HIGH EFFICIENCY, HIGH RELIABILITY 2 KW INVERTER FOR AERONAUTICAL APPLICATION

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Abstract

In aerospace electrical systems, the design trade off is made by the optimization between 5 main constraints : efficiency, EMI, environment, integration level and reliability. In this paper is presented a power inverter solution that enables a high level of integration and a high level of efficiency.
The integration of the power inverter is made by one single module that comprises 3 phase legs and one temperature measurement. This type of assembly enables to reduce the inverter volume by suppressing the use of discrete power components. The first temperature cycling made revealed that this packaging assembly can withstand severe aeronautical environment.
In the same time, the use of IGBT dies combined to SiC Schottky Diodes allows a 45 % reduction on switching losses. The paper will present some tables that summarize the efficiency characterization done on the power module.
Finally, this type of module will enable an easiest integration of the inverter in a complete controller environment with an improved reliability. Moreover this is done in a smaller whole volume due to the heat sink shrinking thanks to the improved efficiency.

1 General Introduction

Nowadays, the replacement of hydraulic systems for the engines with electric ones leads to place power inverter in a harsh environment as the engine nacelle. Here the equipments are under high constraints as high and low temperature, high temperature variations, high humidity and low pressure. In a first paragraph, all these constraints will be explained.

Combined to these environmental constraints, new aircraft system obeys to weight and operating cost reduction. In consequences, efforts shall be done to reduce weight and volume of the power converter. That's why a solution with a high level of integration will be presented. The high level of integration is possible only if this solution has also improved its efficiency and its reliability. So efficiency improvements will be discussed and first reliability tests will be shown.

2 Nacelle environment description

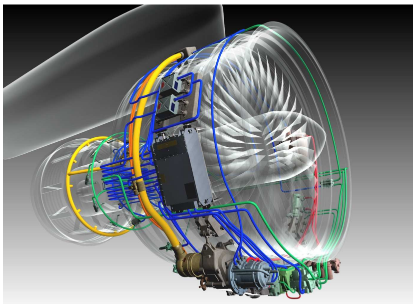

Fig1 : Equipments all around the engine

Each equipment associated to the engine systems is directly mounted in the nacelle all around the engine. To reduce thermal constraints, most of the temperature sensitive equipments are placed in an area where the nacelle temperature can be withstanded.

On the figure 2, the temperature variation during a transatlantic flight is described (~8 hours of flight).

The temperature variations have three different reference curves referring to ISA (International Standard Atmosphere) :

- ISA curve : normal flight : 20 000 flight during the life duration
- ISA max : maximum temperature : 2 000 flight during the life duration
- ISA min : minimum temperature : 2 000 flight during the life duration

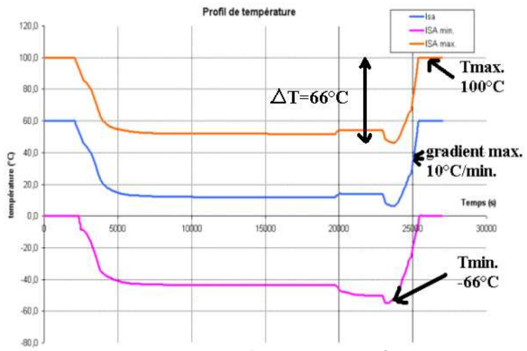

Fig 2 Temperature profiles

These curves show the extreme temperature variation (-66°C +100°C) with the maximum gradient (10°C/min). This explanation is only a summary of the environmental constraints seen, more detailed information are given by T.Lhommeau in [1].

These thermal constraints influence the packaging withstanding due to the assembly of different materials. All of this justify the high level of temperature cycling test asked for each power electronic components. However, we are looking for increasing the maximum temperature withstanded by the packaging and the component. Temperature cycling tests and characterization have been done between –55°C and + 150°C.

Mechanical constraints are the combination of sinusoidal and random vibrations (20 g from 33 to 3000 Hz), shocks and acceleration. Altitude imposes a pressure cycle that is seen by the component. The flight cruise altitude (50 000 feet) corresponds to 0.1 bar. On the graph 3, the pressure variation is described during a flight :

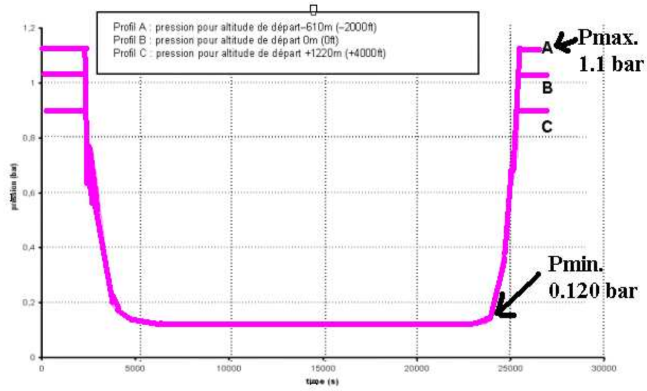

Fig 3 Pressure profile during a flight [1]

As the components chosen are non hermetic, this pressure cycling accelerates the humidity absorption. This relative humidity can reach 95% but mainly depends on the combination of temperature and altitude. The humidity diffusion in the gel can reduce the dielectric withstanding of the component.

3 Inverter solution description

The inverter is made by only one module. This module is made for motor drive applications of about 2 kW with a 270 V dc bus voltage. The module is designed to withstand base plate temperature from –55°C up to 150°C, 20 g of vibration, 95% of humidity and 0.1 atm of pressure. All of these environmental constraints impacts the size of the power converter. The high ambient temperature explains the need for a maximum die temperature over the standard limit of 150°C (generally due to the silicium).

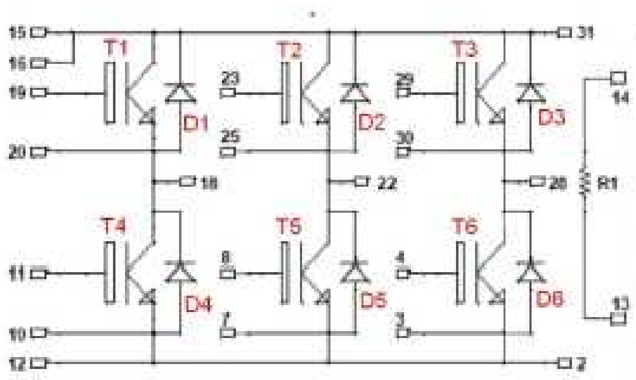

Fig 4 : Electrical scheme of the module with its picture

This inverter module schemed in figure 4 comprises three IGBT/Diode legs plus a substrate temperature monitoring. Two DC bus connection are possible to reduce the parasitic inductance. To reduce module cost development, a standard type of plastic package has been used. In the same way, efforts have been done on the integration of the module (complete three phase inverter), the size of the module is 74 * 41 * 12 mm^3.

Each material has been chosen to withstand the nominal power at the maximum ambient temperature of 150°C.

The material chosen for the substrate and the baseplate are in accordance with the reliability studies done in [2]. Uncertainties on the best substrate for reliability lead to realize two different version to compare the results.

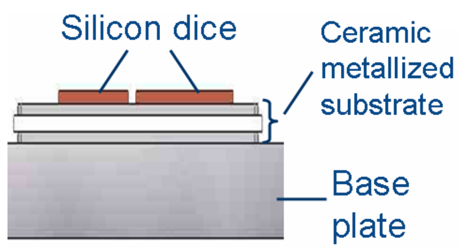

Fig 5 Module topology

The most recent available technologies of dies have been taken. IGBT die chosen is a 600 V Trench\Field Stop, its main advantages are :

- A maximum die temperature guarantees up to 175°C
- One of the lowest drop voltage (compare to other type of available IGBT die)
- A good withstanding to the short circuit pulses[1]

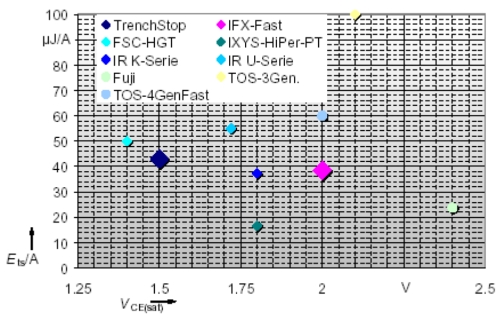

Fig 6 Figure of Merits plane of switching Energy Ets and saturation Voltage Vce(sat) [3]

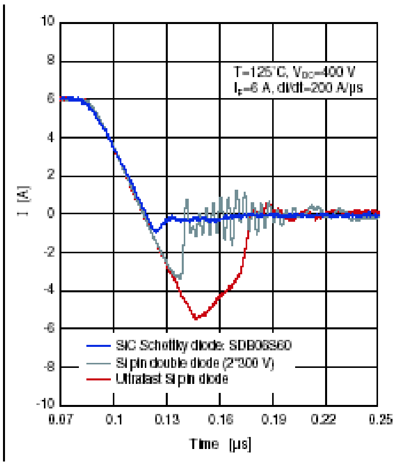

Fig 7 Recovery Comparison between Si and SiC diode[4]

The diode die is a 600 V SiC Schottky diode. The SiC diodes have been chosen for their ability to withstand high temperature (about 200°C) and to have no recovery charge [4]. This choice of no recovery diode will increase the efficiency of the inverter by reducing of 88 % the recovery energy in the diode and also 57% the energy in the IGBT at the turn ON according to C. Miesner [4]. Characterization results presented below will enable to validate these results.

4 Efficiency improvements

The characterization has been done following the picture set-up presented on figure 8. Current and voltage (Vce and Vf) measurements are acquired directly on the scope and registered to allow an accurate losses calculation through a software program.

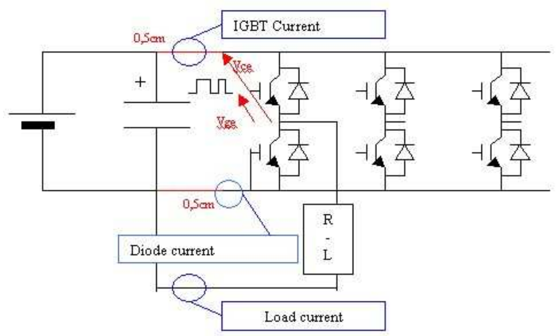

Fig 8 Set Up scheme of the one shot test bench

The main benefit to characterize in such a way is that the switching losses measurement is completely representative of the real use of the module. Indeed, the module is mounted with its final busbar and capacitor design (not represented in this paper). An other advantage is to prevent breakdown of the component thanks to only one or two command signals.

The module losses are compared to a standard module that has the same IGBT die but mounted with its optimized Silicium diode. In accordance with the expectations, the characterization at the switching OFF are not improved(fig 9). These similar values also enable to prove that the test measurement is accurate.

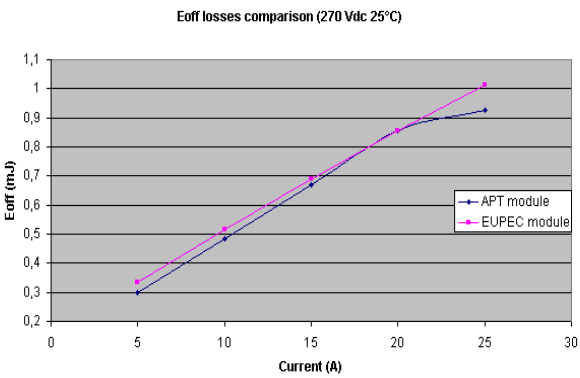

Fig 9 Eoff losses comparison

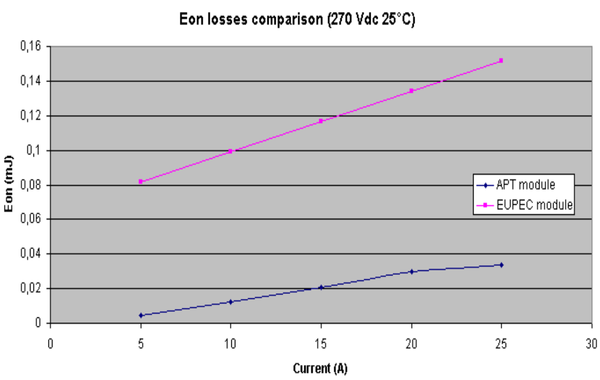

Fig 10 Eon losses comparison

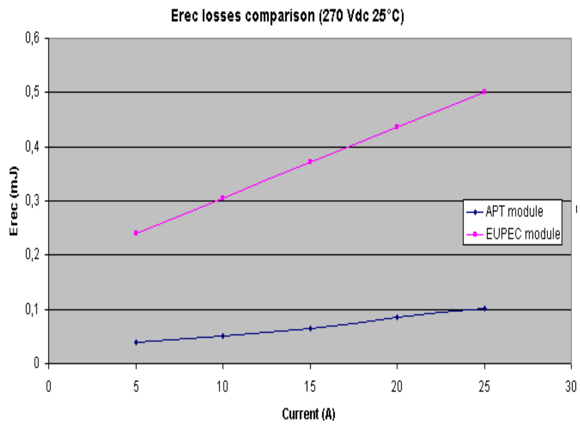

Fig 11 Erec losses comparison

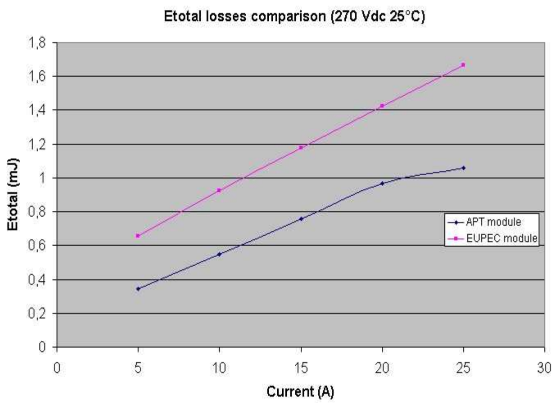

Fig 12 Etotal losses comparison

Eon and Eoff losses measurements (Fig 10 and 11) shows a great reduction of these switching losses. On the complete scale of current, a reduction of 80% of the Erec losses is measured and a minimum reduction of 75 % of the Eon losses is seen. Eon reduction mainly depends of the current level; with a current lower than 7 Amp, the reduction rises 90%.

As the energy at switching ON is the main contributors to the switching losses, the total switching losses reduction reaches only 30 % for high values of current (between 15 and 25). However, for the focused values of current (< 15 Amp), the reduction rises to 40 – 45 %.

These results enables us to validate the benefits of the use of an SiC Schottky diode. A most improved combination would be an IGBT die that has a different sharing between ON and OFF losses

To really quantify the benefit of the designed module, a calculation has been done thanks to the characterizations results to evaluate the total losses of a complete inverter that has to drive a sinusoidal current with a switching frequency of 25 kHz (Table 1). The losses improvement is clearly better with low current (that corresponds to its current sizing). And with no surprise a higher switching frequency corresponds to an higher improvement (Table 2).

Table 1 Losses improvement Vs Current :

Current (A peak)	Total losses in SiC module	Total losses in Si module	Improvement
5	27 W	50 W	44 %
7	36 W	58 W	38 %
10	48 W	71 W	32 %
14	65 W	89 W	27 %

Table 2 Losses improvement Vs Switching frequency (7Apeak) :

Frequency (kHz)	Losses in SiC module	Losses in Si module	Improvement
10	23 W	30 W	25 %
20	32 W	49 W	35 %
25	36 W	58 W	38 %

In certain Hispano Suiza applications, this switching losses reduction allows a reduction of 30 % of the total losses of the inverter compared to inverter module with Si diode.

5 Reliability evaluation

A first reliability study has been performed to evaluate the two different types of packaging. As already said, the only change between the two assemblies is the type of substrate used. The reliability test consists in applying temperature cycling between –55 and 150°C, the delamination is checked each given number of cycles through a Scan Acoustic Microscope.

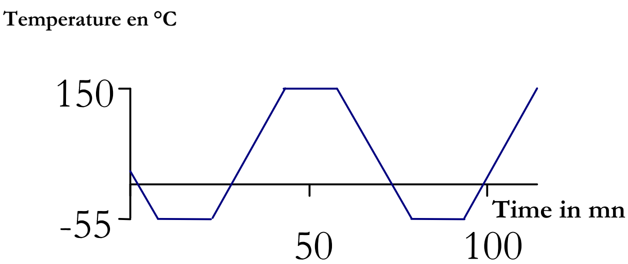

Fig 13 Temperature cycling test

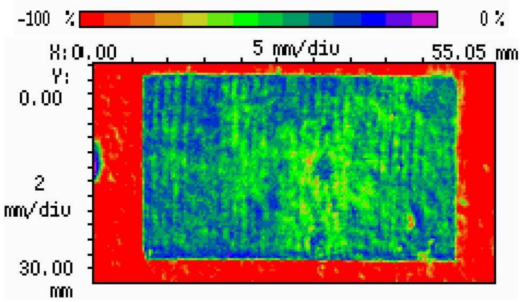

Fig 14 SAM performed on module

In the same time, all the mains electrical and non electrical parameters of the module are monitored :

- Thermal resistance evolution
- Module leakage current
- IGBT and diode dynamic resistance
- IGBT and Diode diffusion voltage (Vce0 and Vf0)

Three hundred thermal cycles have been performed on the two types of modules. All the measurements done on the modules show that no delamination or electrical deviation occur (Fig 15).

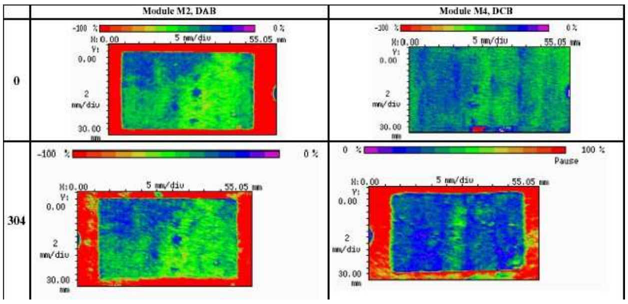

Fig 15 Acoustic scan of the two types of module before and after 300 cycles

On the right scan picture, a difference in the corners of the substrate can be observed. It is not due to delamination but to the solder withdrawal on the substrate that has been rounded off.

These three hundred first cycles confirm that the modules designs are compliant with our thermal environment. Further tests (1500 cycles) will be performed to validate the reliability compliance.

6 Conclusion

This type of module package will bring great improvement to the power electronic in aeronautical harsh environment. Its high density combined to a reduction of 30 % of the inverter losses really eases the integration. A maximum base plate temperature of 150°C linked to maximum junction temperature of 175°C allow us to place power electronics in areas where it were not possible few years ago. First thermal cycles show that the design are compatible with the thermal stress, however complementary tests need to be performed to ensure the good level of reliability. All these improvements will enable to generalize the hydraulic system removal by electrical ones.

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