More Electric Aircraft Forum

Securing the Reliability of Power Electronics Systems by Applying Robustness Validation

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ABSTRACT

In automotive electronics a paradigm change took place recently organized by the German ZVEI and the US SAE. Two handbooks on Robustness Validation are available today – one for Semiconductor Components and the second for Electric/Electronic Modules. Siemens CT used this as a basis to write a “process handbook how to secure reliability of power electronics systems”. Important parts are the translation of the aircrafts mission profile to the power electronics components which are prone to failures, the knowledge matrix of failure mechanisms and life time predictions.

INTRODUCTION

To secure reliability in automotive electronics the German ZVEI and the US SAE have published two handbooks: Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications (Spring 2007), and Handbook for Robustness Validation of Automotive Electrical/Electronic Modules (Summer 2008) [1].

Robustness Validation is a process to demonstrate that a product performs its intended function(s) with sufficient robustness margin under a defined mission profile for its specified lifetime. It should be used to communicate, analyze, design, simulate and to test a power electronics system and/or components in such a manner, that the influence of noise (or an unforeseeable event) is minimized.

The Robustness Validation Process (RV) will be described and consequences for aircraft power electronics discussed.

ROBUSTNESS VALIDATION PROCESS

The RV process consists of seven major steps:

1. Determine/ Define Application
2. Define Application Mission Profile

3. Develop Module Requirements
4. Identify Key Risks and Failure Mechanisms
5. Intelligent Testing
6. Robustness Analysis of Manufacturing Process
7. Execute Robustness Validation Plan

1. DETERMINE/ DEFINE APPLICATION

The more electrical aircraft will enable the power-by-wire (PbW) concept which means that aircraft systems will change from mechanical to more electrical or full electrical operation based on power electronics technologies, e.g. electrical starter generator, environmental cooling system, pumps, flight control actuators, etc.

As primary flight control actuators are one of the main power electronics applications, EMA (Electro Mechanical Actuator) has been chosen by Airbus.

2. APPLICATION MISSION PROFILE

The mission profile according to RV is defined as:

The Mission Profile is a representation of all relevant conditions an electric/ electronic module will be exposed to in all of its intended applications throughout its entire life cycle.

Mission profiles for power electronics systems are obtained from the aircraft reference mission that is one of the major requirements for aircraft designs.

The reference mission describes the different phases of the flight and the altitude, the duration and the distance performed during each phase.

The different phases are: start-up & taxi out, take off & initial climb, climb up acceleration, cruise, deceleration, descent, approach, landing & taxi in. For power electronics, the number of phases can be reduced to 5 to keep only the relevant phases: the initial climb, acceleration (resp. descent, approach) will be included into the climb (resp. descent) phase.

Fig. 1 picture shows the reference mission profile as well as the simplified mission profile.

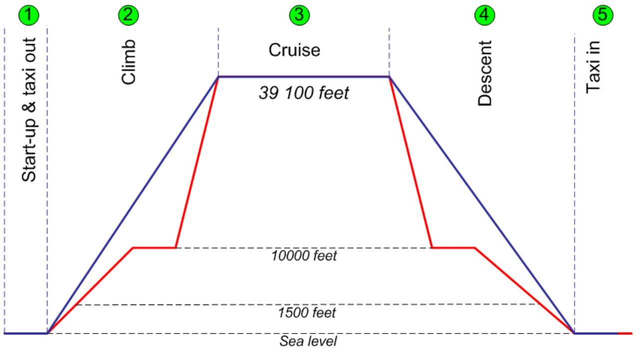

Fig. 1 A320 Mission profile description. (red = reference mission, blue line = simplified mission)

For the simplified mission, the duration of different phases are defined in Table 1.

Table 1 Phase duration

1- Start-up & taxi out	7 min
2- Take-off & climb	15 min
3- Cruise	40 min
4- Descent & landing	20 min
5- Taxi in	7 min

With the A/C mission profile, an environmental envelope is defined featuring the pressure altitude and temperature limits (Fig. 2). Inside this envelope, the A/C performances have been established and the aircraft systems have to meet certification requirements.

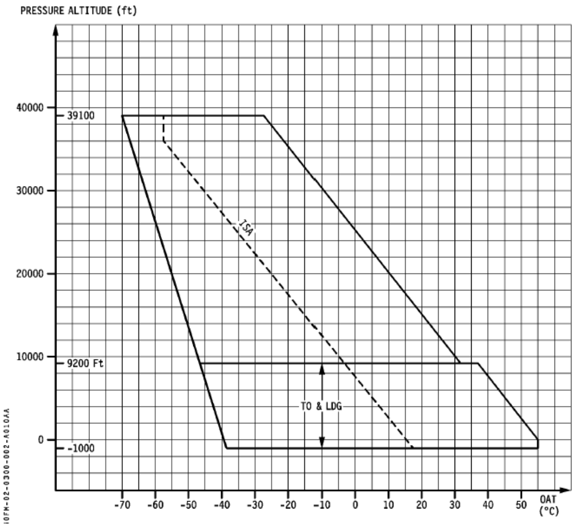

Fig. 2 A320 Environmental flight envelope [2].

The dotted curve in Fig. 3 represents the ISA reference (International Standard Atmosphere) based on an average set of conditions (at sea level: temperature of 15°C at a pressure of 1013.25 hP) that presents temperature versus the altitude. The ISA temperature is used as a reference to compare real atmospheric conditions and the corresponding aircraft performance.

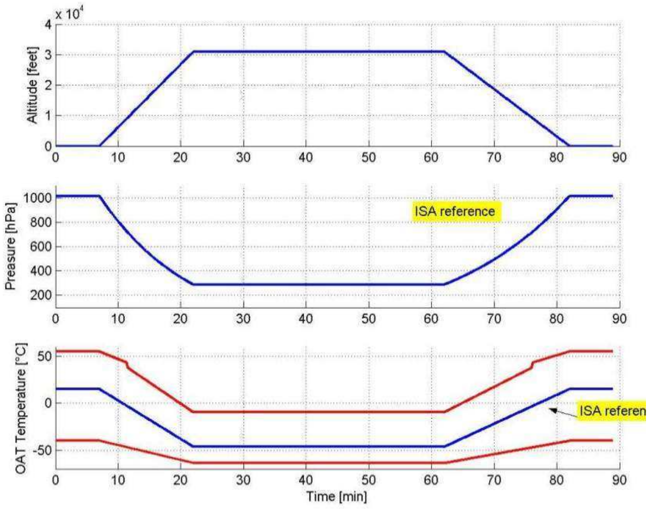

Fig. 3 Environmental profiles at A/C level corresponding to one cycle.

During its service life, a short range A/C will perform cycles (Fig. 3) and the lifetime is defined by design goal objectives: 24 years or 60.000 cycles or 100;000 flight hours whichever comes first.

Daily A/C operation is 7 cycles with 45 min T.A.T and the duration of power up & power down sequences is 30 min. Consequently, the ground soak corresponds to the remaining time.

The flight control actuators are installed in non-pressurized and non-controlled locations and the main environmental conditions are:

In Table 2 the environmental loads are shown which may be important.

Table 2 Environmental loads

Thermal	Normal operating: -55°C/ +70°C Ground survival: -55°C/ +85°C Variation: 10K/ min
Mechanical	Shock: 6g/ 20 ms pulse Operational vibration D0160 cat R/H
Radiation	Cosmic Ray: 1-800 MeV neutron flux of 6000 N/cm2/h Average atmospheric neutron flux
Humidity	95% RH @ 65°C
Icing	DO160 cat B
EMC	Conducted emissions 150 kHz/30 MHz DO160 - cat M
Altitude	Unpressurized area 0.116 to 1 bar Paschen law, Corona discharge

Translation of Mission Profile

A very important task is it to translate the mission profile from the aircraft to the mission profile of the power electronics system and further to the components, materials and joinings. Fig. 4 shows the interconnections of a Si power semiconductor chip, by wire bonding at the top and soldering at the bottom. Due to the differences of the CTE (coefficient of thermal expansion) mechanical stresses lead to fatigues of the bond wire and solder joints.

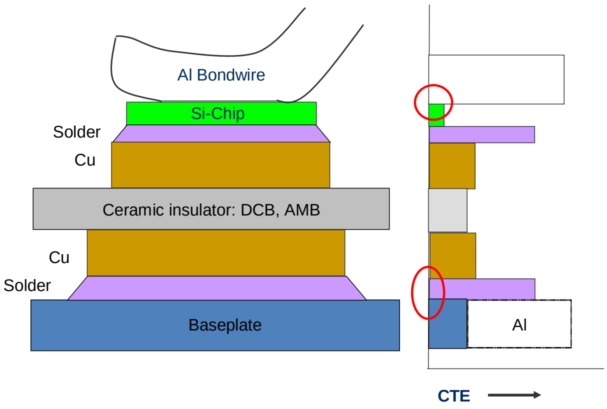

Fig. 4 Cross section of a power module

The translation needs four steps:

Step a: Translate drive cycle to motor current by using the E-motor characteristics

Step b: Determine the thermal performance of the power electronics system by simulation and experiment

Step c: Derive temperature histogram

Step d: Take power cycle results for bond wire lift-off and apply Palmgren- Miner's rule for cumulating the damage

3. DEVELOP MODULE REQUIREMENTS

The power module needed corresponds to a full-bridge module including additional switches on the phase outputs and is used for a fault tolerant 3-phase module AC Motor drive [3].

The major requirements are:

- Nominal AC output current:
  - 18 Arms (normal mode),
  - 27 Arms (abnormal/ reconfiguration mode),
- DC bus max voltage:
  - 540 VDC (normal operation),
  - 670 VDC (abnormal operation),
- DC bus transient voltage:
  - 440 VDC to 820 VDC / 100 ms
- Switching frequency: up to 20 kHz
- Hard switching
- SiC technology for diode
- Efficiency: greater than 97,5% at nominal power / normal operation (including insulation switches)
- Cooling : natural convection

The enhanced intelligent power module was designed, built and characterized according to the RV process [4].

4. IDENTIFY KEY RISKS AND FAILURE MECHANISMS

The information on key risks and failure mechanisms should be available in the knowledge basis. In Table 3 the wire bond lift-off mechanism is described.

Table 3 Knowledge matrix for one of the most common failure mechanism in power semiconductor modules – Thick Al wire bond lift-off

Failure Mechanism	**Thick Al wire bond Lift-off**
Group	Power module
Cause	Thermomechanical stress load at the termination of the interface due to CTE mismatch between Si-chip and Al bond wire
Failure mechanism	Bond lift-off
Failure mode	Functional fail if all bond wires have been lifted off
Material	Al wire; Al metallization
Detection	Increase: of VCEsat by 5%; of Rth by 20%
Characterization	Visual inspection; Pull and/or shear test
Design test structure	No
Design for test, Design for reliability	- More wires with a smaller diameter are more reliable
Stress method	Power cycling test
Lifetime Prognosis:	

• Physical model	• Paris law
• Parameter needed	- Material: Youngs modulus, Poissons ratio, Yield strength/ stress-strain curves -Geometrical: Joint length, Wire diameter, Al metallization thickness, Chip thickness
• Simulator	• FEM simulator
Results of LTP	MTTF vs bond wire diameter

The result of the life time prediction is shown in Fig. 5. The thinner the wire bond the more cycles can be achieved before failure.

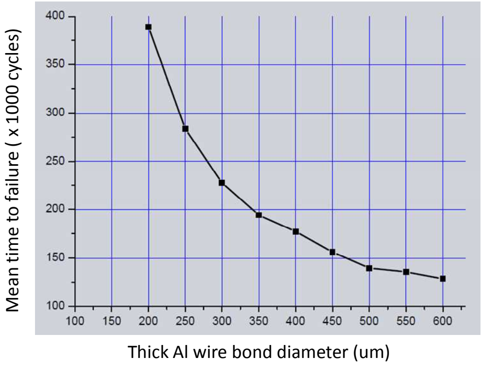

Fig. 5 Lifetime prediction result for thick Al bond wire lift-off

Good tools for risk analysis are FMEA (failure mode cause and effect analysis) and the fishbone diagram. An example for the fishbone diagram is shown in Fig. 6.

Fig. 6 Fishbone diagram showing possibilities for an IGBT module to fail. The four main groups are: Components, interconnects, processing and operation. For operation the mission profile has to be known.

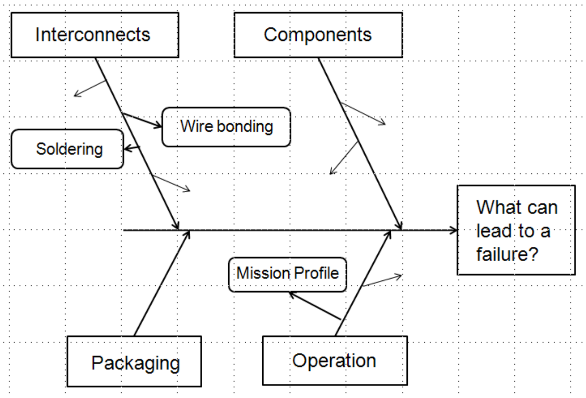

Fig. 5 Fishbone diagram which is used to figure out possible failures

5. INTELLIGENT TESTING

According to the RV Handbook three different tests should be executed:

- Capability testing confirms the ability of the product to withstand specific stresses, thus verifying that the product is capable for such stress factors, which are not related to any life time or durability factors.
- Durability testing assesses how long a product is able to perform to specification when subjected to various stress factors.
- Technology-specific testing activates specific failure modes by applying specific highly accelerated test conditions.

In the case of the thick Al-wire bond lift-off failure mode a high acceleration factor for the power cycle test can be used because of the elastic and plastic behavior of the bond.

In contrast for solder interconnects the visco-plastic behavior has to be taken into account, which does allow only low acceleration factors.

6. ROBUSTNESS ANALYSIS OF MANU-FACTURING PROCESS

Manufacturing process robustness is needed to ensure that the work done to establish robustness during design and development phases of a product life cycle is not eroded by the processes used to manufacture the product. It is necessary to have a knowledge and understanding of how, when and the significance of the issues that can occur during manufacturing which will reduce or affect the robustness of a product related to the mission profile or it's intended use.

An important tool is the "component process interaction matrix CPI" which allows the evaluation of critical attribute interactions.

It is very important to measure the robustness of a product that can be done by using the "robustness indicator figure RIF". Usually a spider diagram is used to compare experimental test results with specification.

7. EXECUTE ROBUSTNESS VALIDATION PLAN

The RV plan is based on inputs with the test-to-failure approach:

- Phase: prototype/ development/ product
- Intention of tests
- Number of devices under tests
- Description of tests (including acceleration models and factors used)
- Assessment and acceptance criteria

The execution of the RV plan means collecting and measuring parameters for the RI calculation.

CONCLUSION

The recently introduced Robustness Validation Process for automotive electronics fits very well to secure reliability in the aircraft industry. It is based on the physics-of-failure approach, on end-of-life testing and on the knowledge of all the stresses that will be applied to the power electronics systems during operation of the aircraft (mission profile). The mission profile of the aircraft is the starting point for translating it to the power electronics systems, subsystems and components. This procedure is necessary for lifetime predictions of components and interconnects.

The identification of risks and failure mechanisms rests on the knowledge base. One example for it deals with the wire bond interconnection. One of the most frequent failures is bond lift-off caused by the difference in the coefficients of thermal expansions between the Si chip (2.6 ppm/K) and the Al bond wire (23 ppm/K). It includes physical models for lifetime prediction as well as the parameters needed for simulation.

The well-known tools like fishbone diagrams and FMEA are still necessary to identify and calculate risk figures.

One of the most challenging part of the RV process is intelligent testing which is subdivided into:

- Capability testing
- Durability testing
- Technology-specific testing

Finally one must not forget to apply RV to manufacturing. The Robustness Indicator Figure RIF gives a quantitative value for RV. The CPI matrix takes care of processing the same components by different processes, like lead and lead-free soldering.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Insert the list (alphabetically sorted) of Definitions/Acronyms, Abbreviations used in this paper

▪ **A/C**	Aircraft
▪ **CTE**	Coefficient of thermal expansion
▪ **CPI**	Component process interaction matrix
▪ **RFI**	Robustness indicator figure
▪ **RV**	Robustness Validation
▪ **TAT**	T. A.T turn around time