Design Methodology of a High Speed Switched Reluctance Generator Drive for Aircrafts

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Abstract

The paper proposes a high speed switched reluctance (SR) drive for aircraft applications, covering the demand of more electric aircrafts (MEA) and defending the particular benefits of this machine technology against others, such as permanent magnet synchronous generators. An appropriate topology of electrical machine and power converter for a high speed DC distribution grid is selected. Firstly, the electromagnetic design of the generator, by means of FEM, is described in detail, paying attention to the problem of the torque ripple and pointing out some solutions to improve it, based on an iterative optimisation of both stator and rotor geometries and phases activation and deactivation angles. Then, the design of power electronics is also analysed, obtaining the required modules and cooling system from a simulation model, using the maximum and average current levels as well as the duty cycles. The model has been developed from the generator electromagnetic design and integrates the control strategy, in charge of controlling the DC-link voltage. An iterative procedure using FEM analysis and the simulation model is also used to validate the thermal and mechanical behaviour of the system. Finally, the integration of the complete electric drive is discussed with the criteria of maintaining the system within the available room and keeping the temperature under the maximum limits. The application of aircraft equipment is specially demanding in terms of robustness, low maintenance, fault tolerance, high temperature and harsh environment, and those are the reasons why the SR generator is a reliable alternative.

1. Introduction and state of the art

Traditionally, electrical generators for aeronautic applications consist of conventional wound rotor synchronous machines (WRSG), excited by means of a PM exciter stage, then a main exciter and finally a main alternator directly connected to the 3-phase AC power system of the airplane [1-3]. The generator terminal voltage is controlled by the excitation stage, which regulates main rotor field strength [1, 4, 5]. In this conventional approach, the speed of the generator must be kept constant, since the stator winding is directly connected to the 115V 400Hz grid [5, 6]. This constant-speed requirement has important disadvantages in terms of additional mechanical components, cost, reliability, speed range [2, 3, 5]. The power electronics present in this topology are: The uncontrolled rectifiers used for the excitation of the generator [4], the DC/DC converter used to perform field control of the generator [1], and the AC/DC rectifiers to convert the AC voltage at the main bus to the multi-level DC voltages at the secondary buses [3]. Alternatively, a controlled thyristor rectifier is used to excite the generator in place of the diode and chopper arrangement in some designs [4].

More recently, the More Electric Aircraft (MEA) concept has brought other alternatives to the table [7]. One of the pillars impelling MEA is variable-speed-constant-frequency technologies. Nowadays, there are three widely accepted proposals: Permanent Magnet Synchronous Machines (PMSM), Switched Reluctance Machines (SRM) and Induction Machines (IM) [2], listed in order of acceptance [3, 5, 8]. All of them are considerably rugged (which is essential for aeronautic applications) due to the lack of rotor windings and/or brushes, can be designed for high speed applications [9], and require very little maintenance [8].
PMSMs are probably the most studied alternative for MEA applications due to its unbeatable power density in terms of both mass and volume [8, 10, 11]. Most of authors claim that they can reach more power density than SRMs and IMs. However, this is only true when the comparison is done in unfair terms: PMSMs are not fault tolerant by default, but they must be for aircraft applications. The good news is that they can be designed to be fault tolerant (but not for high speed machines) [10]; the bad news is that doing so decreases their power density significantly [11]. Besides, PMSM lose torque capability with temperature (due to permanent magnets flux reduction [12-14]), much more than SRMs and IMs. As high temperatures are a common requirement for electric generators in aircrafts, this fact will further reduce the difference between PMSMs and the other two alternatives. After considering these two points, PMSMs present "only" around 25-30% more power density than SRMs [11]. PMSMs also have the highest efficiency [10, 15] (again, temperature worsens efficiency more acutely in this machine than in the other two [12]). Better energy efficiency implies less power losses than SRMs and IMs, but not necessarily less cooling requirements since they are less tolerant to temperature. However, they present significant drawbacks as well. As aforementioned, they are unavoidably intolerant to high temperatures due to the permanent magnets presence [8, 16]. Another important aspect of PMSMs is their intrinsic permanent flux, which cannot be shut down in case of fault [16].

The second most accepted technology is SRMs. Their main advantage over the other two is their ruggedness [8, 16], which is very difficult to beat since the rotor is made exclusively of steel laminations (no magnets as in PMSMs and no squirrel cage as in IMs). Besides, SRMs are extremely tolerant to harsh environments and high temperatures [8]. Another important advantage of SRMs is their intrinsic fault tolerance, in the sense that they will continue to operate in a satisfactory manner after sustaining a fault [11]. Most of SRMs can operate even if one of the phases cannot operate, which means that they are intrinsically redundant. This combination of advantages (ruggedness, temperature and fault tolerance, intrinsic redundancy) could make SRMs the most robust choice overall for aeronautic applications. The SRM presents the additional value of being able to operate as a motor with a good performance as starter (this functionality is commonly required in aircrafts), with extremely simple commutation from motor to generator and no additional components, just a few modifications in the control strategy. In fact, there are some references [17] where this machine is proposed as a starter/motor generator in aircrafts. PMSMs usually are not able to work as a starter unless a particular design is provided.

Finally, IMs are the less promising technology right now because they are surpassed by the other two alternatives in almost every relevant aspect. For instance, they are very rugged, but not as much as SRMs. Besides, they have the lowest power density [8, 16]. It is true that they are the most proved technology of all three, but for motors applications and not for generators.

Taking advantage of the benefits of the SRM technology for this application, it has been selected as the most suitable option as high speed generator for aircraft requirements. The SRM combines many desirable qualities of induction machines as well as PM brushless machines. Some advantages make SRM solution simple, robust and cheap to manufacture compared to other generator alternatives, while some others make it especially suitable for airborne applications, since high speeds, harsh environments, reliability, high performance and in some cases starter/generator operation are basic requirements for such application.

The paper starts with a selection of the topology for the electric generator in section 2, describing the design methodology, power losses analysis and the torque ripple problem, and getting as a result a preliminary solution for the generator. Section 3 studies the definition and design of the power electronics, paying special attention to the losses calculation and control strategy definition. Next, section 4 deals with the thermal analysis methodology, an iterative procedure that uses the results from previous sections. Finally, some discussion about the integration of the final electric drive is included in section 5, to finish with some conclusions.

2. Electromagnetic design of the generator

The solution of a SRM generator is calculated based on the specifications and restrictions from the electric generator of an aircraft, presented in Table I.
Table I. Specifications for the generator

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum outer diameter</td>
<td>150 mm</td>
</tr>
<tr>
<td>Maximum generator length</td>
<td>340 mm</td>
</tr>
<tr>
<td>Maximum generator weight</td>
<td>9 kg</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>12000 rpm</td>
</tr>
<tr>
<td>Rated Power</td>
<td>20 kW</td>
</tr>
<tr>
<td>Rated DC Voltage</td>
<td>270 V</td>
</tr>
<tr>
<td>Rated Output Current</td>
<td>75 A</td>
</tr>
</tbody>
</table>

The design methodology starts with the selection of an appropriate topology for the generator. Phase number should be as small as possible to reduce branches in the SRM power converter and also to increase power density. On the other hand, the smaller the number of phases, the higher the torque ripple. Although this work is focused on the operation of the machine as generator, it is considered that including its capability to work as a motor represents an extra benefit with no additional cost. This circumstance establishes three as the minimum number of phases. The number of poles in the rotor should be the smallest possible one in order to maximize the angular stroke, which is equivalent to minimize the required commutation frequency for a given rotating speed. This consideration sets to four the number of rotor poles, just thinking about fully saturated SRMs. As a consequence, a 6/4 machine is chosen for this purpose.

The design procedure continues with a simple analytic model from basic electromagnetic and geometrical relationships [18] constituting the essence of the SRM.

From the input requirements listed in table I the model provides the machine cross section, including basic parameters such as the rotor radius and the pole dimensions. It also provides the required average current density in the coil to achieve the necessary torque (power). Table II summarizes the overall dimensions as calculated from the model.

Table II. Basic dimensions of the calculated

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DIMENSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases (m)</td>
<td>3</td>
</tr>
<tr>
<td>Number of stator poles (Ns)</td>
<td>6</td>
</tr>
<tr>
<td>Number of rotor poles (Nr)</td>
<td>4</td>
</tr>
<tr>
<td>External diameter of the stator</td>
<td>150 mm</td>
</tr>
<tr>
<td>Internal diameter of the stator</td>
<td>80 mm</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>53 mm</td>
</tr>
<tr>
<td>Total length</td>
<td>110 mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Average magnetic field (airgap)</td>
<td>1.7 T</td>
</tr>
<tr>
<td>Height of stator pole</td>
<td>25.6 mm</td>
</tr>
<tr>
<td>Angular length of stator pole</td>
<td>30 °</td>
</tr>
<tr>
<td>Angular length of slot between poles</td>
<td>30 °</td>
</tr>
<tr>
<td>Height of rotor pole</td>
<td>12.0 mm</td>
</tr>
<tr>
<td>Angular length of rotor pole</td>
<td>30 °</td>
</tr>
<tr>
<td>Average current density at the coil</td>
<td>7.8 Amm²</td>
</tr>
<tr>
<td>Required Ampere-turn</td>
<td>3545 A</td>
</tr>
<tr>
<td>Nominal torque</td>
<td>15.9 Nm</td>
</tr>
</tbody>
</table>

A further analysis is then accomplished by means of a finite elements method (FEM) software to validate the model and refine the design. The results of this study at rated speed condition are presented in Figure 1. First drawing at the left shows the resulting flux lines of the FEM analysis with the final geometry, second one depicts the flux density and the third one presents the 3D grid generation used for the thermal analysis.
The generator is able to provide the required torque value at the defined conditions. However, the design needs to be optimized in order to reduce the torque ripple (torque ripple is required to be less than 10%), since the previous rough analysis is carried out with cylindrical poles and the torque has a high ripple. That is achieved by means of modifying the rotor design and tuning the phase-activation angles during the generator operation. The former consists in a sensibility analysis by modifying the stator and rotor dimensions (angular length and height of stator and rotor poles) in order to minimize the torque ripple. The best option is achieved with a slightly wider angular length of rotor than stator poles. The latter consists also in a parametrical analysis of the phase-activation angles, varying them in order to get the optimal torque ripple. When increasing the rotational speed, both activation and deactivation angles must be led respect to the initial values at zero speed. The conduction angle (between activation and deactivation) increases with the speed to better use the effect of the torque.

After refining the rotor poles profile and modifying the control strategy, the torque could result as presented in Figure 2, corresponding to the SRM design developed.

The switching frequency is defined at this moment of the design procedure in order to succeed the torque ripple condition. Nevertheless, this parameter will be checked later, when power electronics design is accomplished.

The next step is to calculate the iron, copper and power electronics losses, essential to validate the thermal behaviour of the generator. In fact, the high power density required and high environment temperature conditions on board the aircraft are very demanding challenges for the design. In order to calculate the losses it is important to obtain the current waveforms. That is achieved by defining the power electronics topology and control strategy to drive the generator. Iron losses are obtained directly from the FEM software, using the real waveforms obtained in section 3 and considering also the minor hysteresis loops. Both hysteresis, eddy current and excess losses are taken into account based on the Steinmetz equation (1). It is important to confirm that the methodology used by the FEM software is valid for non-sinusoidal waveforms as it is the case of the SRM.

$$P_{Fe} = k_h \cdot f \cdot B^2 + k_e \cdot f^2 \cdot B^2 + k_{exc} \cdot f^{\frac{3}{2}} \cdot B^{\frac{3}{2}}$$  \hspace{1cm} (1)
Copper losses, also known as Joule or resistive losses, depend on the phase current $i$, the DC resistance of the winding $R_{DC}$ (defined by its conductivity, its total length and its cross-sectional area) and the proximity effect and skin effect factor $k_{AC}$, which gives the AC resistance of the winding and depends on the geometrical configuration of the winding, number of turns and the frequency $f$ of the current [19]. Therefore, the instantaneous power dissipated in each coil is presented as:

$$P_{Cu}(t) = k_{AC} \cdot R_{DC} \cdot i^2(t)$$  \hspace{1cm} (2)

The above equation (2) has into account the current tails and phase overlapping of the real current profile. An accurate estimation of the copper losses including the skin and proximity effects on factor $k_{AC}$ could be achieved in a simulation model. Since the current application leads to high speed and thus high frequency, the skin effect must be considered. Conductor division, parallel paths, Roebel bars or Litz wire can help to reduce the factor $k_{AC}$ and therefore the copper losses.

### 3. Power electronics design and control

The most common power electronics converter used for this application is based on the half-bridge per phase topology [17], depicted in Figure 6. DC-link voltage, current carrying capacity, maximum switching frequency and isolation requirements specify the semiconductors used in the system, permitting to calculate the power electronics losses. In this case the electric generator operates connected to a 270V DC-link, therefore the elected blocking voltage for switches will be selected to 600V. Rest of parameters to define the power electronics depend on the current values, the duty cycle as well as cycle duration during operation.

A simulation model which integrates the generator model (based on the FEM analysis results described in section 2) and the power electronics validates the operation performance at rated power and speed. The simulation also permits to adjust the phase activating and deactivating angles to fulfill the torque requirement, getting the current waveforms, as Figure 4 shows.

![Figure 4. Three phase current waveforms from the HV generator designed](image)

Moreover, from the current waveforms it is possible to get the parameters to define the power electronic modules required. Maximum current, duty cycle, average switching frequency and cycle duration define the module to be selected as part of the power converter. Modules packaging is also important because of cooling and maintenance reasons. Two modules with three IGBTs and six diodes each are selected in this case in order to fit in a V-shape arrangement of the heatsinks in the final design, as presented later in Figure 7.

The modulation technique used for this drive is a hysteresis-band control, since the torque ripple is mandatory to be kept under a limit of 10%. When torque ripple is more critical than harmonic distortion, hysteresis-band is preferred to PWM technique.

Cooling conditions will be specified to verify that the maximum junction temperature ($T_j=150^\circ C$) at the semiconductors is not exceeded, as presented in Figure 5. The cooling method required is forced air, with a maximum temperature ($T_a$) of 55°C. A certain heatsink will be defined (PI6) and an air flow rate (225 m$^3$/h) to achieve the steady state temperature of the junction under the safety limits. It is important to ensure the static value of the thermal resistance between heatsink and ambient,
R\textsubscript{ths}, in a value around 0.035 K/W. Another parameter to define is the number of semiconductors per heatsink (switches and diodes). For the topology selected, the number will be six.

Figure 5. Total power losses per switch and diode and evolution of the temperature (Semisel, courtesy of Semikron)

Power electronics losses will be used in the thermal model and switching frequency will affect the torque ripple. Hence, there is an interaction between the different design stages and an iterative procedure needs to be considered.

Figure 6 depicts the control scheme used for the power electronics and the generator. Since a full converter topology is implemented connecting the SR generator with the DC distribution grid at the aircraft, the control strategy has to maintain the DC voltage at the output of the power converter. An external control loop with a P.I regulator will provide the current reference for the generator phases. An inner control loop keeps the current within the reference value, using hysteresis-band technique. Occasionally, the generator would turn into motor mode operation.

The hardware used for the control system is based on a hierarchical structure where a DSP is in charge of implementing the DC voltage regulation, providing the current references to a lower level control devices, based on FPGA or PLD, which are in charge of doing the hysteresis-band control of the phase currents.

4. Thermal analysis of the generator

A thermal model is created from the fine design of the machine, made with an electromagnetic 2D FEM model, the current waveforms of the generator (obtained from power electronics analysis simulation) and the characteristics of the machine materials. From them, a transient electromagnetic simulation is accomplished for a specific operation point (power, DC current and angular velocity) to
obtain the electromagnetic losses (core and copper losses, in particular), and using them as a heat source. Power electronics are supposed less critical in this case and authors are not including it as part of the thermal model in order to simplify the analysis.

After establishing the thermal loads and the boundary conditions (temperatures, heat transfer processes) the thermal maps in steady-state are obtained, considering conduction, convection and radiation heat transfer.

After the thermal model is achieved, a new analysis is required considering the influence of the coolant fluid. A Fluid-Structure Interaction (FSI) model can be carried out using FEM as well. An iterative study using two models (simulation model and FEM model) will be accomplished. When the analysis converges to a steady state, temperatures, pressures and air velocities would be obtained to validate thermally the design.

In a final step, mechanical deformations of the structure due to temperature could be calculated from a steady-state structural model in order to validate the mechanical behavior of the machine elements (specially the bearings), although this assessment remains out of the scope of the paper.

A complete scheme of the procedure is presented in Figure 7. Analytic equations (basic SRG design), FEM analysis (electromagnetic, thermal and mechanical) and electric simulations (power electronics and control) interact together to accomplish the final design of the electric drive.

![Figure 7. Complete scheme of the electric drive design procedure.](image)

### 5. Complete system integration in the aircraft

Once the electrical generator and the power electronics and control are designed to accomplish the requirements, the complete system needs to be integrated to fit the available space in the aircraft. Considering the available frame to be included, depicted in Figure 8, the generator is located in front and the power electronics converter at the back, as Figure 8 shows.

The shaft coming from the turbine moves a cooling fan, designed to provide the appropriate air flux to keep the generator temperature under the recommended limits, and trying to reduce at maximum the additional aerodynamic losses produced. Power density and difficult thermal requirements seem to be opposite goals but it is very common that both characteristics must be achieved. In this case, the same air current is used to cool the generator and the power electronics heatsinks, less thermally demanding than the former. Due to the very demanding requirements in terms of ambient temperature and available room for the generator the design leads to a very high power density, thus the cooling system is quite critical. Temperature in both generator coils and power electronic modules will be continuously monitored by the central control unit.
6. Conclusions

The paper presents the complete methodology to design an electric drive for an aircraft, consisting on a high speed electric generator and its power electronics and control.

A 6/4 SR generator and a half-bridge per phase converter are considered for the electric drive as the most suitable option. The selection of this machine technology is due to different comparative advantages with respect to WRSG and PMSG, such as: robustness, ease to manufacture (concentrated coils), less maintenance, more resistance to harsh environment and high temperature (absence of magnets), intrinsic fault tolerance (phases are supplied separately) and the fact that a DC distribution system is proposed for the aircraft, hence sinusoidal waveforms are not required for the output voltage.

Once the control strategy is defined, a simulation model is developed to design the power electronics, using the FEM model of the generator, and getting as a result the current waveforms, very useful for the losses calculation. An interaction between these models and additional thermal and mechanical models is considered in order to take advantage of the accuracy of the different tools, avoiding this way too many simplifications, and improving therefore the reliability of the design procedure.

Since the specified available space, weight and boundary temperature are very strict conditions at this application, the analysis of losses results a key issue to determine the heat sources at rated power. A combination of FEM analysis, electric and electronics simulation, and again FEM analysis considering also mechanical effects permit to develop a thermal model to provide the temperature evolution in steady state.

Moreover an optimized design of the generator stator and rotor geometries as well as the control of the phase activation and deactivation angles lead to minimize the torque ripple, other critical parameter to fit the requirements of such a demanding application.

References


