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High Reliability Power Electronics – Key Note Speech PCIM ASIA 2012

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Abstract

Power Electronics find numerous applications in a variety of HiRel fields, including space, aviation, automotive and other allied fields. To get desired MTBF and MTTR, many special design criteria, critical quality assurance and extensive testing are called for. Over time, these design criteria, quality standards, testing methodology have evolved, which, when properly implemented, result in long term reliability in harsh environment. To achieve high reliability of power electronics, recommended methods and considerations are mentioned and explained briefly.

Space applications call for some additional considerations such as radiation hardness towards Total Ionization Dose (TID), Single Event Effects (SEE), ELDRS, Neutron effects**;** functional redundancy; heat dissipation through conduction and/or radiation due to vacuum; shock and vibrations and restrictions on weight and volume. Space applications also need unattended long term reliability for decades and remote operation through telecommand and performance monitoring through telemetry. Radiation hardness of MOSFET and Schottky require special design and manufacturing techniques, while power management ICs require techniques that incorporate “Radiation Hardness by Design” and other redundancy considerations.

Military and Commercial aviation fields put equally demanding constraints on reliability of Power Electronics with certain special considerations based on human safety.

The paper discusses all these aspects and gives an overview of the subject with metamorphosis of development over past few decades

1. Introduction

1.1 Historical Perspective:

Historically reliability became a matter of concern after experiencing rather high failure rates, while using electronic equipment during World War II. Then the constant failure rate (CRF) model, which attributed failures solely to the random causes, became popular. MIL-HDBK-217 was created in 1965 and became the de-facto standard of reference for reliability prediction of Electronics.

However, after 1980 it was felt that the CFR model was not sufficient to fully explain the observed field failures such as infant mortality and device wear out, especially with the introduction of Integrated Circuits. It was felt that every failure of component or subsystem can’t be attributed to random causes and that CFR model can’t be applied to all cases. Prior to 1991 it was common to use MIL-HDBK-217 for predicting failure rates but later it was recommended that MIL-HDBK-217 should be used as a reference and general comparison of reliability but not directly to predict life. Instead, industry moved to “Improved Design Process” and “Designing in Reliability”, while simultaneously incorporating common analytical practices, such as “Cone of Tolerance, WCA, FMECA, PFMECA, Finite element modeling (thermal and mechanical), KPC, CPK, etc. to gain better insight and improve methods of manufacturing, quality control and testing to ensure reliability.

Study of physics of failure mechanisms has greatly influenced and improved reliability modeling. When the causes underlying various failure modes and wear out mechanisms are understood for different power electronic components and sub-systems, appropriate steps can be taken during designing & manufacturing to avoid all these pitfalls. This can virtually eliminate failures, thus achieving highest possible reliability.

1.2 Reliability and MTBF- Basic Concepts:

Reliability is defined as the probability that a given component or system will perform its intended function for a given period of time under a given set of conditions. This definition has four parts, namely, 1) probability, 2) intended function, 3) time, and 4) conditions. Thus, a reliability statement is complete when all four parts have been provided.

MTBF stands for Mean Time Between Failures and is applicable when the underlying distribution has constant failure rate. The lifetime of the population of power electronic products can be explained using the classical Bathtub Curve as shown in Fig. (1). This curve is not drawn to scale and thus the useful life phase could extend for many years. The initial Burn-in Phase shows decreasing failure rate and is due to latent manufacturing defects in power electronic components or systems. The useful life phase will have low and relatively constant failure rate and consists of random failures typically caused by "stress exceeding strength." The Wear-out-Phase, which occurs at End of Life shows increasing failure rate and is due to fatigue or depletion or both.

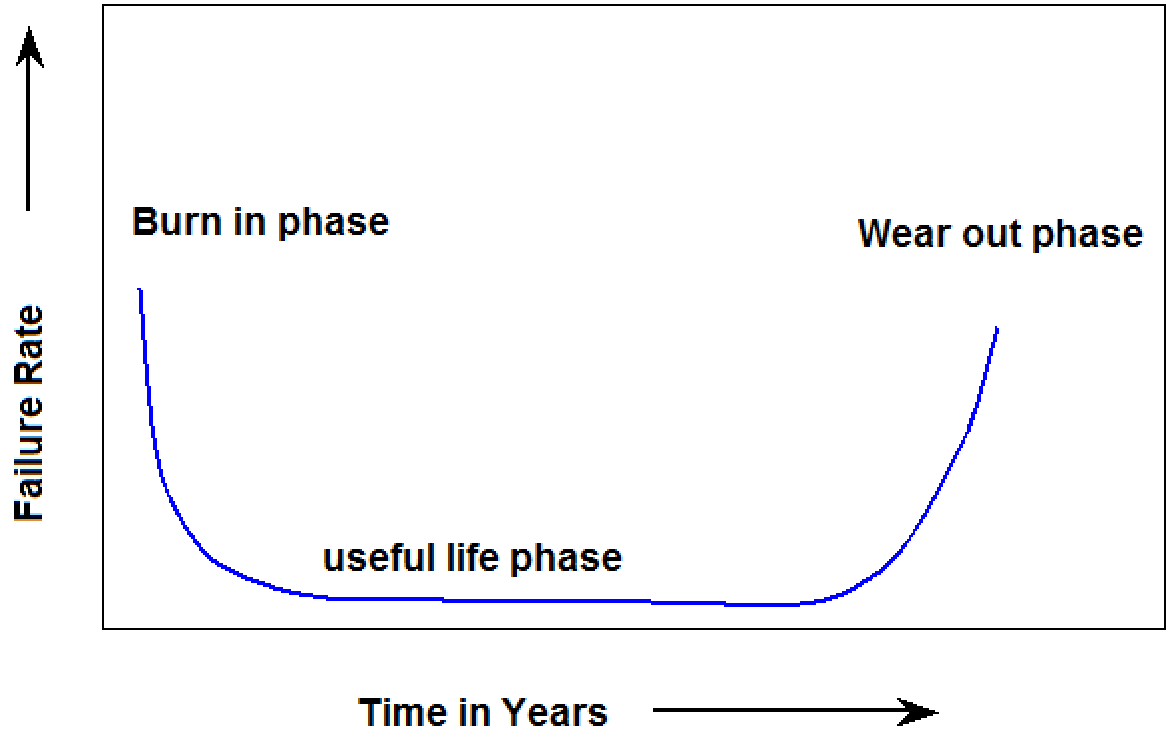

Fig. 1. The Classical Bathtub curve of Failure rate vs. lifespan of manufactured product.

MTBF can also be expressed as MTBF = 1 / failure rate. It is important to differentiate between MTBF and service life of power electronic equipment. MTBF is to be used as a measure of failure rate during useful life phase only. Mean Time Between Failure (MTBF) is not the same as the operational life of a product. In fact, MTBF represents the statistical approximation of the percentage of units that will pass during a product's useful life period.

The most important reliability concepts that have evolved over time are those based on study of Physics-of-Failures. This requires multi-disciplinary approach armed with knowledge in basic sciences such as materials science, heat transfer, electromagnetic theory, structural engineering & mechanics and probability theory. Over the past two decades the application of Finite Element Methods has become popular and helps to provide a much better understanding of reliability based on Physics-of-Failures. Design engineers can create virtual prototypes of power electronics systems and then use software to predict failure mechanisms, based on physics of failure, using finite element methods and taking into account physical properties of various materials used, applied stress and thermal properties to guide them before undertaking actual manufacturing.

Accelerated stress screening, accelerated life testing and environmental stress testing will help find out quality issues of finished power electronic products and, by correcting these, higher reliability can be achieved. To find out about infant mortality, Highly Accelerated Life Tests are designed to suit the power electronics sub-systems. This can combine thermal cycling and random vibrations. While the temperature ramps up and down between – 55 ^{0} C to +125 ^{0} C, linear and rotary vibrations are applied to test-bed in six axes. The rate of change of temperature and dwell times and amplitude and frequency of vibrations should stay within designed limits.

1.3 Failure Mechanisms Due to Stress and Wear-Out:

The potential or likely failure mechanisms of power electronic components, modules or systems have many facets and likely causes & effects. These are shown in Fig. (2) and Fig. (3).

A less likely but lethal electrical stress could be lightening. Very special provisions have to be made to prevent any damage to power electronics from lightening. Amongst the mechanical stresses, shock and vibrations can cause damage and Power Electronic system has to be designed with suitable protection.

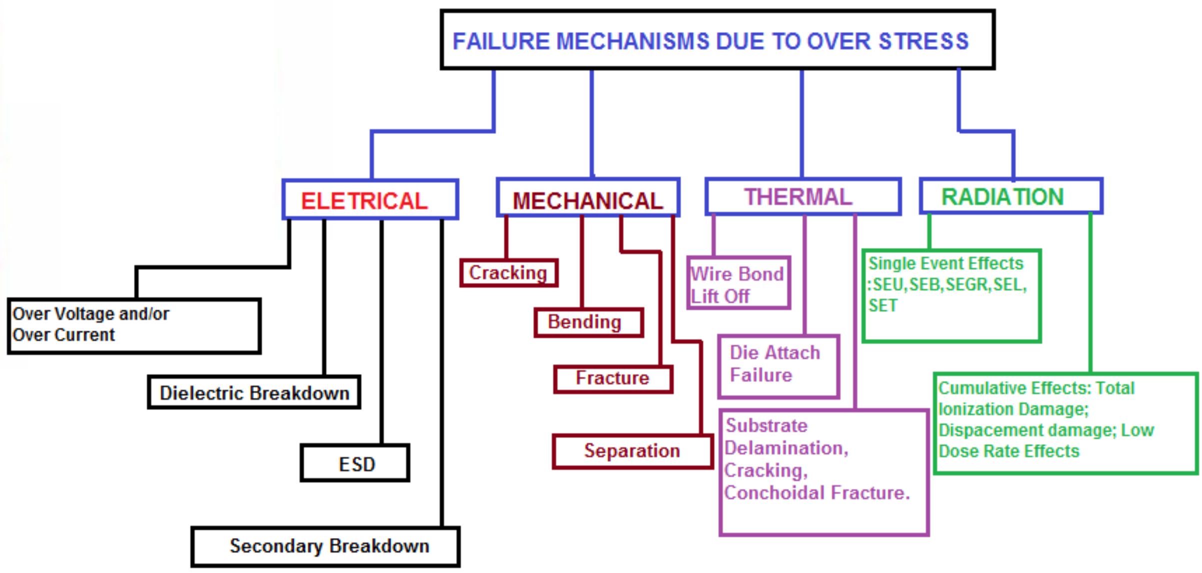

Fig. 2. Potential Failure Mechanisms Due to Over-stress

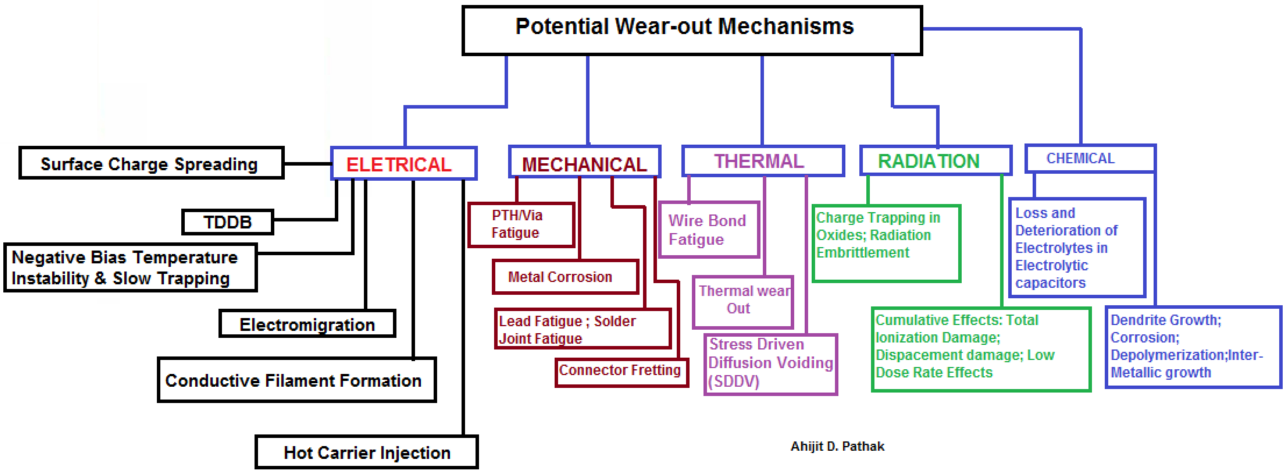

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Fig. 3 Potential Failure Mechanisms Due to Wear-Our Phenomenon

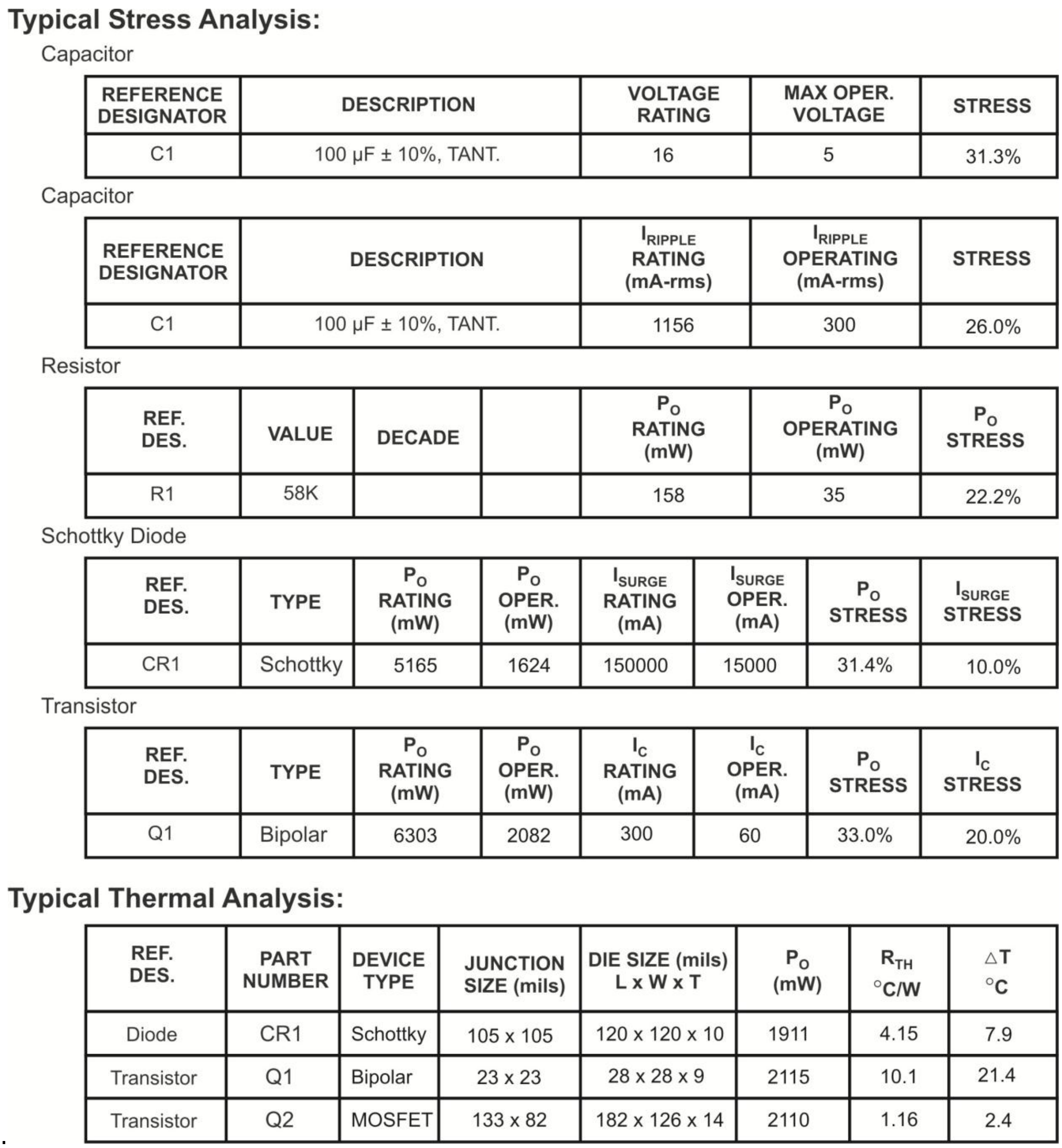
2.0 Recommended Practices for Ensuring Reliability of Power Electronics:

2.1 Methodical Steps from Design to Installation:

1. Prepare most comprehensive design process, taking into considerations all margins, following fail-safe methodology and required redundancy.
2. Choice of reliable components and parts. Keep in mind the wear out mechanisms of each part. Use minimum components. Making a simpler design helps attain higher reliability.
3. Use of established manufacturing processes followed by quality assurance & inspection at each stage.
4. Study the environment and worst case operational conditions envisaged and translate this in to adapting or changing the first three steps above.
5. Incorporate EMI protection by incorporating EMI/RFI filters and other mitigation schemes.
6. Testing the finished product thoroughly against all specifications in simulated environments.
7. Ensure that the manufactured power electronics product is safely transported and correctly commissioned.
8. Make sure that the concerned users are well educated about correct application aspects, ensuring no out of bound stresses are applied during the life of the product.

2.2 Typical Stress and Thermal Analysis and Safe Operating Area:

As an example of analysis recommended for determining stress and thermal margins, following table in Fig. (4) provides typical stress analysis and thermal analysis data of just a few components



Typical Stress Analysis:

Capacitor

REFERENCE DESIGNATOR	DESCRIPTION	VOLTAGE RATING	MAX OPER. VOLTAGE	STRESS
C1	100 µF ± 10%, TANT.	16	5	31.3%

Capacitor

REFERENCE DESIGNATOR	DESCRIPTION	I_{RIPPLE} RATING (mA-rms)	I_{RIPPLE} OPERATING (mA-rms)	STRESS
C1	100 µF ± 10%, TANT.	1156	300	26.0%

Resistor

REF. DES.	VALUE	DECADE		P_O RATING (mW)	P_O OPERATING (mW)	P_O STRESS
R1	58K			158	35	22.2%

Schottky Diode

REF. DES.	TYPE	P_O RATING (mW)	P_O OPER. (mW)	I_{SURGE} RATING (mA)	I_{SURGE} OPER. (mA)	P_O STRESS	I_{SURGE} STRESS
CR1	Schottky	5165	1624	150000	15000	31.4%	10.0%

Transistor

REF. DES.	TYPE	P_O RATING (mW)	P_O OPER. (mW)	I_C RATING (mA)	I_C OPER. (mA)	P_O STRESS	I_C STRESS
Q1	Bipolar	6303	2082	300	60	33.0%	20.0%

Typical Thermal Analysis:

REF. DES.	PART NUMBER	DEVICE TYPE	JUNCTION SIZE (mils)	DIE SIZE (mils) L x W x T	P_O (mW)	R_{TH} °C/W	△T °C
Diode	CR1	Schottky	105 x 105	120 x 120 x 10	1911	4.15	7.9
Transistor	Q1	Bipolar	23 x 23	28 x 28 x 9	2115	10.1	21.4
Transistor	Q2	MOSFET	133 x 82	182 x 126 x 14	2110	1.16	2.4

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Fig. (4) Stress and Thermal Analysis of few components of a Power Supply

In Fig. (5) general concept of safe operating area, explaining relationship between stress amplitude and time duration of application for any parameter is explained. As an example SOA graph of a radiation hardened MOSFET is shown in Fig. (6). In both the figures, left lower corner of the graph shows Safe Operating Area and restricting operation within this region ensures higher reliability of power electronics components or systems.

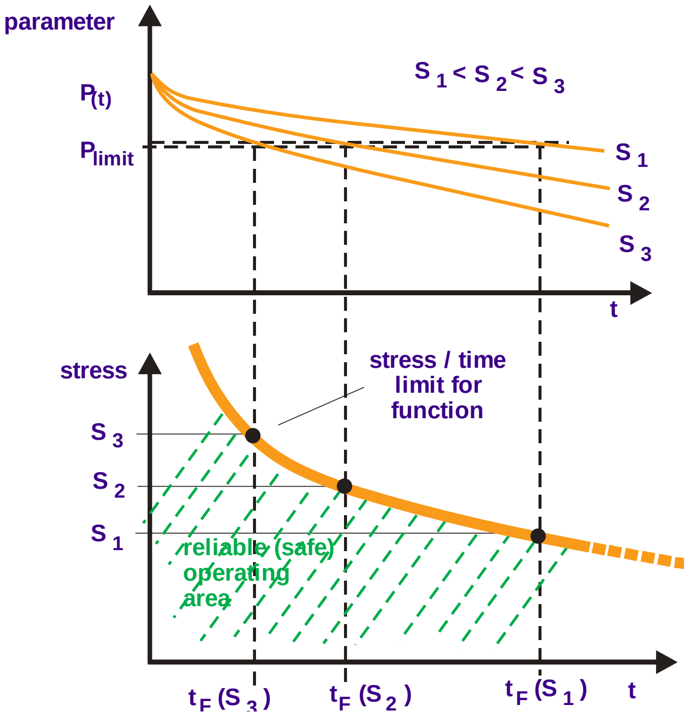

Fig. (5) Relationship between Stress amplitude and time duration of application for reliable operation

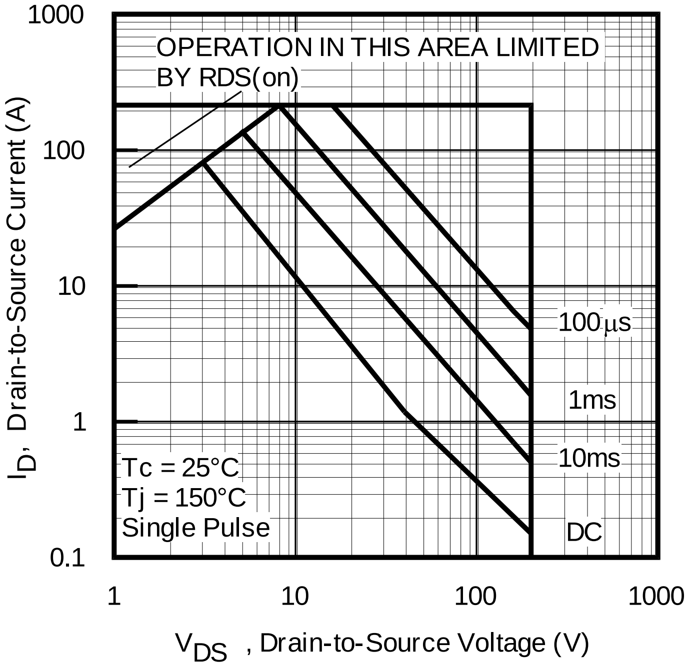

Fig. (6) A typical Safe Operating Area (SOA) curve of a Radiation Hardened MOSFET IRHNA57260SE.

2.3 Other Analytical Methods:

"PFMECA" stands for "Process Failure Modes Effects and Criticality Analysis". It can be advantageously used to identify potential failures in a power electronics manufacturing process, rank the criticality of the failure types and to identify actions required for mitigating failures. The main use for PFMECA is for early identification of potential failure modes so that one can eliminate or minimize them quickly.

The FMECA (Failure Mode & Effects Criticality Analysis) of power electronic system is a detailed quantitative work. It lists function performed by each constituent component, explores all probable failure modes, gives failure rates, provides information about effects and determines criticality of every likely failure.

Worst Case Analysis (WCA) takes into account the worst operating conditions and End of Life behaviour of all components and sub-systems of power electronics and provides various data on specifications of interest for manufacturer and user. As an example for the control loops of power electronics, computed and measured phase margin and gain margin under worst case conditions should ensure unconditional stability. Likewise computed junction temperatures of all power semiconductor devices should be well within limits under worst case operating conditions & environments. As another example, For a DC to DC Converter operating aboard a satellite, a Worst Case Analysis (WCA) can confirm that its voltage regulation, ripple, efficiency, Phase and Gain margins should all be well within specified limits at End of Life under worst case conditions.

Other simulation software solutions allow design engineers to create virtual prototypes of power electronic systems so that they can predict how such complex power electronics product will behave under actual operating conditions. This guides design engineers to tweak their designs and rerun the software to arrive at final design.

3.0 Designing Methods & Processes and Selecting Standards for Different Applications to Achieve Highest Reliability

3.1 Space Applications:

Of all applications of power electronics, its use in space calls for ultimate reliability. Reasons for this are:

1. The power electronic sub-systems can’t be repaired or replaced in space.
2. The cost, objectives & time required for the space mission can’t tolerate failure or malfunction in any sub-system or component as it could jeopardize wholly or partially the mission objectives.
3. Space environment is unique with radiation, absence of atmosphere and gravity, making it necessary to use radiation hardened components and dissipate heat by conduction and radiation only.
4. Weight, volume and power are costliest in space and hence maximum efficiency in smallest volume and weight are to be achieved with highest reliability and longest life.
5. Power electronic sub-systems should feature remote operation through telecommand and performance monitoring through telemetry, justifying need for special reliability measures.

Screening, testing and inspection requirements for power semiconductors for space applications are done as per MIL-PRF-19500. MOSFETs, Schottkys and Solid State Relays required for building power electronic subsystems should be radiation hardened. Likewise, the power management ICs and other ICs, should be radiation hardened by design with required redundancy. All DC to DC Converters and Motion Control Products should be radiation hardened. Immunity towards Total Ionization Dose (TID) and Single Event Effects (SEE), is a must for ensuring reliable operation for all the above. SEE includes all its variants such as SEU, SEB, SEGR, SEL, and SET. Level of radiation hardness required depends upon type of orbits. In addition, one has to test for ELDRS, Neutron effects and displacement damage in certain cases.

MIL-STD-1547 is for electronic part, materials and processes for space and launch vehicles. NASA has produced EEE-INST-002, which contains Instructions for Electrical, Electronic & Electromagnetic Parts Selection, Screening, Qualification and Derating. A comparison between EEE-INST-002 and MIL-STD-975 for derating of many power electronic components was done and is shown in Fig. (7). MIL-STD-750/5 is for High reliability space application test methods for semiconductor devices. When the relevant standards are followed, it helps towards achieving compliance and reliability. EMI compliance is done as per MIL-STD-461 to ensure reliable operation.

	EEE-INST-002		MIL-STD-975		
Device Type	Parameter	Class K	Class H	Class J	Class K
Capacitor Ceramic	Voltage	60% with Max ambient temp.=110 ^{0}C	80% to 125°C	60% to 110°C	50% to 85°C 30% at 125°C
Capacitor, Metallized Film	Voltage	60% to 85°C	80% to 125°C	60% to 85°C	50% to 85°C
Capacitor, Tantalum	Voltage Ripple Current	50% to 70°C 50% to 70°C	65% to 125°C 70% to 125°C	50% to 85°C 70% to 85°C	50% to 70°C 60% to 85°C
Resistor	Power	60%	75%	65%	60%
Diodes	Reverse Voltage Forward Current Surge Current Power Junction Temperature	70% 50% 50% Tj = 125 °C or 40 °C below the manufacturer's maximum rating, whichever is lower.	80% 80% 75% Limited by max TJ Mfg. rated	75% 75% 75% Limited by max TJ 125°C	70% 50% 50% Limited by max TJ 105°C
Zener Diodes	Power Zener current Junction temperature	50% 75% Tj = 125 °C or 40 °C below the manufacturer's maximum rating, whichever is lower.	65% 50%	65% 50%	50% 50%
Current Regulator Diodes	Operating Voltage	80%	80%	80%	80%
Microcircuits, Digital	Load Current Supply Voltage Fan-out Power Dissipation Junction Temperature	80% 90% N/A 80% Tj = 110 °C or 40 °C below the manufacturer's maximum rating, whichever is lower.	80% Mfg. rated 80% Limited by max TJ Mfg. rated	80% 110% of Nominal 80% Limited by max TJ 125°C	80% 110% of Nominal 80% Limited by max TJ 100°C
Microcircuits, Linear	Supply Voltage Input Voltage Output Current Gain Power Dissipation Junction Temperature	80% Output Current=80% N/A 75% Tj = 110 °C or 40 °C below the manufacturer's maximum rating, whichever is lower.	Mfg. rated 100% of VCC 80% Limited by max TJ Mfg. rated	80% 100% of VCC 75% Limited by max TJ 125°C	80% 100% of VCC 75% 75% Limited by max TJ 100°C
Bipolar Transistors	Voltage (VCE) Current (IC) Power Dissipation Junction Temperature	75% 75% 60% Tj = 125 °C or 40 °C below the manufacturer's maximum rating, whichever is lower.	80% 75% Limited by max TJ Mfg. rated	75% 75% Limited by max TJ 125°C	75% 75% Limited by max TJ 105°C
MOSFETS	Voltage (VDS) Voltage (VGS) Current (ID) Power Dissipation Junction Temperature	75% 60% 75% 60 % Tj = 125 °C or 40 °C below the manufacturer's maximum rating, whichever is lower.	90% 75% 75% Limited by max TJ Mfg. rated	75% 60% 75% Limited by max TJ 125°C	75% 60% 75% Limited by max TJ 105°C

Fig. 7 Comparison between EEE-INST-002 and MIL-STD-975 for derating of Power electronic components

3.2 Military and Aviation Applications:

Power electronics built for military and aerospace fields have different requirements, as the operating environment and application aspects are different. MIL-STD-810G describes test methods and environmental aspects for this application. This can involve tests in presence of high "G" pyrotechnical shock & vibrations, thermal cycling and corrosive atmosphere such as salt spray and fog. Other environmental tests are done as per application requirements. For checking reliability, accelerated stress screening, accelerated life testing and environmental stress testing are used. Tests are performed to verify compliance with EMI standards: MIL-STD-461, MIL-STD-1275 and Mil-STD-704.

As the World moves from "More Electric" to "All Electric" Air crafts, accent is on lighter, but more efficient and reliable power electronic components and sub-systems. Removing hydraulic systems with power electronics improves aircraft reliability and reduces complexity, weight, installation, maintenance & replacement and running cost. Air craft designers are demanding much more power processing from smaller and lighter components.

Power electronics are designed into a wide variety of military and commercial aircraft for applications such as cockpit electronics, radar, electronic warfare systems, signal conditioning of sensors, wiper motor controls, automatic test equipment, displays, computers, in-flight entertainment systems and in galleys for food preparation. Use of DSPs and microcontrollers help in developing software based controls, which can be adapted, modified or improved at will. These DSPs and Microcontrollers use Point of Load converters, which need to be highly efficient and reliable, to supply low voltage with high current at high di/dt.

Modularization and standardization of power electronics for air crafts is desirable. Achieving reliability of power electronics for air crafts is an equally challenging field. Location of power supply or DC to DC Converter should be optimized to reduce wiring length between power and load. At the same time, one understands that in wing or belly fairing areas and in many other parts of air craft, power electronics systems have to face environmental hazards. Installing power electronics systems in locations with pressurized air help its operational reliability. Commercial and Military Aviation are fields, wherein human safety are of paramount importance and hence reliability of power electronic systems have to be treated with special care and attention.

4.0 Conclusion:

Power Electronics has progressively gained important status in the realm of engineering and in modern day living. Now nearly 70% of all electrical energy, from Watts to Megawatts, is processed through power electronics. This is likely to go to 80% in 2015. Hence achieving reliability of power electronics becomes all the more necessary, while optimizing its design and manufacturing with highest efficiency in smallest volume. Power electronics forms critical segment of many HiRel applications, making it all the more necessary to achieve highest reliability during long life, without requiring any maintenance or repair.

Principles of reliability practices are more or less universal and also applicable to both power electronics components and systems. Deeper understanding of the physical processes involved coupled with modern simulation software enable more reliable design and manufacturing methods. Accelerated testing in simulated environment, while using thermal cycling coupled with shock & vibrations have benefitted detection of early failures. Greater understanding of various wear out mechanisms has helped in taking necessary precautions and maintaining safety margins.

Applications of power electronics in space require attention to radiation hardness, heat dissipation in vacuum, absence of gravity and adherence to many quality standards established. Likewise applications in military and aviation also demand high reliability and long life but have different standards, environment and requirements to comply with.

Power electronic systems use more and more of digital controls using DSPs, FPGAs and microcontrollers. I hasten to add here that the total reliability of such a power electronic system has to take into account integrity of the hardware and software of such digital platforms. This is, because “a chain is only as strong as its weakest link”.

The observed trend is healthy and more and more manufacturers are following many of the required steps and recommendations to ensure that power electronic components and systems continue to be more reliable and long lasting.

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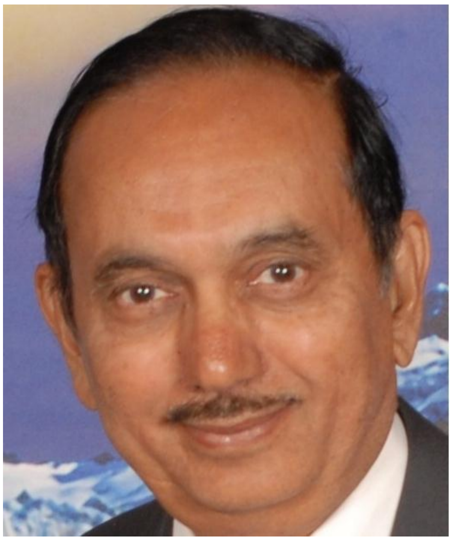

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