Solutions Analysis for Electric Generator to be Coupled in Aircraft Turbines
Cardoso, José

Abstract — The aircraft industry is developing the More Electric Aircraft (MEA) concept with an ultimate goal of distributing only electrical power across the airframe. The replacement of existing systems with electric equivalents has, and will continue to, significantly increase the electrical power requirement. This has created a need for the enhancement of generation capacity and changes to distribution systems. To achieve this goal it is necessary to redefine the generation of the electric power on-board since a solution of scaling up the existing one is set aside, due to the fact that the space in an aircraft turbine is very limited.

One of the possibilities for this application is the introduction of a synchronous permanent magnet generator directly embedded in a shaft of the turbine, therefore eliminating the traditional gearbox. In this paper, a previous solution is analysed in what mainly concerns the ferromagnetic materials to be used in the application. This way, soft ferromagnetic materials such as silicon electric steel, iron cobalt alloy and the more recent soft magnetic composites are studied as well as permanent magnets of NdFeB and SmCo for the hard magnetic materials. These materials are characterized throughout this work in terms their magnetic induction levels, Joule losses, resistance to mechanical stresses and thermal capability.

The results of this work set some limitations in the usage of the different materials while several simulations were realised. Additionally, a concrete localisation of the future generator is suggested.

Keywords: On-board electric generators, permanent-magnet machines, ferromagnetic materials.

I. INTRODUCTION

The aircraft industry is an industry characterized by its excellence and forefront of technological developments. Over the past years, the concern about creating a “More Electrical Aircraft” (MEA) is getting more attention of the community.

In a conventional aircraft the jet fuel is converted into power by the engines which are mostly used as propulsive power in order to move the aircraft. It is the desire of all who work in this concept to replace or minimize the existing range of secondary systems across the airframe by a single electric power system. This would eliminate some components of the traditional architecture such as [1] [2]:

- The mechanical system, which provides power with engine mounted accessories as hydraulic pumps and to the main electric generator.
- The hydraulic system provides primarily the hydraulic pump to the actuation systems for primary and secondary flight control and also the landing gear.
- The electric system, which is obtained from the main generator in order to power the avionics, cabin and aircraft lighting.

Over the years this systems have become more and more complex and some drawbacks are inherent of the interactions between different pieces of equipment. Furthermore the maintenance of some of these systems are hazardous requiring much attention to a innumerable details and not all the failures are easily detected.

As a result of these conditions as well as the increased cabin loads for improved in-flight entertainment, it has been estimated that future electrical power requirements will exceed 500 kW per engine. To achieve these goals a major revaluation of the common electric generation onboard the aircraft is being undertaken.

Different approaches are required to meet these new requirements since it is unlikely that current technology will ever meet future demand. One of the preferred concepts is to fully embed the generation systems within the engine. If this innovation is successfully applied, there is no need for the conventional gearbox because the generator is directly attached in the fan shafts.

In literature the most proposed electrical machine for this application is the permanent magnet machines because they do not need self-excitation, have high efficiency compared to other machine types and have high power density.

II. CONSIDERATIONS FOR THE GENERATOR

A. System Location

Nowadays the majority of modern civil airplanes use turbofan engines as propulsion system. Inside an aircraft turbine there is a process that can be described as a Brayton cycle. In its interior there are usually two shafts: a low pressure shaft and a high pressure shaft. This number of shafts can be different from aircraft to aircraft depending on the technical approach of the manufacturer.

The low pressure shaft connects the inlet fan, the low pressure compressor and the low pressure turbine. Externally to this component, there is a high pressure shaft which connects the compressor to the turbine in the high pressure system.

Due to the fact that the shafts are connected to the gas turbine their speed will change according to the operation
conditions of the engine. Typically, for two-shaft architecture, the low pressure shaft operates in a range of 1000-3000 rpm while the high pressure shaft can go up to 10000-20000 rpm [3].

Moreover, there are two possible locations for the embedded electric generator: either at the cooler front end of the engine, behind the fan or in the exhaust tailcone. The choosing process is a major decision because of the environment. The future generator must tolerate the intrinsic conditions of each location. An illustration of the several places for placement of the generator is presented in Figure 1.

![Illustration of an aircraft turbine](image)

**Figure 1 - Illustration of an aircraft turbine**

The attractive cool end installation on the front end of the engine, where the temperature is estimated to be in the range of -50°C to 150°C, has certain drawbacks as regards operation and maintenance. If the generator is installed in the tailcone as a quickly detachable unit, the working temperature can go up to 300°C.

**B. Magnetic Materials**

At this point of work there are several hypotheses left open to explore in the design of the electric generator. Therefore, the ferromagnetic materials must be studied for all the possibilities and working conditions.

With faster electrical machines there are problems related to the centrifugal forces acting on the rotating parts, and the eddy-current losses, due to high electric frequencies.

One of the purposes of this work was to study if the recent soft magnetic composites would be suitable for this type of application. These materials can be described as ferromagnetic powder particles surrounded by an electric insulating film. They are normally manufactured by the powder metallurgy industry with new techniques, such as two step compaction, warm compaction followed by a heat treatment at relatively low temperature. The unique properties of these composite materials include three-dimensional (3D) isotropic ferromagnetic behavior and flexible machine design, when compared to the traditional anisotropy of laminated steel cores and designs restrictions [4] [5] [6].

Therefore, these composites will be compared with other types of materials in terms of its magnetic and mechanical properties such as: magnetic saturation; core loss; initial permeability; magnetic flux density after the linear stage of its BH characteristic and tensile strength. These comparison will be proceed against traditional electric steel of a common machine (M270-50A), with a lamination thickness of 0,5mm, and with an advanced alloy of iron-cobalt (Hiperco50) with 0,15mm lamination [7] [8].

In what concerns the hard ferromagnetic materials, the discussion will be centered between the samarium-cobalt (SmCo) magnets or recent neodymium-iron-boron (NdFeB). These tow materials belong to the same family of permanent magnets, the rare-earth magnets. The NdFeB magnets generally exhibit a higher remanence than the SmCo but otherwise are less tolerant to higher temperatures as they can work only up to 200°C while the SmCo magnets can go up to 370°C. This will require studying the different B-H characteristics of the magnets to see if they are capable to operate when they are expected to.

**III. PM SYNCHRONOUS MACHINE FOR AIRCRAFT TURBINE**

In order to study and record the performance of the several materials with respect to core losses, a previous work from a direct driven generator was studied. The solution presented in [9] [10] was the base for the study of a new generator that could be directly embedded onto a shaft. Some of the general properties of the adopted generator are described in Table I.

As previously discussed, there are two different shafts in an aircraft turbine. At this point of work it is desirable to maintain the two possible options of the generator location. Since a low speed generator was tested in the latest chapter it is time for study a generator that could also operate at higher speed.

<table>
<thead>
<tr>
<th>General properties of the embedded generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poles</td>
</tr>
<tr>
<td>Stator outer diameter [mm]</td>
</tr>
<tr>
<td>Stator inner diameter [mm]</td>
</tr>
<tr>
<td>Rotor outer diameter [mm]</td>
</tr>
<tr>
<td>Length [mm]</td>
</tr>
<tr>
<td>Air Gap [mm]</td>
</tr>
</tbody>
</table>

The generator adopted was a permanent magnet synchronous machine with magnets located in the rotor. This type of machine is common in applications such as wind generators and has to be adapted to the harsh conditions of an aircraft turbine.

This model has few poles since it was designed for the high speed shaft and therefore, according to (1), fewer poles are desirable for a high speed machine so, its frequency does not have higher values. Since this is a synchronous machine the synchronous speed, \( n_s \), is obtained from:

\[
n_s = \frac{60}{pp} \times f \quad \text{[rpm]} \quad (1)
\]

Where \( pp \) are the number of pair of poles and \( f \) the desired electric frequency in[Hz].
Another design parameter chosen by the authors in this previously work was to set the generator at the engine tail-cone where the temperature would not allow the use of neodymium-iron-boron magnets. However, the main idea of this study is to verify the different responses of the several materials at our disposal and therefore every possibility will be left open.

In [9] there are no specifics to whatsoever of the ferromagnetic materials applied, only the reference for the type of the magnets and that the soft material is an iron-cobalt alloy. Since the materials needed to be defined to have at least a standard for future comparisons, it was set that the material for the core of the machine was the Hiperco50 alloy and that the Samarium-Cobalt magnets were the S2268 with the commercial name of Sam22 presented by Magnetic Component Engineering Inc..

Thus, an electromagnetic model of this machine was built and solved with a finite element analysis (FEA) software. The mesh consists of 39276 distinct elements and is finer close to critical parts such as air gap and coarser in areas like the yoke of the stator. The result of these simulations for the steady state condition is shown in Figure 2 where the magnetic flux density is presented.

![Magnetic flux density, norm](image)

**Figure 2 - Magnetic flux density, norm**

No currents in the stator slots were declared. The open circuit test was produced for purpose of studying only the losses of the core material and to analyze the performance of the magnets.

The magnetic potential,$\vec{A}$, which is normal to the image plane, is illustrated in Figure 2 as black lines and it is used to, calculate the norm of the magnetic flux according to (2) since there is only the z component.

$$ B = \nabla \times \vec{A} \quad [T] \quad (2) $$

The referred materials were added to the software library. While for the Hiperco50 it was added its $B-H$ characteristic, for the S2268 only its remanence, $B_r$, was set for 0.947T since it was assumed that they would operate in the second quadrant of their $B-H$ characteristic where we can assume that the magnet can be described with (3) for 20°C, commonly known as normal curve.

$$ B_m = \mu_0 \mu_r H_m + B_r \quad [T] \quad (3) $$

Where $\mu_0$ is the vacuum permeability, $\mu_r$ is the relative permeability of the magnet and $H_m$ is the magnetic field in the magnet. This aspect of the magnets are very important because the remanence of each magnet can vary in relation with the temperature that it supposed to be operating.

For the time-varying analysis it was set that the rotor would rotate at 8000rpm which gives a frequency of 400Hz. This was chosen since this is the usual working frequency on nowadays conventional aircrafts. The result of this simulation is presented for one electric cycle in Figure 3 where the time varying magnetic flux norm is presented for a point between two slots and near the air gap, where there is a bigger density of magnetic lines and, therefore, a higher value of flux is obtained.

As it can be seen in Figure 3 the software plots of the magnetic flux density norm. This way, the values of the magnetic flux are always positive instead of being opposite. Since adjacent magnets have opposite polarities these field lines tend to close with nearby magnets. A maximum value of 1.6T is obtained with the Hiperco50 as core. This is a crucial aspect of the material, because a high value of magnetic flux density is needed since it’s related with the creating electric field as determined by Faraday’s law (4).

$$ \oint_C \vec{E} \cdot ds = - \frac{d}{dt} \int_S \vec{B} \cdot d\vec{a} \quad (4) $$

Where the line integral of the electric field intensity,$\vec{E}$, through a closed path, $C$, is equal to time-varying of the magnetic flux in a surface bounded, $S$.

Then, a similar procedure was carried out but with the silicon electrical steel M270-50A for the same point of extraction of the values and same time-varying. The results are also in Figure 3.

![Time][B]

**Figure 3**

After a quick inspection it can be seen that the maximum value obtain in Figure 3 is 1.4T. This way a difference between the materials can be written down since for the same conditions the Hiperco50 offers a plus 0.2T of induction than the M270-50A. This can be explained by the BH characteristics of the materials where for the same magnetic field, the Hiperco50 can offer a higher level of induction as can be seen in Figure 4.
A. Core Losses

In order to produce the core losses calculations of each material and to observe how they behave in different working conditions two distinct areas in the machine were defined:

- A zone: area between the stator slots for the electric cables (commonly known as stator teeth)
- B zone: area between the top of the slots and end generator stator

The rotor losses are neglected since no considerable variation of magnetic flux is normally expected in a permanent magnet machine, with the magnets located in the rotor. In Table II the levels of induction obtained for each material and in the zones previously described are summarized.

Table II

<table>
<thead>
<tr>
<th>Material</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiperco50</td>
<td>1.6T</td>
<td>1T</td>
</tr>
<tr>
<td>M270-50A</td>
<td>1.4T</td>
<td>0.9T</td>
</tr>
</tbody>
</table>

For the core loss study of each material it was decided to analyze the range between 3000rpm and 10000rpm. Although this range of speed is not normally available in the aircraft turbine shafts, it can show how the two materials behave with the increment of its working frequency. This way, the maximum speed of the low pressure shaft and the minimum speed of high pressure shaft will be studied.

The total core losses of a given material can be estimated by adding the contribution of hysteresis losses (6) to the eddy current losses (7) resulting in (8).

\[ P_h = K_f B_{max}^2 \]  
\[ P_e = K_f f^2 B_{max}^2 \]  
\[ P_{total} = K_f f. B_{max}^2 (1 + f) \]  

Where \( K_f \) is a constant for each level of frequency which is given by \( f \) and \( B_{max}^2 \) represents the maximum magnetic induction registered. For the same level of frequency it can be assumed that \( K_f \) is constant in (6) (7) (8) since the error introduced by approximations can be despised. This way, despite the level of frequency or induction, the total core losses could be estimated by an extrapolation of the given values from the manufactures.

However, during this work it was realized that the final results of a material were very different, depending on which frequency of the core loss given by the manufactures, the extrapolation was based on. The frequency of core losses given in the datasheets can vary from manufacture to manufacture. For instance the manufactures of Hiperco50 offers on their datasheets core loss for 60Hz, 400Hz, 800Hz and the manufactures of M270-50A offers for 50Hz, 100Hz, 200Hz, 400Hz and 1000Hz. On the other hand, the range of frequencies in study went from 150Hz to 500Hz with an increment of 50Hz resulting in eight different levels of frequencies.

If the present frequency in study was 300Hz the final result for the total loss (8) of Hiperco50 would be dependent of the values that the extrapolation was based on. 60Hz or 400Hz are the frequencies between the 300Hz given by the manufactures. The final results showed a very large discrepancy.

To overcome this unforeseen problem, for a given material, with different values of core loss for different frequencies but at the same level of induction, it was possible to make a mathematical regression in order to obtain an expression that could simulate the behavior of the correspondent material, in a range of frequencies.

In Figure 5 is shown the two regressions made for 1T and 1.6T for Hiperco50 from the total losses given by the manufacture. This way, we can have an overall idea of what we can expect for the core losses. Notice that the resulting expression of regression as a similar format that the one described in (8) and the coefficient of determination, denoted \( R^2 \) is close to 1. A similar work for 0.9T and 1.4T for the silicon steel M270-50A was also produced.

In order to validate the previous results for the same range of frequencies, it was carried out the calculation of the constant \( K_f \) for each of the frequencies and levels of induction starting from the values given by the manufactures. This way extrapolations were made from the constant calculated for a given level of induction and made a scan for the desired frequency.

Figure 6 and Figure 7 present the respective graphics for the specific losses of Hiperco50 for 1T and 1.6 T calculated.
directly from the manufacturer's data. These charts are indicated in the figure legends with the letter "k", representing the constant K, followed by a number which refers to the frequency for which this constant was calculated. Thus, for each induction we obtained three graphs of K's for 60Hz, 400Hz and 800Hz to which the trend line calculated previously for the corresponding flux density was added. In these graphs the data for the calculation of the constant 1000Hz were discarded because this value is outside the limits of the desired frequencies. The graph referring to the trend line is identified in the caption of the following image as a "trend line".

These calculations were made according to the respective division of zones presented before and its respective induction levels. As it can be seen in Table III the iron cobalt alloy Hiperco50 shows about half the core losses of the silicon steel M270-50A.

### B. Mechanical stress

For applications with considerable rotational speed, as is the case in the present work, the materials that make part of the solution must be studied in order to ascertain whether they possess mechanical properties that allow its use. If this procedure is neglected may be at risk throughout the project since there are no guarantees about the behavior of certain materials when subjected to mechanical stress.

A study for the two core materials was carried on with the same FEA software and therefore same model already built but with some additional constructions.

For a rotational speed of 10000rpm the distributions of stresses if presented in Figure 8.

With the tensile strength given by each manufactures for the materials and assuming a 50% plus security margin the materials were tested and the results plotted in Table IV.

<table>
<thead>
<tr>
<th>rpm</th>
<th>M270-50A</th>
<th>Hiperco50</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.34%</td>
<td>0.25%</td>
</tr>
<tr>
<td>1500</td>
<td>0.77%</td>
<td>0.55%</td>
</tr>
<tr>
<td>2000</td>
<td>1.37%</td>
<td>0.98%</td>
</tr>
<tr>
<td>2500</td>
<td>2.13%</td>
<td>1.53%</td>
</tr>
<tr>
<td>3000</td>
<td>3.07%</td>
<td>2.21%</td>
</tr>
<tr>
<td>10000</td>
<td>34.12%</td>
<td>24.52%</td>
</tr>
<tr>
<td>11000</td>
<td>41.26%</td>
<td>29.66%</td>
</tr>
<tr>
<td>12000</td>
<td>49.13%</td>
<td>35.31%</td>
</tr>
<tr>
<td>13000</td>
<td>57.64%</td>
<td>41.43%</td>
</tr>
<tr>
<td>14000</td>
<td>66.87%</td>
<td>48.06%</td>
</tr>
<tr>
<td>15000</td>
<td>76.75%</td>
<td>55.16%</td>
</tr>
<tr>
<td>16000</td>
<td>87.35%</td>
<td>62.78%</td>
</tr>
<tr>
<td>17000</td>
<td>98.6%</td>
<td>70.86%</td>
</tr>
<tr>
<td></td>
<td>18000</td>
<td>19000</td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>110.53%</td>
<td>123.15%</td>
<td>136.48%</td>
</tr>
<tr>
<td>79.43%</td>
<td>88.5%</td>
<td>98.08%</td>
</tr>
</tbody>
</table>

In Table IV is shown the percentage of the limit stress that the material can withstands in relation with the correspondent rotational force. The Hiperco50 can be equipped for all the rotational speeds whereas the M270-50A can only be settled up to 17000rpm.

IV. PERMANENT MAGNETS STUDY

Up till now the permanent magnets on the machine were of Samarium-Cobalt with the commercial name S2268 [11]. Since the magnets of Neodymium-Iron-Boron, such as the N4025 [12], have a higher energy product, $(BH)_{max}$, they can theoretically deliver higher values for the magnetic flux and therefore a higher voltage can be induced in the stator coils of a permanent magnet machine. However these magnets do not support temperatures far above 200°C.

As previously discussed the magnets have a BH characteristic where the designer must observe if they are able to work properly according to the existing conditions. When a generator is designed, all possible working points must be tested and not only its nominal behavior.

A. Permanent Magnet Losses

In case of a short circuit in the stator cables it must be studied if it can generate an overheat in the magnets which can lead to a demagnetization. This is a critical issue, since as stated in (3), if the magnetic field in the magnet, $H_m$, increase beyond its coercivity, $H_c$, the magnet will demagnetize. Furthermore, an increase of the magnet temperature will lower the value of coercivity of the magnet since its BH characteristic is translated closer to the origin of the axis.

According to (3) the magnet normal curve is being treated as straight line but for higher temperatures the magnet may present a rapid reduction of the coercive magnetic field, this way, the BH line is characterized by the appearance of a decay knee where the induction of the magnet drops drastically until it reaches zero when a demagnetization has occurred.

If for several different temperatures the working point is known $(B_m;H_m)$, a straight line can be plotted from these points to the origin $(B_m = 0 \text{T}; H_m = 0 \text{A/m})$. In the presence of currents an approximation can be made

$$-\frac{NI}{h_m}$$

(9)

Where $NI$ is the number of $A/\text{turns}$ through the circuit and $h_m$ the magnet thickness [13].

Using this graphic method it can be predicted if the magnet will work properly and if its choice is correct. This way, the working point in a magnet should never be above the knee of the normal curve or there is a serious risk of demagnetization.

The previous studies have been made with the stator currents set to zero but the generator will work naturally with stator currents. This current associated with the rotational movement of the magnets can produce a variation on the magnetic flux $B_m$ that the magnet delivers for one mechanical cycle. For a rotational speed of 3000rpm and a correspondent electric frequency of 150Hz, three current signals were defined with a 120° electric discrepancy. The variation in a single rotor SmCo magnet is plotted in Figure 9 for its no load state for a complete rotation and therefore the results presented were obtained for 0.02 s.

![Figure 9](image_url)

Based on previous works in [13] [14] and [15] on ways to estimate and predict the eddy current losses for permanent magnets in a rotor of a synchronous machine, a similar study was conducted using (4) that is rewritten for a remembering propose:

$$\oint_C E \cdot ds = \frac{d}{dt} \int_S B \cdot da$$

In this equation, the following assumptions are used:

- The magnetic flux density is perpendicular to the plane of drawing (xy);
- The effect of eddy currents in the magnets on the magnetic field is negligible;
- End effects are negligible, so that the current density only has a component in the z-direction, and the two sides of the closed path parallel to the x-axis do not contribute to the line integral. This assumption is reasonable if the magnet length in the z-direction is much larger than the magnet width $d_m$.
- The magnetic flux density was declared as uniform all over the magnet.

For a better understanding of these assumptions Figure 10 is presented.
The electric field strength can be replaced by the product of the current density and the resistivity of the magnet as follow (10):

\[ E = \rho_m J \]  

(10)

With this, the resulting expression for the current density becomes (11)

\[ J_2(x) = \frac{x}{\rho_m} \frac{dB}{dt} \]  

(11)

Regarding (4), (10) and (11) in (12) it is presented the power losses per unit of magnet volume:

\[
\frac{P_m}{Vol} = \frac{1}{b_m^{n/2}} \int_{-b_m^{n/2}}^{b_m^{n/2}} \rho_m J_2^2(x) dx = \frac{b_m^{n/2}}{12\rho_m} \left( \frac{dB}{dt} \right)^2
\]

(12)

Where Vol \([m^3]\) stands for the magnet volume, \(b_m [m]\) its width, \(f [Hz]\) the electric frequency of the magnetic induction and \(\rho_m [\mu\Omega \cdot m]\) its electric resistivity. The amplitude of the variation of the magnetic flux density in the magnet is represented by \(B_m[T]\). The way the magnet losses can be predicted with (13):

\[
P_m = Vol b_m^2 (\Delta B_m)^2 (2\pi f)^2
\]

(13)

As (13) shows the magnet losses vary quadratically with its width. In Figure 9 we can observe the evolution of the magnetic flux in the magnet. To determine what is the value of \(B_m\) an analysis of the signal spectrum must be conducted. Therefore, with the auxiliary of the function fft, Fast Fourier Transform, a study of the harmonic content was conducted. In Figure 11 it presented the amplitude spectrum of B(t). For this analysis it was declared a sample frequency of 2000 Hz, whereas 10 cycles like the one in Figure 9 were studied.

B. Thermal Model

Since there is the presence of Joule losses in the magnets it is necessary to study if it will influence the temperature of the magnet. As discussed before, an increase of the temperature of a magnet can result in a demagnetizing of itself.

An electro-thermal model was constructed where the losses obtained by the previous calculations where declared in the permanent magnet as a current density and converted to heat. This approach was already used in previous works [13] and [14]. The thermal constants are presented in Table V.

<table>
<thead>
<tr>
<th></th>
<th>Hiperco 50</th>
<th>NdFeB</th>
<th>Sm(<em>2)Co(</em>{17})</th>
<th>Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho) [kg/m(^3)]</td>
<td>8110</td>
<td>7600</td>
<td>8300</td>
<td>5850</td>
</tr>
<tr>
<td>(C_p) [1/(kg \times K)]</td>
<td>650</td>
<td>502</td>
<td>370</td>
<td>503</td>
</tr>
<tr>
<td>(k) [W/(m \times K)]</td>
<td>29</td>
<td>8.93</td>
<td>12</td>
<td>269</td>
</tr>
</tbody>
</table>

Where \(\rho\) is the density of the material, \(C_p\) its specific heat and \(k\) the respective thermal conductivity. The column for the mix is related to the domains of the model in order to simulate the stator slots. In this mix a proportionality of copper, air and insulating material was taken into account.

On the model built for the previous machine, with the Hiperco50 alloy as the core material and magnets of SmCo, a model of thermal conductivity was coupled. The temperature of all its components was set to 20°C and for a rotational speed of 3000rpm the final distribution of temperature is presented in Figure 12. In this model the magnets the joule losses of the magnets were declared as the heat source as previously discussed. An additional zone was declared as solid aluminum in order to simulate the presence of the shaft.
on where the generator will be coupled. In this model the Joule losses calculated for the Hiperco 50 in the previous chapter were also taken into account.

In Figure 12 the regions with white color are the regions where a higher increment of the final temperature was reached whereas the red regions are regions were a small deviation on the temperature is detected. As it can be seen, near the source of heat, the permanent magnets, higher temperatures are reached. For this simulation, an increase of near 5°C is obtained inside the magnets.

The Figure 12 is the solution for the final instant, $t = 2500$ s, nearly 40 minutes. In Figure 13 the evolution of the temperature is showed for a point in the center of one magnet. At almost 30 minutes it can be observed that the temperature inside the magnet as already stabilized.

Since the power losses used to simulate in the previous examples were calculated when the rotor speed was set to 3000 rpm, a very wide range of speeds had to be studied. As stated before, the shafts of an aircraft turbine can vary from 1000-3000rpm and 10000-20000rpm. Analyzing (13) it can be seen that an increase of the rotational speed produces an increase of the electric frequencies to which the magnet is subjected. These losses are quadratically proportional to the electric frequency as can be seen in Figure 14 despite the type of magnets used. A model as the previous one was built for the testing of magnets of NdFeB in order to make a result comparison.

In Table VI it is registered the values obtained in what concerns the temperature of the magnet for the maximum rotational speed of the low pressure shaft and the upper and lower limits of the high pressure shaft as well as a mid rotational speed. For the various simulations it was defined that the initial temperature of the model was 20°C.

<table>
<thead>
<tr>
<th>rpm</th>
<th>$T_{\text{max}}$[°C]</th>
<th>$\Delta T_{\text{max}}$[°C]</th>
<th>$T'_{\text{max}}$[°C]</th>
<th>$\Delta T'_{\text{max}}$[°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>25,3</td>
<td>5,3</td>
<td>24,2</td>
<td>4,2</td>
</tr>
<tr>
<td>10000</td>
<td>79</td>
<td>59</td>
<td>64,5</td>
<td>44,5</td>
</tr>
<tr>
<td>12000</td>
<td>104,5</td>
<td>84,5</td>
<td>86</td>
<td>66</td>
</tr>
<tr>
<td>15000</td>
<td>155,2</td>
<td>135,2</td>
<td>131,5</td>
<td>111,5</td>
</tr>
<tr>
<td>18000</td>
<td>218,6</td>
<td>198,6</td>
<td>182</td>
<td>162</td>
</tr>
<tr>
<td>20000</td>
<td>256</td>
<td>236</td>
<td>219</td>
<td>199</td>
</tr>
</tbody>
</table>

The column $T_{\text{max}}$ presents the maximum value obtained for a rotational speed in the interior of the magnet while $\Delta T_{\text{max}}$ represents the difference between 20°C and the final temperature. Since there were no big differences for the simulations of the shaft of lower speed only the higher speed was presented.

As stated in the beginning of this article, there are four main possible locations for the generator to be coupled. In what concerns the temperature that the generator materials have to withstand, the favorable situation is if the generator is located at the front of the turbine. Here, the higher expected temperature is 150°C. In case of the location is at the end of the turbine, near the exhaust gases exit, 300°C can be reached.

In order to observe if the permanent magnets are able to work at such conditions knowing that they also work as a source of heat, simulations of the distributed temperatures were made in order to survey the BH characteristics of such materials. Since at the front of the turbine the highest expected temperature is 150°C, this was set as the initial
temperature of the model in which the following results have occurred for SmCo and NdFeB magnets in Figure 15 and 16 respectively.

![Figure 15](image)

**Figure 15**

![Figure 16](image)

**Figure 16**

In both Figure 15 and Figure 16 the operation points of the magnets for each simulation of the set final temperature/speed is marked in the respective BH characteristic as a dot. As expected from equation (13), the highest final temperature is obtained for the highest speed.

In Figure 15 it can be observed that at 348.7°C / 20000 rpm the final temperature reached inside the SmCo magnets is beyond to the knee of the BH characteristic, therefore the magnets would demagnetize. This way some undesired risks could be at stake. However is this type of application there are techniques of liquid refrigeration which can drop the temperature of the SmCo magnets and therefore make them applicable in both the low and high pressure shaft but only in a generator displayed at the front of an aircraft turbine.

The NdFeB magnets can only operate to 12000rpm since after that speed the temperature reached in the magnets will make them demagnetize as can be observed in Figure 16. No further BH characteristic were present in Figure 16 since the NdFeB magnet in study can only withstand a maximum working temperature of 250°C against the 350°C of the SmCo magnets. This way, the NdFeB magnets can only operate at the front of the turbine and in a solution of a generator coupled to the low pressure shaft.

No tests were conducted in order to simulate the presence of the generator in the end of the turbine since with an initial temperature of 300°C it is not expected that any material can support an increase of temperature from their Joule losses. As showed in Figure 15 and Figure 16 there are some constraints in the usage of permanent magnets in such harsh conditions.

V. CONCLUSIONS

This paper was realized with the intention of testing the limitations and the advantages/disadvantages of the soft and hard materials that could be assembled in a synchronous permanent magnet generator to be coupled in a shaft of an aircraft turbine. Throughout this work, a model of a previous permanent magnet generator was designed to simulate different responses of the materials taking into account several conditions to observe if there were some limitations in the usage of the studied materials, specifically in the location of the generator as well as the shaft that it could be attached to.

For the soft magnetic materials, a cobalt alloy and more traditional electric steel alloy were tested whereas magnets of SmCo and NdFeB represent the hard materials. The soft magnetic composites were left out in these studies since they cannot compete at the present time for such harsh applications as the one of this work. In what concerns the magnetic flux density, the Hiperco50 presents slightly better results than the M270-50A but this difference would tend to get higher if the construction of the generator was optimized (a smaller air-gap) and a higher magnetic field could be achieved. In what concerns the Joule losses, the cobalt alloy has 50% of the losses of the traditional electrical steel for all the ranges studied despite of having a higher magnetic induction. Through a mechanical simulation, it was shown that the Hiperco50 can withstand the stresses imposed by the two shafts while the M270-50 can only be used in a solution in the lower speed.

Due to the increase of temperature because of eddy currents in the magnets, the solution of a permanent magnet generator in the exhaust tailcone should be abandoned. For the usage of the magnets it was showed that NdFeB magnets can only be assembled in a generator located after the fan and in the low speed shaft whereas magnets of SmCo are suitable for the two available shafts, if a cooling system is used, but again in a solution displayed at the front of an aircraft turbine.

REFERENCES


[12] Integrated Magnetics, Technical Data Sheet Grade:N4025, Culver City, EUA.

