanwhile liquid ones for automotive applications. In the next graph, an analysis from CIRA [5] is presented.

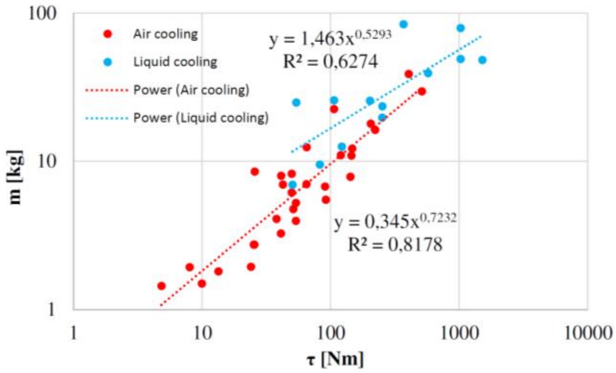

Figure 3 – Correlation between mass and continuous torque for EMs air or liquid cooled

It is possible to understand that the best way to fit the data is an exponential correlation between mass and continuous torque. In the same way, the peak power is considered as exponentially correlated to the weight of the EM.

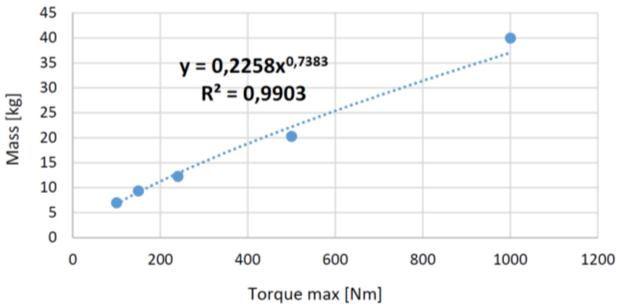

Figure 4 – Motor mass as a function of the maximum torque

Usually, a flight envelope presents a peak power and a continuous power. For this reason, for our analysis we considered both the formulae [5] to precisely define EM weight required to satisfy the power spectrum.

$$m_{EM} = \max\left(0.345\ \tau_{cont}{}^{0.7232};\ 0.2258\ \tau_{max}{}^{0.7383}\right) \quad (1)$$

where τ_{cont} is the continuous MR torque due to continuous power required, meanwhile τ_{max} is the maximum MR torque due to maximum power required. In

Eq. (1) the evaluation between the two formulae is considered: in fact, the maximum results between them is the one that satisfies both the conditions. For our analysis, only the formula for continuous power is considered because the flight envelope considered doesn't have a peak power, as it is a simple descent. The efficiency considered for this component is equal to 95%.

3.3. Battery

This component can be sized considering two main characteristics of it: power and energy densities.

Energy density is the amount of energy stored in a given system or region of space per unit volume or per unit mass, meanwhile power density expresses the ratio between the amount of stored power and the mass of the battery. Knowing these two values and the power required during landing condition, it is possible to calculate the mass of the cells of the battery. In fact, the two densities are referred to the cells of the battery and not the whole one. So, the formulae system is as in Eq. (2):

$$\begin{cases} m_{cell} = \max\left(\frac{P_{in}}{\rho_P}; \frac{P_{in}\, t}{\rho_E}\right) \\ m_{batt} = \frac{m_{cell}}{0.7} \end{cases} \quad (2)$$

where P_{in} is the input power required to the battery to move all the electric propulsion system, due to the MR power and the efficiencies of all the components that compose the system, t is the time lapse of the energy due to the power required, ρ_p is the power density of the cells, ρ_e is the energy density of the cells. To calculate the total weight of the battery, the following factors are considered:

- Packaging factor, equal to 70%
- Aging factor, equal to 0.9
- Discharge factor, equal to 0.9

With the actual benchmarking, it is possible to understand the minimum time required for a battery to satisfy energy conditions instead of power conditions.

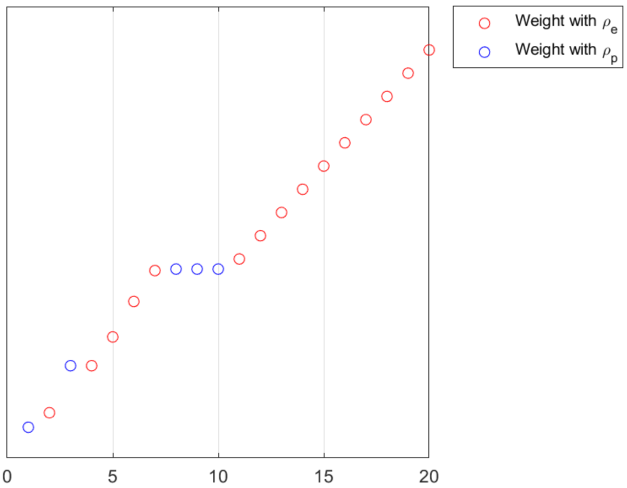

Figure 5 – Correlation between time and energy and power densities

In Figure *5*, each point is the best weight calculated with either energy or power density. It means that there's no clear correlation with time lapse: in fact, the power density is enough to guarantee the lowest weight for some flight conditions considered, for others power density is not enough so that energy density is the satisfying characteristic.

This analysis depends on the correlation between the two densities, analysable with the following Ragone Plot.

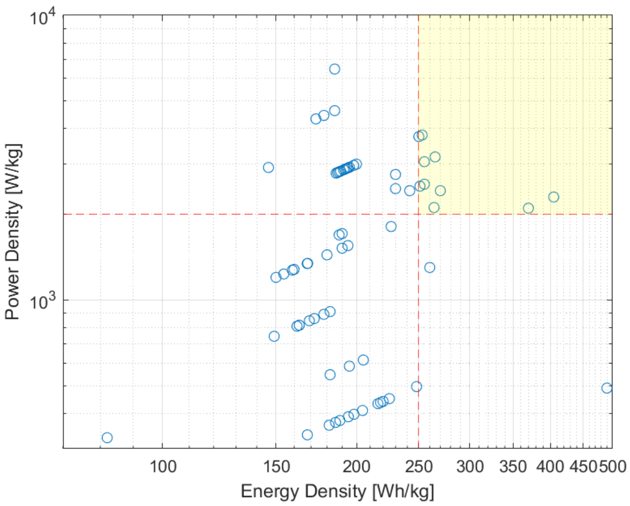

Figure 6 – Ragone Plot of the benchmarking

Actually, the benchmarking has not a good correlation between energy and power densities. In fact, many cells are under the first quadrant, the yellow one, that represents the best correlation between the two characteristics. The cells in the second quadrant are the best that suite high power requirements for short time lapses, meanwhile the cells in the fourth quadrant are the best that suite long time lapses for the flight conditions considered.

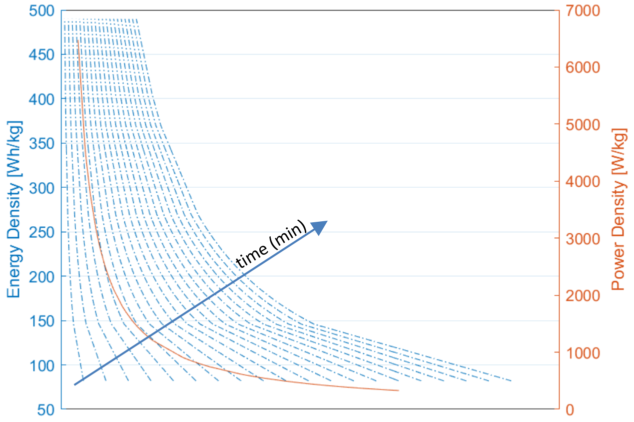

Figure 7 – Energy and Power Densities correlation in function of time

If these cells have a good correlation between energy and power densities, it is possible to affirm that the actual benchmarking can guarantee a possible flight envelope of 4 minutes considering only the power density as the sizing characteristic. As shown in Figure *7*, the blue lines represent weights calculated for each minute considered (for this analysis, a range of 20 minutes is considered) using the energy densities, meanwhile the red one represents the weights resulting for power densities. This line is located between the lines for 4, 5 and 6 minutes.

3.4. Inverter and associated cooling system

An inverter is required so that the electric motor can work. Unlike the electric motor, the inverter does not have any kind of integrated cooling system, so an independent liquid one is required. For this reason, the following system [5] must be used to dimension these two components:

$$\begin{cases} m_{inv} = \ 0.0508\, I_{max} + 2.5249 \\ m_{cooling} = 0.0356\left(\frac{Q}{DT}\right) + 3.664 \end{cases} \quad (3)$$

where I_{max} is the maximum current released from electric motor, Q is the heat loss due to the efficiency of the inverter, equal to 95%, DT is the difference between air and liquid input, equal to 20 K.

3.5. Cables

To calculate the weight for the cables, the actual benchmarking was analysed to define a possible estimation formula.

With Curve Fitting app by MATLAB, it was possible to analyse different kinds of equation that could best fit the benchmarking. In the next Figures, results are shown for the following kinds of equation: Fourier equation, Gaussian equation, power equation with one and two terms.

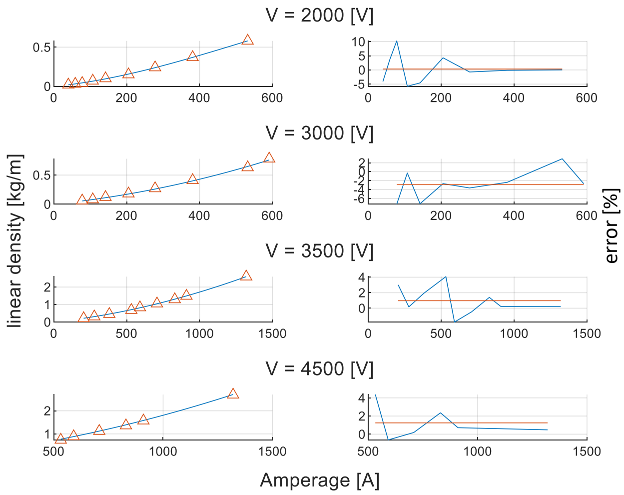

Figure 8 – Fourier equation analysis

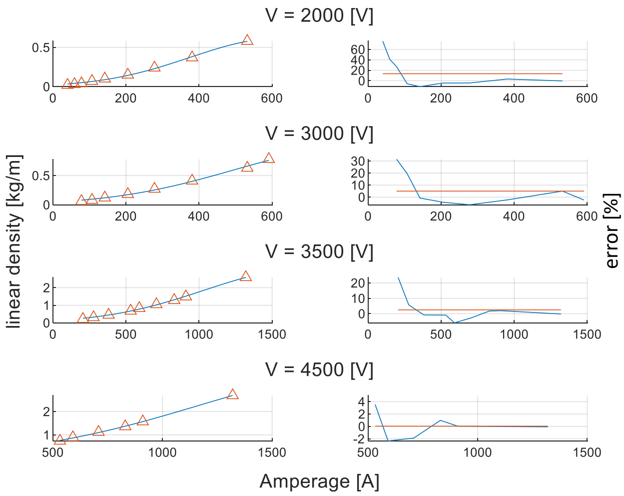

Figure 9 – Gaussian equation analysis

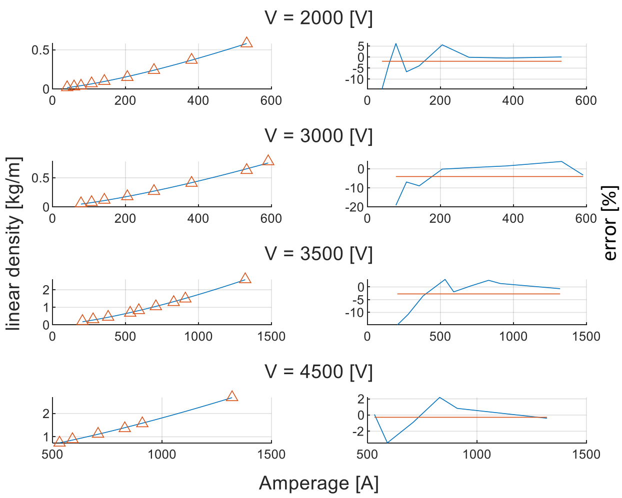

Figure 10 – Single term power equation analysis

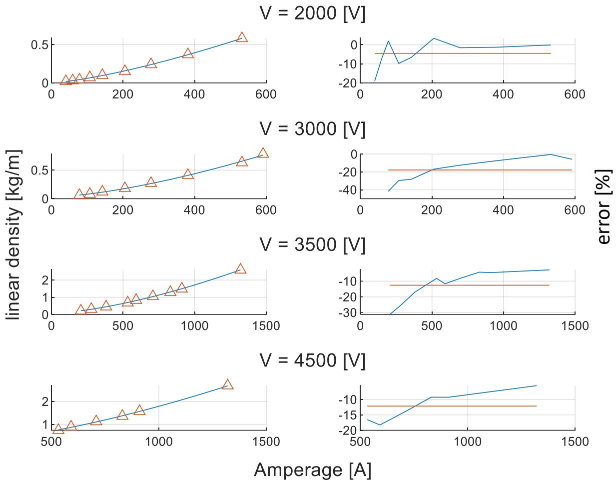

Figure 11 – Double term power equation analysis

As shown, the best equation that can fit all the voltage conditions is Fourier equation: in fact, for each case, the average error is not over 2% and each point has not an error over 10%. So, for the power system analysis the following equation system is considered as the best one to fit the results for the cables.

$$(4) \quad \begin{cases} m_{cabl} = (a_0 + a_1 \cos(I_{max} w) + b_1 \sin(I_{max} w)) l \\ a_0 = 0.560 \\ a_1 = -0.563 \\ b_1 = 0.200 \\ w = 0.002372 \end{cases}$$

where I_{max} is the maximum current derived from EM, l is the cable length required from the system.

4. RESULTS

4.1. EM Installation

If the electric motors should be installed on or around the mast, it is important to consider the mast shear forces applied during the function and the failures of them. In fact, different configurations of installation can have shear forces components different from each other. In Figure *12* shear forces areas due to EMs position are shown.

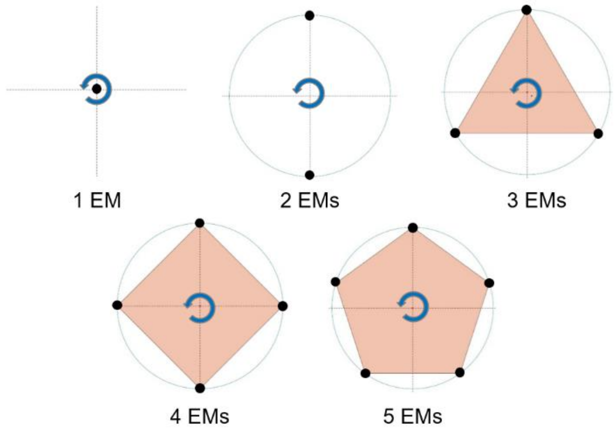

Figure 12 – EMs Installation Configuration

A maximum of 5 EMs installed is considered. As illustrated, all the installations have an area of shear forces applied that can change because of failures. In fact, with 1 EM installed, the point of application of shear forces is the same of the mast torque resultant. The theory of shear forces is that there is an equilibrium to the mast when the resultant of the torque of the mast is inside the area of the shear forces generated by the functioning electric motors. When electric motors fail, the area is reduced.

In case of 2 EMs installed, the shear forces area is a line along which the mast torque resultant is positioned. When one EM fails, the line is reduced to one point that is the remaining EM, distant from the torque resultant. So, this means that this configuration does not satisfy the equilibrium with mast torque in case of failure.

The configuration with 3 EMs installed has a triangular area, where the mast torque resultant is in, at the centre of the area. When one EM fails, the area is reduced to one line that links the remaining EMs, distant from the mast torque resultant. So even this configuration does not satisfy the equilibrium.

Meanwhile, 4 EMs guarantee a square area with the mast torque resultant in it. In case of one EM failure, the area is reduced to a triangular one with the mast torque resultant along the perimeter of it. So, this means that this configuration guarantees the equilibrium of the shear forces in case of one EM failure. For 2 EMs failure the configuration cannot fully satisfy the equilibrium because it depends on the position of the failed EMs. In fact, if the failed EMs are close, the area is reduced to a line that links the remaining ones that are distant from the mast torque resultant application; otherwise, if the failed EMs are in the opposite positions, the line that links the remaining ones passes through the point of the application of the mast torque resultant.

The same consideration can be made for the installation of 5 EMs, with the result that this configuration can guarantee the equilibrium with a maximum of 2 failed EMs.

For these reasons, the configuration analysed are with 1 EM and 4 EMs installed.

Actually, the perimeter of analysis are light helicopters, from LHD and competitors, that guarantee CS.27.

4.2. EPS with 1 EM

In this section, results for EPS with 1 EM installed are presented. This is the simplest architecture because the electric motor is directly installed to the mast. In the following Figure, results for each component of the EPS and for the whole EPS are presented for each helicopter considered in our benchmarking.

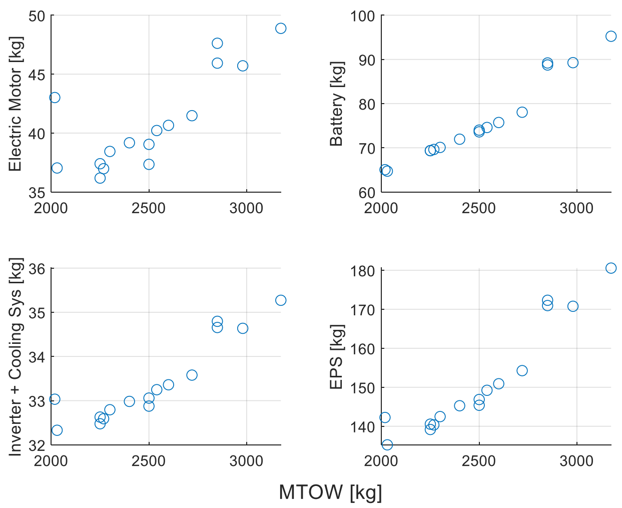

Figure 13 – EPS with 1 EM installed results

For this condition, the main component of the system is the battery: in fact, its weight covers almost 50% of the weight of the total system. Then, EPS weight is almost linear as a function of MTOW. The range of EPS weight is from 135kg to 180kg for light helicopters, which is equal more or less to 6% of MTOW.

This system is the simplest in terms of modification to the helicopter architecture: in fact, it requires small modifications and little provisions to be installed to actual architectures of the helicopters. But the strongest constraint concerns the guarantee of catastrophic condition: in fact, actually there are no such information about how a single electric motor pays safety condition, so the risk is that there is no electric motor that can satisfy safety condition.

4.3. EPS with 4 EMs

In this section, results for EPS with 4 EMs installed are presented. This is the most secure architecture because redundancies are guaranteed in case of failure. In the following Figure, results for each component of the EPS and for the whole EPS are presented for each helicopter considered in our benchmarking.

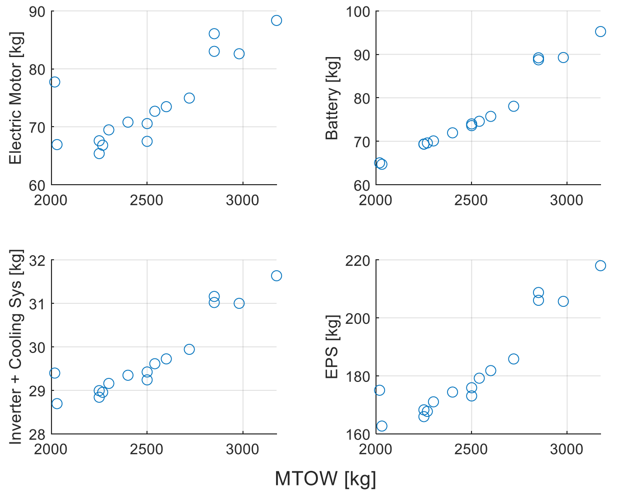

Figure 14 – EPS with 4 EMs installed results

For this condition, the main components of the system are EMs and, again, the battery: in fact, their weights cover almost 30% each of the weight of the total system. Then, even for this architecture, EPS weight is almost linear as a function of MTOW. The range of EPS weight is from 160kg to 220kg for light helicopters, which is equal more or less to 7% of MTOW.

This system is the safest: in fact, redundancies guarantee the function of the system even in case of failure of 1 EM even if they cannot guarantee catastrophic condition alone. But the main problem concerns the modification of helicopter architecture: in fact, actually there is not enough space to install all the electric motors in the same place, so it is possible that modification to the drive system is required so it is possible to install them inside the second stage, fixed to the solenoid.

5. CONCLUSIONS

This analysis has the validity as predictive method, based on the new technologies data available mixed with our solid experience as a helicopter manufacturer. It is clear that these technologies are in a continuous development, so that the actual results could change because of it, but being aware of that, this work present results applicable with actual technology conditions with potential refinement for future outlook.

Then, this predictive method is based on a really basic architecture of the system because only main components are considered, but it was run on real flight conditions.

Effective considerations have not been made regarding possible structural modifications, battery location, cables and EMs installation, so there is already an idea of possible weight increase, although it is not possible to quantify it at this stage. Meanwhile, it is possible to consider a revision of CS.27, trying to integrate an engine backup system to give support in case of thermal engine failure.

The work that has been done allows us to make an objective and predictive assessment of the hybridization of a single-motor machine, obviously making assumptions as a basic machine and modest evaluation of impacts. The rest of the modifications will be evaluated and presented later.

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