ELECTRICAL ROTATING MACHINES AND POWER ELECTRONICS FOR NEW AIRCRAFT EQUIPMENT SYSTEMS

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Abstract

Generators and electrical loads designed for More Electrical Aircraft are described. Two types of generators were studied for this application: the first one is the Permanent Magnet machine and the second one the Wound-Field Synchronous machine. Loads are powerful electrical motors which can be used on future aircraft in replacement of current loads driven mechanically or pneumatically. These pieces of equipment were all designed. Manufacturing and testing of some of them are complete. They are in progress for other ones.

1 Introduction

Aircraft and Engine manufacturers study different ways to reduce the non propulsive power and improve the engine efficiency. Electricity can contribute to this research as it is an efficient, simple and flexible power. Additionally, it leads to fault tolerant, reliable and maintenance friendly systems. So it can replace favourably the pneumatic, hydraulic and mechanical energies in these non propulsive powers. It will result an electrical power increase on future aircraft also due to the apparition of new consumers like In Flight Entertainment (IFE) and security devices. The current challenge of electrical equipment manufacturers consists in designing attractive high power rotating machines and electronic converters which can meet these aircraft manufacturer needs. In this aim, THALES AES have been involved for several years in different research programmes funded by French or EU organisms.

As the More Electrical Aircraft (MEA) needs more than 1 MW installed electrical power for a twin aisles commercial aircraft, 150-250 kVA generators are required. Since the mechanical power needed to start a large engine is in the range 100 to 200 kW, such high power generators offer the capability to start the engine in place of the conventional pneumatic start. This is possible because of the reversibility of electric machines. Generators become therefore Starter-Generators (S/G); the pneumatic start system can be removed, which contributes to conventional load removal and simplifies the engine itself. THALES AES have recently developed such S/G's in two research programmes:

- The first one is the Power Optimised Aircraft (POA) programme which allowed to study a Permanent Magnet Synchronous Machine (PMSM) to be embedded inside the engine of a commercial aircraft, on the HP shaft.
- The second one is the MEGEVE programme the aim of which is the manufacturing and testing of a Wound-Field Synchronous Machine (WFSM) to be fitted on the Auxiliary Gear-Box (AGB) of an engine.

Another PMSM demonstrator was designed, manufactured and tested for an Auxiliary Power Unit (APU) of small aircraft or helicopter. Directly driven by the APU turbine it can start the turbine from a 28VDC battery and then supplies a 270VDC power to the helicopter equipment.

In addition, two powerful electrical motors were manufactured for a MEA application: a fuel pump motor and a high speed motor driving an Environmental Control System (ECS).

Requirements, characteristics, test results and issues if any are presented below for these pieces of equipment.

2 Embedded Permanent Magnet Starter Generator

In POA study the MEA concept is associated to the More Electrical Engine (MEE) concept where the AGB is removed to reduce maintenance costs. THALES AES studied a High Pressure Starter Generator (HPSG) embedded inside the engine without any auxiliary shaft between the machine and the HP shaft: its rotor is directly fixed on this HP shaft. But as the machine is inside the engine its environment is harsh and a lot of technical difficulties had to be solved during the study to be compliant with the generator requirements.

2.1 Requirements

During starting, the machine has to deliver a maximum mechanical torque of 350 N.m up to 4800 rpm and a maximum mechanical power of 180 kW up to 8800 rpm. In generating mode it was required a steady state power of 100 kW in the speed range 9100 – 15000 rpm. But it was shown during tests that, considering its high torque in starting mode, the system can provide a 150 kW steady state power. Fig. 1 shows these power requirements:

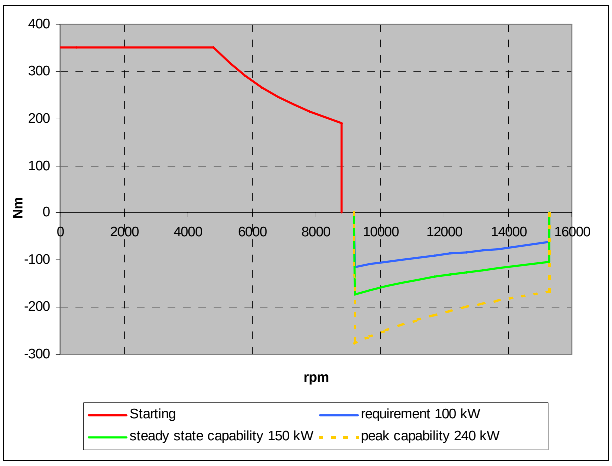

Fig.1 - HPSG requirements

High number of constraints are applied to the rotating machine: limited volume and imposed dimensions, severe environment (ambient air temperature up to 330°C, air pressure up to 5 bars, high vibration level) and safety.

In POA the generators have to deliver a High Voltage Direct Current (HVDC) voltage equal to 350 VDC. In this aim, the rotating machine has to be associated to a reversible Power Electronic Module (PEM) able to:

- convert the input DC power to a variable frequency AC power which is delivered to the rotating machine during the starting mode,
- convert the input variable frequency AC power to a controlled voltage DC power which is delivered to the electrical network during the generating mode.

This PEM is designed to be fitted on the fancase of the engine where the maximum temperature is approximately 70°C. It has to sustain a higher vibration level than equipment inside fuselage.

2.2 System main characteristics

2.2.1 Rotating machine

A PMSM has been chosen for its rotor robustness and its ability to have a large airgap without oversizing its electromagnetic parts. However the PMSM presents two main drawbacks: the permanent magnets are sensitive to high temperatures and, in case of failure inside or outside the machine, the short circuit current can cause damage to the machine and its environment, as the machine excitation can not be turned off.

To avoid a magnet demagnetisation at the required high temperature levels, the rotor is internally cooled by oil circulation. To ensure the safety of the machine when a short circuit current occurs inside the machine windings or inside the associated PEM, the windings have been sized so that a three phase short circuit current can be sustained permanently without overheating.

Moreover, as the ambient temperature is higher than the maximum temperature the current impregnation and insulation can sustain during the machine life, it has been chosen to isolate the wound stator from the ambient air by immersing it in oil. In this aim, the stator has to be separated from the airgap by a sleeve the material of which has not to be magnetic and conductive. A ceramic material has been chosen and tested previously before mounting it on the machine. The validation work associated with this sub assembly was very important because directly related to the feasibility of the generator. The capacity to withstand the vibration level inside the engine had to be tested. A special test bench was built to submit the ceramic sleeve to the engine harsh environment.

To allow the rotor to have a large internal diameter, the pole number has been chosen equal to twelve. This embedded machine has to be very reliable as it can not be easily disassembled from the engine due to its internal location. So the stator winding is divided into three sub-machines to ensure a redundancy. Each sub-machine has three phases and is the most independent it can be from the others in terms of location around the stator. This independence between sub-machines was possible thanks to the high pole number.

Fig. 2 shows the rotor and the stator of the PMSM (rotor external diameter: 265 mm).

Fig. 2 - HPSG rotor (weight: 16 kg)

Fig.3 shows the stator assembly ready to be integrated inside the engine:

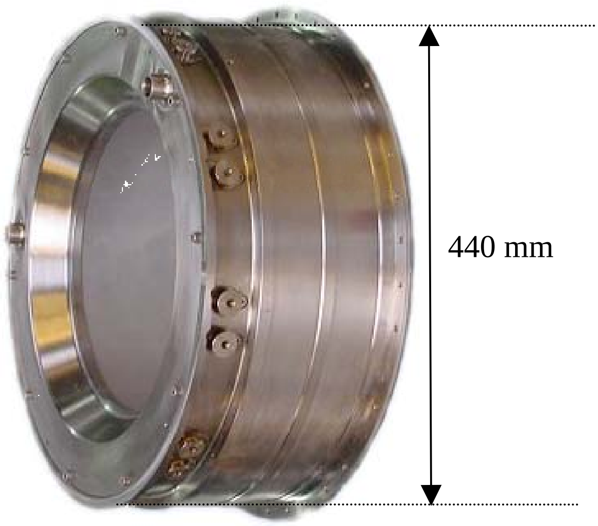

Fig. 3 - HPSG stator assembly (weight: 72 kg)

2.2.2 Power Electronics

As mentioned above, the PEM has a dual function: it works like an inverter supplying the rotating machine during the starting mode, and like a controlled rectifier supplying the electrical network during the generating mode. To ensure the redundancy of the system and the independence of the three sub-systems, the PEM has also three sub-converters and two of them can operate when the third one has failed. When a failure is detected in the machine windings (AC voltages are measured) or in the PEM (AC currents are measured), the failed sub-system is short-circuited by a dedicated device, different from the main converter, so that the failed sub-system remains safe and the two other sub-systems can operate normally. This special “crowbar” circuits are composed by thyristor bridges whereas main sub-converters have 1200V/600A IGBT modules. Two modules are connected in parallel to create one of the six power switches.

Fig. 4 shows the PEM input stage synoptic and Fig. 5 shows the synoptic of one third of the PEM.

As the PEM has to be mounted on the engine fancase it has been designed according to the engine fancase vibration level. A special casting has been realised for this purpose and the PEM interface includes shock absorbers.

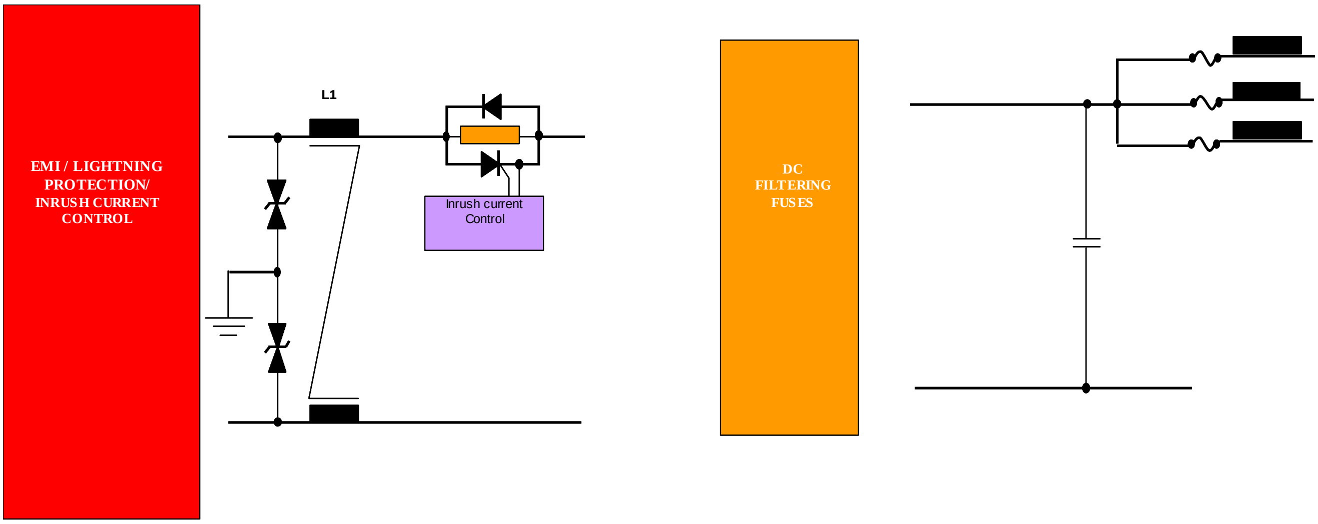

Fig. 4 - HPSG PEM input stage synoptic

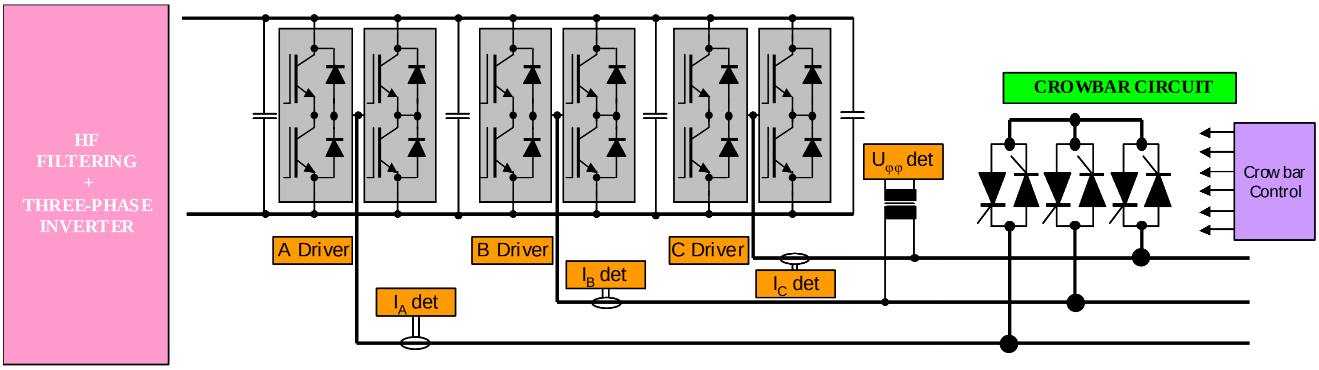

Fig. 5 - HPSG PEM (one third) synoptic

Fig. 6 shows the elementary power components of a sub-converter: IGBT's, capacitors, busbar and driver control board.

Fig. 6 - HPSG PEM power components

The PEM is fuel cooled. Fuel flows inside channels machined in a heat sink.

PEM dimensions are indicated on Fig. 7.

Total weight: 86 kg for a 200 kW power (> 2 kW / kg).

Fig. 7 - HPSG PEM (600x520x283mm)

Two different strategies have been chosen in starting mode and in generating mode. In starting mode, machine currents are controlled using a Pulse Width Modulation (PWM) and flux weakening at high speed. In generating mode, the DC output voltage is controlled directly by the power angle (full wave AC voltages).

2.3 Test results

The HPSG and the associated PEM were tested on THALES AES rig and on the Aircraft System Validation Rig (ASVR). Results are in accordance with requirements. In starting mode, the measured mechanical torque meet the requirement (see Fig. 8) and in generating mode, dynamic performances are compliant with voltage transient limits generally specified on an aircraft.

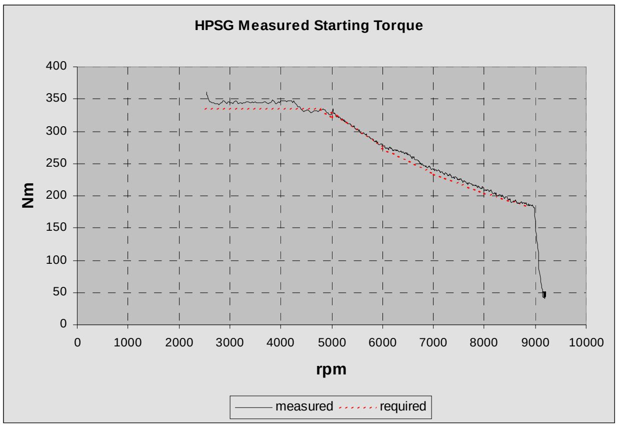

Fig. 8 – Measured torque / speed curve

Fig. 9 and 10 show transients between no-load and 100 kW.

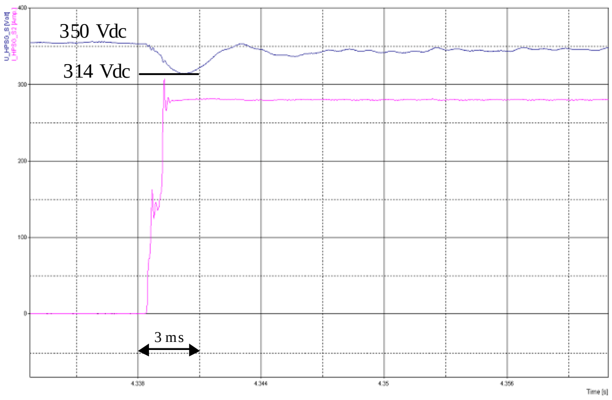

Fig. 9 – No load – 100 kW transient

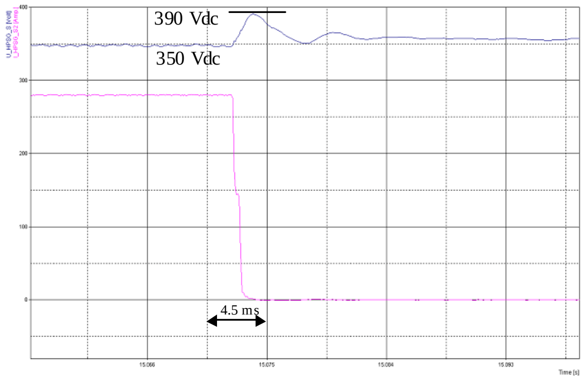

Fig. 10 – 100 kW – no load transient

Fig. 11 shows the voltage ripple at 100 kW:

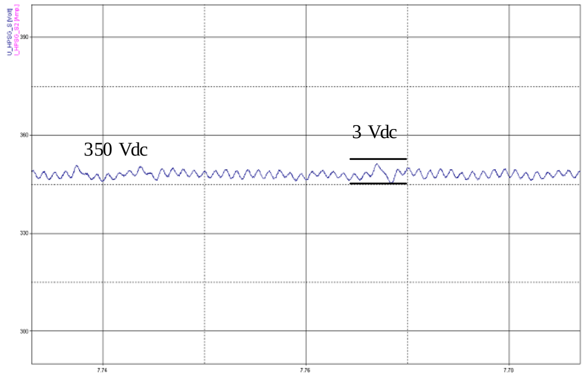

Fig. 11 – voltage ripple at 100 kW

The HPSG system will be tested on a Rolls-Royce engine at the end of 2006.

3 Stand alone Wound Field Starter Generator

In MEGEVE programme, the S/G is coupled to the conventional AGB. In generating mode, it provides a variable frequency AC voltage without PEM, as it is a conventional WFSM. Its permanent power is 200 kVA under 230/400 V 360-800 Hz.

This power level has led to select a 6 poles design and the speed range is defined accordingly, i.e. 7600 - 16000 rpm.

The rationale of this choice is as following: a 4-pole machine has a speed range of 11400 rpm to 24000 rpm (corresponding to 380-800 Hz), which gives the advantage of a smaller and lighter machine, but beyond 150 to 180 kVA, at 200 kVA the machine size is no longer compliant with such a speed.

The weight of the Generator is approximately 90 Kg, including oil circuit accessories (pump,…).

Because of the power level, the network voltage is twice the conventional one that is 230 V instead of 115 V. However this has no major influence on machine size, since the number of turns is adapted to the voltage.

In starting mode, the S/G operates as a synchronous motor controlled by a converter. The torque-speed characteristic is shown in figure 12 below.

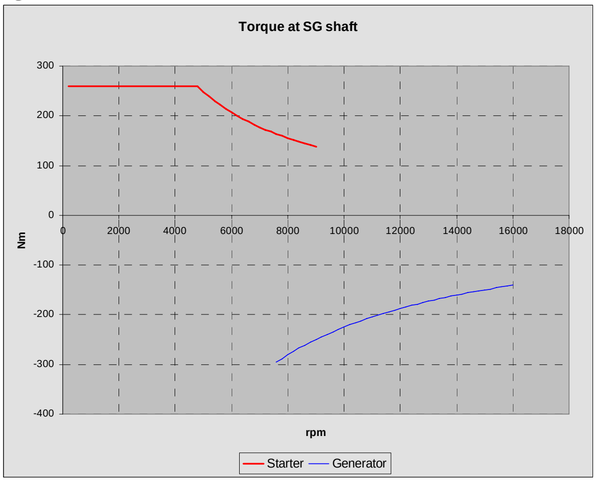

Fig. 12 – S/G torque speed curve

The maximum torque is 260 Nm and the maximum power 130 kW. The base speed (at which the maximum power is reached) is 4800 rpm. The torque and power values are within the capability of the 200 kW generator and therefore the starting operation does not require oversizing of the machine. The machine is in this case sized by generating requirements.

The specificities of Starting mode compared to Generating mode lie in the excitation of the S/G, the control of the angle of the phase current and the cooling capability.

In generating mode, the exciter operates as a generator itself. But, in starting mode, at low speed and particularly at standstill, the exciter cannot provide the required power to the main rotor in the same manner. The alternative is to feed the exciter with AC current and makes it works as a transformer. A module in the converter is used for this purpose and is connected to the exciter field winding. The power to the main rotor is therefore supplied by the converter excitation module (and not mechanically as in Generator mode); this means significant size to this module, which has to provide the excitation power to the main rotor (approximately 4 kW) and reactive power to magnetize the exciter.

Moreover the conventional field winding of the exciter cannot be used as it is: since it is used in transformer mode and supplied by AC currents, the number of turns must be adapted to this specific operation. This leads to two different configurations of the exciter field winding corresponding to generating and starting modes.

Lastly the core of the exciter stator must be made of lamination because of the AC currents.

Operation of the Generator in both starting mode and Generating mode needs therefore adaptation of the exciter.

The control of the machine in starting mode is based on the phase current control, using a rotor position sensor, and on the field control as well. In the range zero to base speed (constant torque command), the magnitude and phase of the AC current and the excitation are constant, while the PWM voltage at machine terminals increases with rpm. Beyond the base speed, and up to idle speed, the maximum available voltage at S/G terminals is reached, and therefore, the control has to vary the phase and excitation currents according to the speed. Phase advance is applied to the current using the rotor position sensor.

The oil flow is provided by an integrated oil pump, which is driven by the S/G. During start mode, the oil flow, which is produced by the pump, progressively increases from zero to rated value as the S/G speed increases, and as a consequence, cooling of the S/G particularly at low speed high torque has to be carefully examined.

The prototype of S/G has been manufactured. Tests will be carried out in generating mode and in motoring mode with the associated converter.

4 High speed permanent magnet Starter Generator

Helicopter manufacturers are highly sensitive to mass reduction. In this perspective, the brushless starter generator directly driven by an APU turbine can be attractive: there is no more AGB and the starting and generating functions can be carried out by a single machine instead of two machines like in the current version. But to reach this goal, the associated converter has to be optimised in terms of volume and mass.

4.1 Main characteristics

The permanent magnet machine is mounted on the shaft of a MICROTURBO turbine. Its nominal speed is 56000 rpm and it can provide an electrical power of 50 kW at the output of the associated PEM. This power is delivered under a regulated 270 VDC voltage. Moreover the PEM includes a DC/DC boost converter which allows the starting mode from a classical 28VDC battery.

In starting mode, it delivers 8 kW up to 28000 rpm. In generating mode, the associated converter delivers 50 kW in the speed range 48000 – 52000 rpm. This power is shared between three outputs: 10 kW 28 VDC (including battery charging), 40 kW 270 VDC to the network and a separate 1.5 kW 270 VDC to supply the turbine auxiliaries.

Fig. 13 – S/G on the test bench

Machine weight: 19kg.
Converter weight: 31 kg.

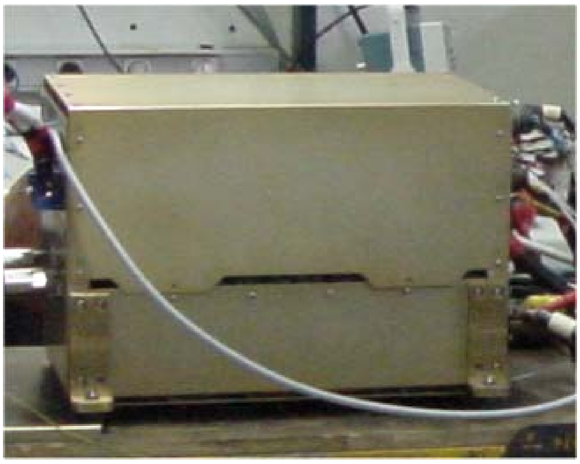

Fig. 13 – 50 kW 270 VDC converter

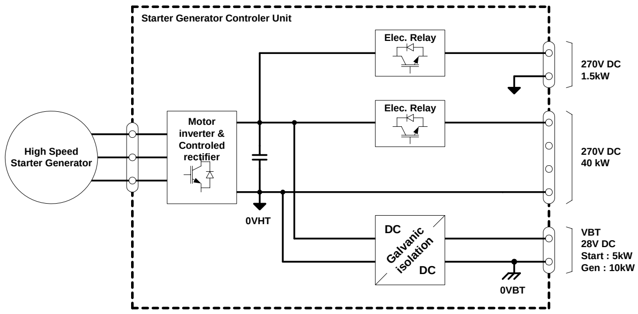

Fig. 14 – converter synoptic

4.2 Test results

The system was tested successfully on the turbine up to 52000 rpm, in MICROTURBO facilities. The system started the turbine with a substantial reduction of fuel consumption. In generating mode, the expected power was delivered.

5 Fuel pump motor

This study was also part of the POA project. The permanent magnet motor drives the centrifugal pump of an Electrical Fuel Pumping and Metering System (EFPMS) for a civil aircraft engine. This system, is attractive because it allows to optimise the fuel flow to the engine independently of the engine speed and the current AGB is no more needed.

The motor can deliver a 100 kW peak power. As the application needs a high reliability the machine and the PEM have been divided into three independent ways so that if one of them fails the system can deliver all the power needed during the take off phase (approximately 70 kW).

Fig.15 shows the motor torque and power during the different flight phases of the aircraft:

Condition	Speed (rpm)	Torque (N.m)	Mechanical power (kW)	Duration
MFF	7419	83.3	65	2min
Climb 3	2679	45.4	13	25min
Cruise	2102	40.3	9	Permanent
Ligthing	1521	26.7	4	2min

Fig. 15 – motor specifications

Fig. 16 shows the winding arrangement which allows the independency of the sub-machines.

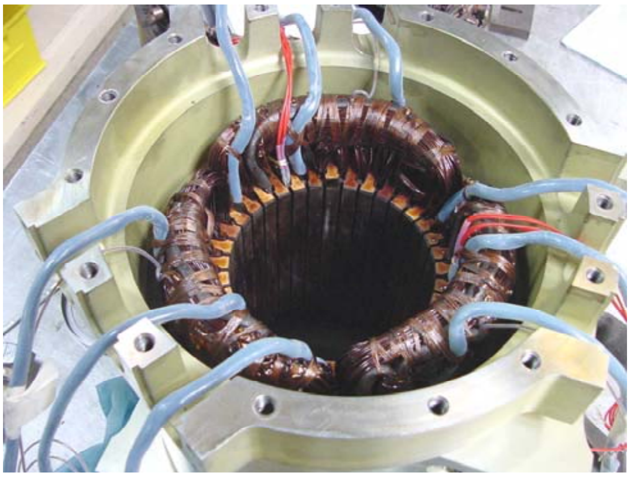

Fig. 16 – redundant machine winding

All tests have been successfully performed on a fuel test bench of the pump manufacturer (Hispano-Suiza) and the Electrical Fuel Pump has been shipped to the engine manufacturer (Rolls-Royce) to be integrated and tested on the engine.

6 ECS motor

Electrical ECS is now baseline for MEA. It is expected to reduce the fuel consumption and to simplify the engine arrangement as the bleed air pipes can be removed.

The permanent magnet rotor of the electrical machine is located inside the air machine between two wheels. The air machine and the integration of the rotating machine inside the air machine have been studied by LTS (LIEBHERR TOULOUSE). The maximum mechanical power is about 125 kW at 53000 rpm nominal speed. The associated PEM is supplied by a +/- 270 VDC source.

Machine and PEM are air cooled.

Mass of the rotor and the stator: 17 kg.

Fig. 17 shows the high speed permanent magnet rotor.

Fig. 17 – high speed permanent magnet rotor

The project is currently at the end of manufacturing and tests on the machine and the PEM are beginning.

7 Conclusion

All these pieces of equipment are major items for the MEA. The results obtained for those which were tested are encouraging. Some issues need more studies like the weight reduction of PEM’s and the integration of these power converters on board of commercial aircraft (effects of these non linear loads on the network stability and harmonic content, dedicated cooling systems at the aircraft level).

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