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A road map for reliable power electronics for more electric aircraft

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ABSTRACT

The gradual evolution from hydro-pneumatic to electrical disposition of power in aircraft has placed stringent requirements on the reliability of power electronic components in current and future aerospace applications. This paper examines the prevalent state-of-the-art in power electronics and provides an analytical overview of power electronics in More Electric Aircraft (MEA) vis-à-vis the generation and distribution of power within these aircraft.

The types of power devices currently employed for multiple conversion topologies are analysed and weighed according to their respective reliability characteristics. Beginning with an in-depth review of failure modes in the currently available devices, the paper highlights the salient emerging state-of-the-art Wide Band Gap (WBG) technologies such as Gallium Nitride (GaN) and Silicon Carbide (SiC) and draws an extensive comparison with their Silicon counterparts.

A comprehensive examination of techniques employed for the estimation of the reliability of WBG power devices has revealed a number of areas that merit due consideration. For instance, the physics-based models that have been developed to assess the operational lifetime of silicon-based devices for given failure modes require revamping in light of the new materials and the unique electrical and physical characteristics the WBG devices possess. Similarly, the condition monitoring techniques, with respect to the primary and secondary parameters, require further investigation to determine highly representative feature vectors that best describe the degradation within these devices. More significantly, optimisation of the proposed techniques for the health assessment of these devices needs to be pursued through the optimal use of vital parameters. Keeping these critical findings in perspective, a road map highlighting various avenues for power electronics optimisation in MEA is put forth to apprise the aerospace fraternity of its growing significance.

1. Introduction

Traditionally, the use of secondary power within civil aircraft has fallen into three general categories, namely, Hydraulic, Pneumatic, and Electrical power. Current trends are seeing manufacturers moving towards replacing traditional secondary hydraulic and pneumatic power systems with electrical alternatives.

Hydraulic technology has three major downfalls: The average efficiency of power generation and control through throttling is poor; power networks are heavy and present problems due to (design, production, operation) constraints; and finally, hydraulic fluid is harmful to people and the environment. All the above downfalls can be solved using electrical systems, and make the “fully electric” commercial aircraft an evolutionarily viable prospect. The power-off taken at the engine by all the aircraft’s systems are typically responsible for 3–5% of the total power produced by the engine [1]. By developing a more electric aircraft (MEA), this power requirement can be significantly reduced, enabling lower fuel burn and emissions.

Several initiatives have been proposed to reduce the emissions in the next generation of aircraft currently being developed. These include Power Optimised Aircraft (POA), More Open Electrical Technologies (MOET) project, and the CLEAN SKY Joint Undertaking (CSJU), CLEAN SKY 2 and 3 [2]. CLEAN SKY 2 aims to further increase the goals of CLEAN SKY by cutting 80% of air transport CO_2 emissions by 2050. CLEAN SKY 3 due to the life expectancy of aircraft, would require technologies to enter service in 2030–35 and should be demonstrated by 2025–27.

However, before full electrification is observed there are still numerous reliability issues to be resolved; especially within power electronics. Aerospace presents a demanding operational environment for power electronics. Stressors, which present either individually or mutually, the challenge to the reliability of these systems are high

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temperatures, temperature cycling, vibration, humidity, dust, electromagnetic interference, as well as cosmic radiation [3]. All of which can lead to component failure and ultimately endanger the safety of the aircraft. The components that constitute a power electronics system consist of semiconductors, capacitors, electro-mechanical, electromagnetic, sensors, and auxiliary devices. As well as danger to the aircraft, failure of these devices also incurs costs from maintenance and downtime.

This review paper investigates the reliability of these electrified systems and presents a road map to improving the design and in-service condition monitoring of this evolving technology.

The paper starts by examining the current architecture of the More Electric Aircraft (MEA) and the associated power electronic component failures in sub-systems within the aircraft.

Lifetime expectations and the root cause of these failures are then analysed in terms of the critical stressors and component failure mechanisms. Current and potential ideas aimed at improving reliability are critically examined. Improvements to components, Physics of Failure (PoF) approach and active methods design methodologies, testing strategies and sensor technologies are also highlighted.

Finally, a roadmap of challenges and suggested improvements to the future of MEA is presented [4–8].

2. MEA architecture and failure modes

Boeing 787 and the Airbus A380 are the two wide bodied commercial aircraft currently using MEA principles within their aircraft. These aircraft are characterized by intensive electrification with services like the Environmental Control System (ECS) (for B787) and flight-control electro-hydrostatic actuators (for A380) are electrically powered. [9], outlines the major changes from electrification and in actuation in the B787 and A380.

Electrification, however, comes at a cost of increased complexity. For example, on current long-range aircraft e.g. Boeings 747, there are 13,400 functional power lines (for both power and signal) with a length of 240 km and with a total mass of 1800 kg (20% mass for connectors and fasteners). The Airbus A380 increases this to 500 Km, whereas the Boeing B787 has 120 miles of cables with a mass in excess of 4 tons [10].

Traditionally aircraft have used a 3-phase 115 VAC electrical standard based upon Constant Speed/Constant Frequency (CSCF) generators on each engine and the auxiliary power unit. MEA uses CSCF and Variable Speed/Variable Frequency (VSVF) generation. The main advantage of this system is better starter/generator systems, with higher reliability, lower recurring costs, and shorter mission cycle times [11].

The MEA power distribution system can be classified into three architectures based on the *frequency of the voltage in the generator output.* Constant Frequency Distribution, Variable Frequency Distribution and DC Distribution [12]. Full-wave rectification results in 270 (±135) V DC, available for high power applications and 28 V DC for low power systems.

The electrification architecture for Boeing 787 MEA is shown in Fig. 1 [13]. Variable Frequency Generators (VFGs) supply 3-phase power from the engines and auxiliary power unit on a 230VAC (300–800Hz) bus, where it is converted using power electronic converters and or/transformers. The step up to 230VAC bus architecture is to allow for the increased power demand. A737 aircraft's power consumption is around 100 KW, where the 787 is greater than 1 MW.

Auto-Transformer Units (ATUs) provide 3-phase 115VAC and Auto Transformer full-wave Rectification Units (ATRUs) of the three-phase voltage of 230V yields a direct voltage of 540 (±270) VDC. Finally, 28VDC is provided by Transformer Rectification Units (TRUs). Several energy-consuming loads (e.g. pumps, fans) are frequency-insensitive and can be used directly, implementing the so-called hybrid distribution system. Power electronic functions in the main will consist of AC/AC (Autotransformers), AC/DC (rectifiers), DC/AC (inverters) and DC/DC power converters (Buck and Boost-or Buck-Boost) [14].

2.1. Reliability of subsystems

Reliability is the probability that a system or component will perform a required function without failure under stated conditions for a specified period of time [15]. In a commercial aircraft, there are five levels of failure defined by DO-254 [16]. Each level defines a failure rate compliance and is governed by the impact the failure would have on the aircraft. For critical loads this is defined as 10^{-9}/h (1 failure in time (FIT)) e.g. 1 FIT corresponds to 114,000 years of operation of a component without failure. This metric is taken from large samples of test data for components and cannot however be related to the lifetime of an individual component.

Knowledge of stress influences relevant to the application is

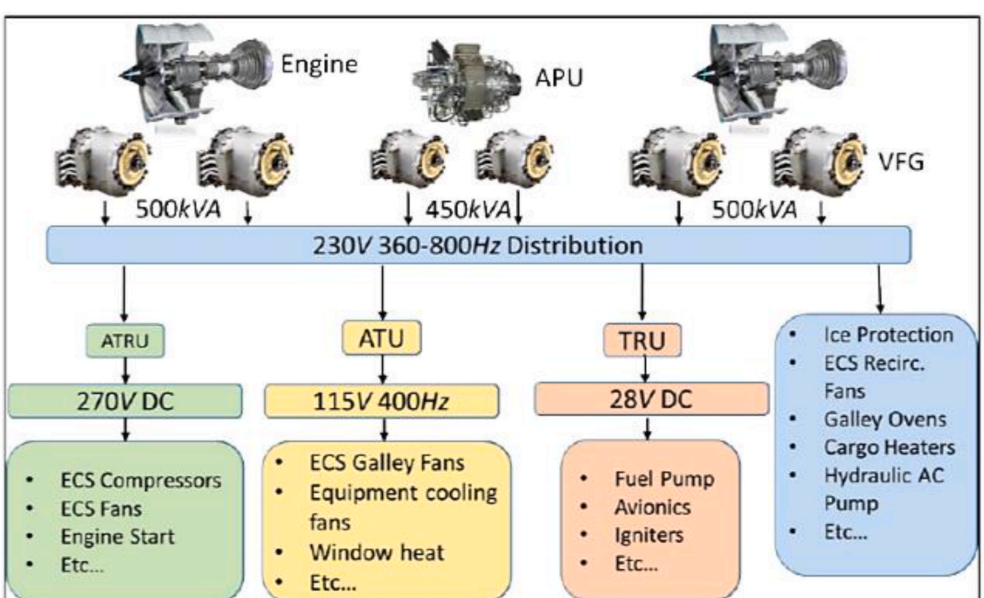

Fig. 1. Simplified diagram of electric distribution systems for the Boeing B787 [9]. Note: ATRU -Auto-Transformer Rectifier Unit, ATU – Auto-Transformer Unit and TRU - Transformer Rectifier Unit.

extremely important and governs the correct choice of components for the given operational stressors involved. An aircraft will be subject to various environmental stresses which can affect the reliability of sub-components. Fig. 2 shows a typical mission profile where temperatures may vary from 80 °C to −25 °C, with vibration exceeding 40 g and humidity more than 60% [17].

2.2. *Critical stressors*

The primary stressors affecting the reliability of several components within power electronics systems, such as printed circuit boards (PCBs), semiconductors, and capacitors are temperature-related [18].

The effects of temperature may be sub-divided into a further two stress factors. In semiconductors, both the average temperature of the junction as well as the cycling temperature are known inducers of stress. The temperature cycling of the junction may again be sub-divided into Junction temperature cycling that is evoked by ambient temperature and that evoked by the components' self-heating (also known as *power cycling*). The widespread nature of thermal stressors, especially thermal cycling due to internal losses is hard to avoid [3]. In aircraft, this problem may be compounded by where the unit is situated. Placing the power electronics within the pressurized airframe brings its own problems in terms of natural cooling (often forced cooling is required).

The influence of ambient effects on aircraft power electronic systems due to extreme changes in the operating environment, especially high humidity, is great. Humidity build-up within the system enclosure leads to water condensation, which can cause increased leakage currents and corrosion of components [19]. The typical aircraft mission profile, see Fig. 2, induces cycling ambient temperatures causing a significant increase in water vapour concentration. The effect of humidity has also been studied for PCB assemblies [20].

Mechanical impacts, such as vibration and shock, primarily affect the robustness of mechanical components and the interconnections of electrical connectors and PCBs, vibration-induced failures are often caused when a relative motion is set up at the resonant frequency of the PCB [21–23].

There are two basic types of vibration, sinusoidal and random excitation. The former involves a periodic repetition, such as simple harmonic motion, where random motion does not. Studies have shown that the component leads, and solder joints will fail before subsequently the failure of the PCB e.g. copper etchings [24]. The combination of thermal cycling and mechanical vibration on solder connections was investigated in Ref. [22]. Solder crack propagation on PCBs was shown to increase with the combination of stressors (such as temperature) compared to the individual stressors.

Electromagnetic interference (EMI) can cause avionic equipment performance to degrade or even malfunction. Power electronics are themselves a source of Electromagnetic Interference (EMI), which may affect the system itself or electronics within range (radiated susceptibility). Hence, Standards such as RTCA DO-160 for environmental conditions and test procedures for airborne equipment and MIL-STD-461 exist to control EMI issues. One way to mitigate such effects is shielding a device or system, another is to employ filtering [34].

Particles confined in the Earth's magnetic field can cause damage to power semiconductor devices due to the ionization and displacement from these heavy ion sources. Cosmic rays have been identified as a source of single-event induced burnout when they strike a device. This is prevalent in the avionic industry, where burnout both in bipolar and MOS devices has been observed [25,26].

2.3. *Component failure mechanisms*

A chain is only as strong as its weakest link. For an aircraft electrical system, for example, the power by wire actuator driver Fig. 3, if the target lifetime is to be achieved, the reliability of every component within the system needs to be assured.

Failure mechanisms along with the resulting failure modes are briefly discussed for selected components of power electronics systems and evaluated regarding their effect on reliability in this section.

Power device failures can be attributed to two main categories; namely, random failures and wear-out failures. Random failures are attributed to external accidental events such as voltage transients, damage in service leading to momentary over-stress, and particle radiation. The second type of failure, wear-out, occurs due to the accumulation of incremental physical damage under the operating load conditions, which in turn alters the parameters of the device beyond its specified boundaries.

Various surveys [3,27], have shown power modules and semiconductor packages are devices susceptible to failure during their lifetime. This is due to the devices being subjective to large stresses due to high operating currents and voltages typically involved. The construction of the devices, typically with multiple layers of substrates, each having its own coefficient of thermal expansion (CTE), sets up stresses within the device, which can over time impact reliability. The thermo-mechanical stresses set up within the power module or package are of a magnitude sufficient to cause potential reliability problems. The major failures within the modules or packages typically include bond wire lift-off [28,29] and solder fatigue [30,31]. Both modes of failure are due to a result of the mismatches of CTE from temperature excursion during operation.

Chip-related failure mechanisms are those that ultimately destroy the device and are separate from packaging-related failures, however,

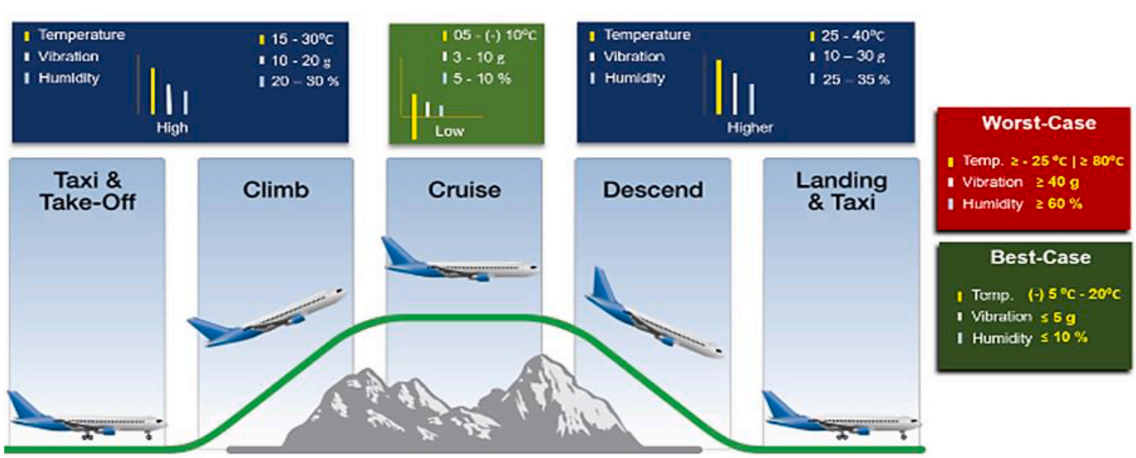

Fig. 2. Typical environmental mission profile.

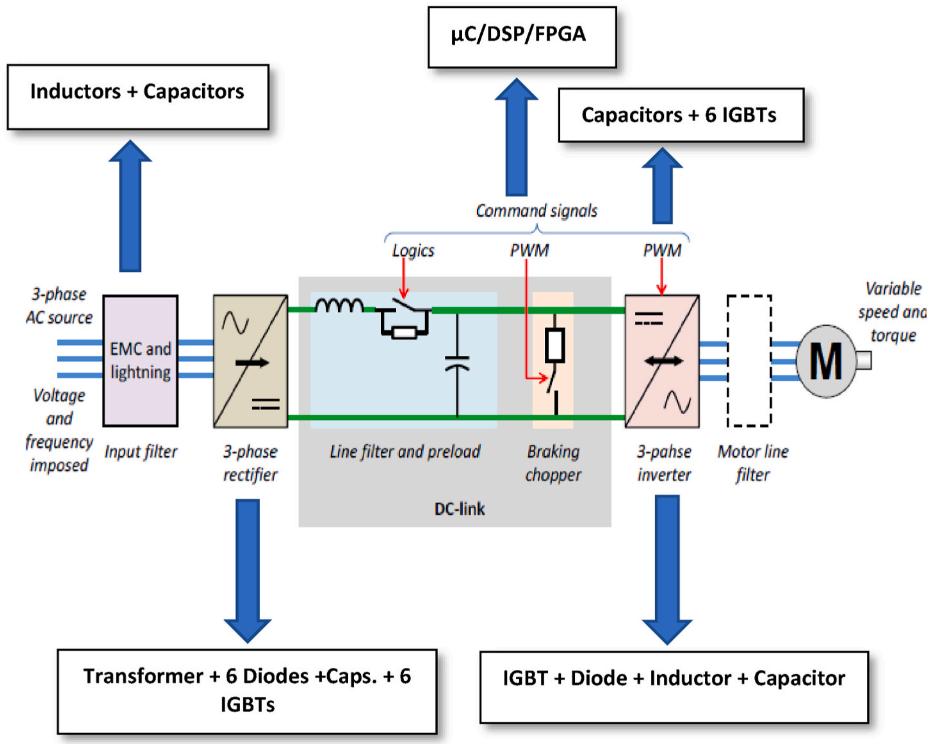

Fig. 3. Components in a power by wire (PbW) actuator.

the two may be interlinked for a failure event [32,33]. If devices are operated within datasheet parameters, it may be safe to assume that issues such as parameter shifts, and other degradations will not occur. However, overload stress can still cause device failure [3].

The operation of power modules is reliant on the driver circuity employed. Failures such as open circuits, short circuits and timing issues can cause considerable variation in the operation parameters and can result in harm or destruction of the module or individual device. EMI, and parasitic elements may also disrupt the operation, therefore careful consideration needs to be given to earthing to avoid low current loops, as well as component placement [34].

Capacitors are essential in most power conversion systems, unfortunately they are the most unreliable component [3,27]. The three main types of capacitors are aluminium electrolytic capacitors (Al-Caps), metallized polypropylene film capacitors (MPPF-Caps), and multilayer ceramic capacitors (MLC-Caps) [35].

The failure mechanisms are device-specific. High temperature and ripple currents can accelerate the electrolyte vaporisation in Al-caps, which is also voltage dependant. MPPF and MLC-Caps, also suffer from ripple, current and humidity. Dielectric loss is associated with failure in the former and oxide vacancy migration and insulation degradation accelerated by vibration in the latter [36]. These failure modes may present either as open or closed-circuit failures.

Aerospace has one of the highest operating demands for PCBs. Vibration and temperature being the main stressors, which are especially compounded in aerospace applications. The electrical paths and solders joints are required to maintain their functionality far in excess of what may be expected of a commercial product. This is one reason for the delayed switch from lead to lead-free solder.

Fatigue, however, may manifest in the form of mechanical strain due to the different resonant frequencies experienced by the board and solder joints. Temperature, frequency, and power cycling can also act to increase failure time [37]. Encapsulation and application of specific conformal coatings may help against vibration and moisture ingress. Assembly of the PCB may lead to damage of the soldered components due to deformation and tension.

Other components susceptible to failure in aerospace applications include electro-mechanical devices such as transformers, contactors, relays, and motors. These devices may see open and short circuits in windings due to delamination of the insulator from heat over time. Relays and contactors suffer from increased contact resistance leading to eventual welding due to fretting and arcing.

2.4. Components to focus on in future research

The industry surveys carried out by Refs. [3,27] based on the parts most prone to failure, cite switching devices, capacitors, electromechanical components, and cooling systems as priorities to be addressed by future research. The surveys also identified that more research should be focused on power semiconductors, power semiconductor modules, and capacitors. This research should especially address those parts exposed to harsh environments (e.g., high temperature or humidity).

3. Reliability

Ultimately, the reliability is set at the design stage. Increasing the reliability of power electronics systems can be divided into two main research paths. Firstly, identifying the hardware materials and interconnections that are prone to failure and secondly, changing the utilization of the components to relieve stress [3].

Accelerated testing may be used to gain a deeper insight into how a device or system behaves over the designated lifetime [38]. To generate this knowledge about the lifetime of the device, accelerated testing reduces the operational timeframe from what may be 30 years in the case of an Aircraft to tens of hours, by accelerating the degradation. To enable successful accelerated testing, the stressors need to be identified. These are external stresses or loads which have a direct impact upon the device's life, and may include, as already discussed; temperature, vibration, humidity, current, and voltage.

3.1. Improved components

As well as modifications in circuit design methodology such as better PCB layout to mitigate EMI effects and allow improved cooling. A great deal of responsibility lies with the manufacturer to facilitate better testing and feedback to identify failure modes. This understanding has resulted in improved manufacturing and connection technology. For example, sintering and low temperature joining instead of solder between layers and advancement in bond wires [39,40].

3.2. Future components (WBG)

Silicon Carbide (SiC), Gallium Nitride (GaN), and Diamond belong to a class of semiconductor materials classified as wide-bandgap (WBG) devices [41]. The properties that make WBG semiconductors so desirable are characterized as follows [42]: Higher operating temperatures as well as much lower leakage currents, improved radiation hardness, higher critical electric field layers resulting in thinner devices, higher operating frequencies, and higher thermal conductivities, allowing devices to operate at much higher power densities. In order to achieve higher efficiencies in future MEA, semiconductors must adhere to lower conduction and switching losses. The benefits WBG devices exhibit over silicon devices in terms of size, weight and power density make them the obvious choice in the future electrification of aircraft [1].

A comparison of the material properties of Si, SiC and GaN is shown in Fig. 4 [43]. For high voltage (>600V) and high-temperature applications, SiC excels; however, the material characteristics of GaN are superior in high-efficiency and high-frequency converters. This is due to GaN's wide band gap (3.4eV), large critical electric field, and high electron mobility, permitting devices with higher blocking capability and faster switching transients as well as relatively good thermal conductivity when compared to Si [43–46].

The majority of the GaN devices available today are lateral heterojunction field-effect transistors (HFETs), also known as high electron mobility transistors (HEMTs). They are typically rated at 600–650V, although manufacturers propose higher voltage devices [46]. These switching devices are typically of an enhancement mode, normally-OFF type, as they offer a fail-safe operation for simpler gate drive circuitry. The fabrication of normally-OFF GaN HFETs has resulted in the cascading of devices, typically a depletion-mode GaN HFET in series with a low-voltage enhancement mode Si MOSFET. The increased packaging complexity in GaN cascading due to the series connection of the two devices however, can introduce parasitic inductance [47].

Fig. 5 outlines the unique parameters that make GaN a superb choice of material for high power electronics devices. These include high thermal stability, high saturation drift velocity, and large conduction band discontinuities which are superior to Si and SiC. GaN also has a lower on-resistance ($R_{DS(ON)}$), resulting in lower conduction losses and chip size when compared to Si and SiC. This enables simpler cooling and heat sinking strategies to be employed [48]. However, the thermal conductivity of GaN is poorer, making for reduced heat conduction from the devices' junction to case, and heatsink, if present. Hence, it may be expected that the device will experience higher operational temperatures for the same dissipated power compared with SiC and Si counterparts [47].

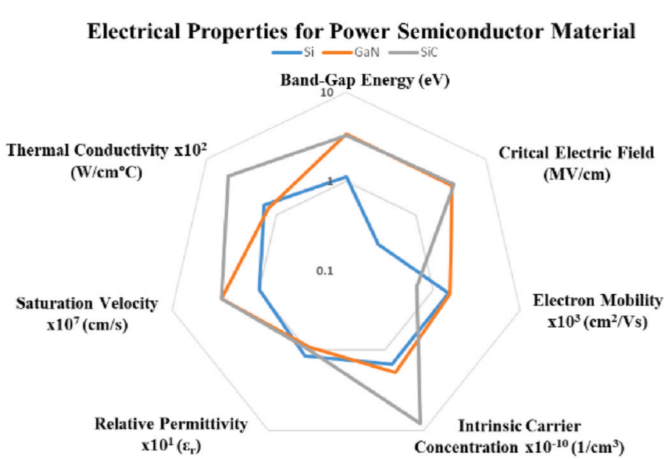

Fig. 4. Comparison of the material properties of Si and WBG semiconductors [43].

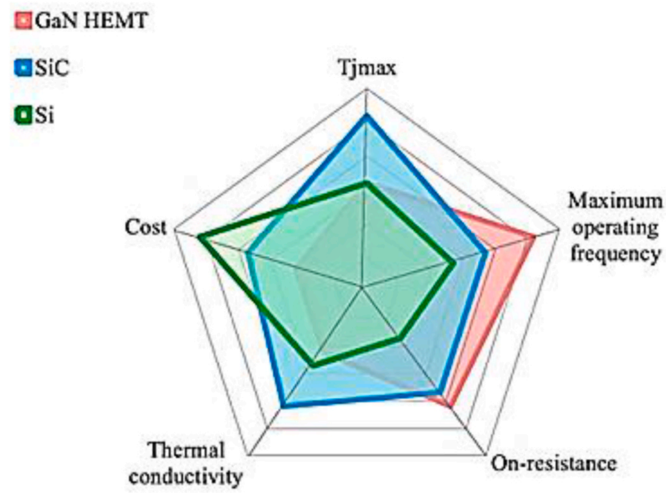

Fig. 5. Device parameters for 650V GaN, Si and SiC switches [47].

Compared to Si, GaN switches have a lower gate-drain capacitance (C_{gd}) and gate-source capacitance (C_{gs}), primarily due to the lateral structure used. The effect of the total gate charge when GaN is compared to Si is approximately half (7.5 nC for GaN as opposed to 15 nC for Si, typically) [44]. Along with the gate resistance, the junction capacitances contribute to the time constant during the switching transient. WBG devices, with smaller junction capacitances, are able to switch at higher speeds than Si MOSFETs. As shown in Fig. 6, the turn-on and turn-off time of GaN HEMT is 40% shorter than Si MOSFET [44]. This relates to higher switching efficiencies in GaN, since gate charge is directly related to the switching transient.

One disadvantage outlined by Refs. [43,47] is the faster switching speeds, high switching frequencies, and high frequency voltage and current ringing in GaN HEMT devices due to parasitic inductance. These can all increase the spectrum of both conductive and radiated Electromagnetic Interference (EMI).

This has the potential to cause reliability concerns such as sustained oscillation and gate failure within devices.

One challenge in increasing the electrification of aircraft is the cooling and control of power generation systems due to the higher electrical power demands. Both GaN and SiC have the properties of low losses, high switching capability, and high operating temperatures which assist greatly in addressing these problems [46]. The maximum allowed temperature of SiC and GaN can be as high as 600 °C. In comparison, the maximum temperature of Si is around 150°C-300 °C. However, due to the limitation of packaging techniques the devices made from a WBG material normally have lower maximum allowed temperature limits than the material itself. Manufacturers' data gives typical maximum allowed temperature of SiC MOSFET and GaN HEMT as 150°C-175 °C. WBG materials, however, have the potential to endure higher temperatures [47,48].

Currently, the cost is significantly higher for WBG devices, however, this is changing as the industry becomes more confident in the technology and embraces greater adaptation. The mass production of devices will see future cost parity with Si counterparts.

As mentioned in Section 2.2, the effects that radiation can have on

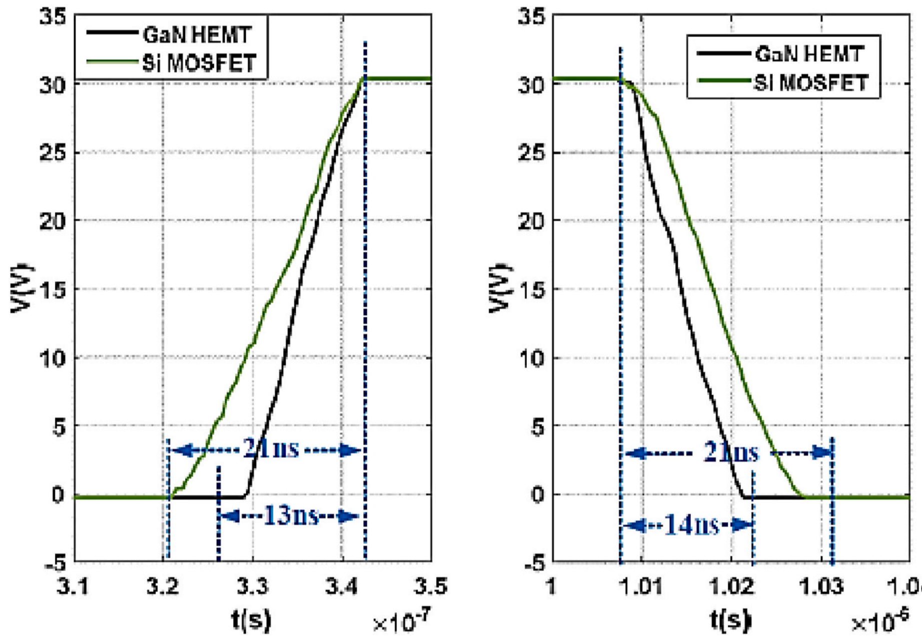

Fig. 6. (a&b). Switching waveform comparison between GaN HEMT and Si MOSFET during (a) turn-off and (b) turn-on [44].

electronic devices in aerospace applications is well documented [49–51]. Single Event Effects (SEEs) are one of the most catastrophic mechanisms, which could cause failure in WBG power devices.

Early studies have focused on the effects of protons, neutrons, and electrons. Failure modes generated by the protons in the AlGaN/GaN HEMT were first examined by Cai et al. [52], resulting in a decrease in the dc current and trans-conductance for different proton frequencies. [53,54] have, however, shown that the GaN devices are extremely hardened to radiation.

Irradiation of protons at different energies has a significant effect on the amount of defects created in the two-dimensional electron gas (2DEG) of the HEMT because of differences in the loss of nonionizing energy. The shift of electrical characteristics before and after irradiation has also been explored in several works [55,56].

An experimental investigation of neutron induced single event failures in Si and SiC power MOSFETs found neutrons to give rise to significantly fewer failures in SiC power MOSFETs compared to their Si equivalents [57].

The development of WBG devices has not been without problems and different issues have had to be resolved with the manufacturing process: gate electrical instability, large leakage currents due to wafer defects, and poor long-term chip tolerance at high temperatures [38].

In the last few years, tremendous progress has been achieved by the semiconductor industry in improving reliability; using innovative fabrication processes that result in good quality, large-size wafers and by producing cost-effective parts. This has resulted in failure-in-time (FIT) rates being reduced dramatically to a level comparable to, and in some instances, lower than those for Si parts. For example, a field failure rate with 0.12 FIT was reported for Cree's SiC MOSFETs and Schottky diodes, covering a span of 970 billion device-hours between 2004 and 2014 [58]. Similar research work predicted an FIT rate <10 with 90% confidence interval upon stress testing of GE 1.2 kV, 30A, SiC MOSFETs under a gate bias of 20 V and a junction temperature of 150 °C [59].

3.3. Physics of failure (PoF)

PoF has started to replace the Military-Handbook-217F and statistical methods such as Weibull analysis. The PoF approach is based on analysing and modelling each failure mechanism under various environmental and usage stresses. In practice, the PoF analysis focuses on critical components under critical stress conditions. From the PoF models, a prediction of reliability may be made. Two steps are involved in reliability modelling [60] as follows: 1) Electro-thermal modelling of the device chip and packaging during a given load cycle, generating the temperatures throughout the load cycle. 2) Thermo-mechanical modelling of the packaging materials, predicting the accumulated damage and/or lifetime, dependent on the thermal cycling.

Devices such as IGBT modules have had intensive research carried out into the failure mechanisms and subsequent development of physics-based lifetime models [32]. This approach has been demonstrated to improve thermal stress analysis of Si and SiC-based devices under long-term mission profiles [61] and increase the lifetime reliability of power electronics modules [62]. PoF models for capacitors are also outlined in Ref. [35]. Finite Element Analysis (FEA) [63,64] may be used as an alternative to modelling based upon a numerical approach for calculating stress-strain from experimental results and parameterization from a given temperature cycle. [65], demonstrates the diagnosis of package degradation of individual chips using external measurements and a neural network (NN) model produced from Thermo-electrical measurement data is used for training and validating the NNs.

Physics-based modelling by FEA requires detailed knowledge of geometry and material properties of the power module assembly, which is often not available in the public domain e.g. datasheet, and is only accessible from the manufacturer.

Design software, Fig. 7, embracing the *design for reliability* methodology is now commercially available [66]. Design for reliability enables the assessment of a systems reliability for a multitude of load profiles under stressors that may be encountered during operational lifetimes [67].

Lifetime assessments of components, as well as strengths and weaknesses within a system can be determined. It can also help with component placing to enable efficient cooling and stress reduction from vibration.

3.4. Active methods

Active methods may be used to increase the reliability of power electronic systems. These are software-based control structures that change system operation to release stress from its components while allowing none or only minor influence the overall performance [68].

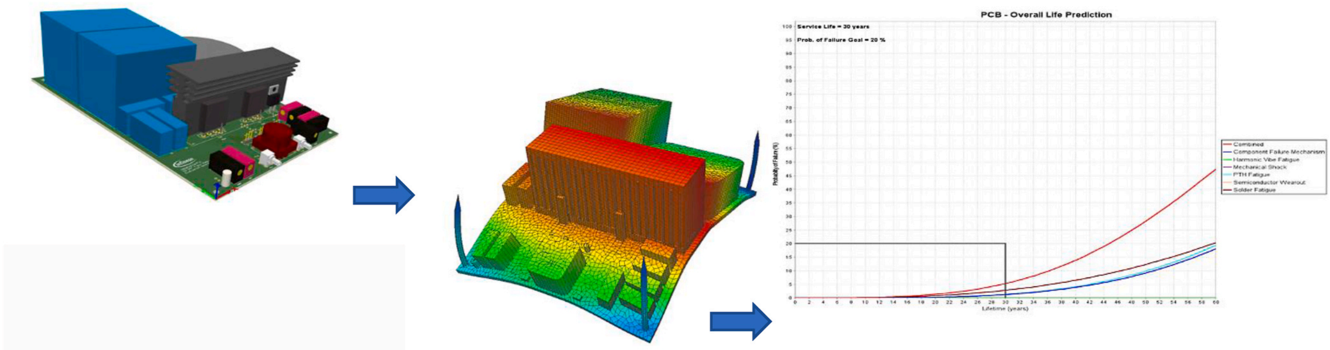

Fig. 7. Design for reliability software.

Firstly, condition monitoring, which enables the 'health status' of components within the system to be evaluated and can be used to predict reliability. Secondly, intelligent control can drive components with respect to their remaining lifetime.

3.5. *Condition monitoring & prognostics*

Condition Monitoring (CM) is a process or technique used to monitor the operating characteristics of a physical system [27]. A correctly implemented CM system can provide information on the development of device degradation and warn of impending failures, as well as providing aid to scheduling maintenance to extend the serviceable lifetime. To implement a successful CM programme for power conditioning devices, several problems need to be addressed [60].

Firstly, the identification of signatures relating the failure mechanism needs to be acquired, often these signals may be hidden in larger signals or be buried in noise during the normal operation of the device.

Secondly, the embedding of sensors within the high-density packaging of power semiconductor devices is a challenge, and may itself, alter the operation and reliability. Hence, the preference is to use external measurements to capture health signatures from signals used in devices control and protection. Lastly, variation in the operational characteristics of the power converter needs to be understood, as well as temperature and loss excursions.

For example, changes in R_{ON} or $V_{CE,sat}$ in devices such as IGBTs or diodes, subjected to long-time power cycling has been related to the bond wire lift-off mode of packaging degradation [69]. V_{ce} is the main Temperature Sensitive Dependent Parameter (TSDP) and it increases with the corresponding increase in junction temperature. Due to the high degree of accuracy and high voltage input range to the measurement circuit required for this measurement, suitable online V_{ce} measurement techniques can be challenging [70]. Changes of waveforms including V_{CE}, V_{GE}, I_{CE}, and I_{GE} during turn-on or turn-off have been utilized in switching time-based CM techniques [71,72].

Accurate estimation of the junction temperature has been deemed critical to the assessment of solder joint damage [73,74]. Measurement of the junction temperature by placing a temperature sensor near the junction [73], and case ambient temperatures has been investigated [75]. Subsequently calculating the additional power loss from the measured temperature changes was used to monitor solder layer damage.

Adopted CM methodologies for MEA currently in-service, if they are invasive and require alteration of circuitry will be subject to CAA approval. Hence surveying what information is available from current on-board sensors or the use of non-invasive techniques would be preferred. Non-invasive CM of IGBT modules, have been investigated; they include embedded sensor-based, time-domain reflectometry (TDR)-based, and inverter output-based CM techniques [76–78].

3.6. *Active thermal control*

Active thermal control uses temperature-related control parameters to influence the junction temperatures of power semiconductor modules online [79]. Thermal stress in the module is reduced by decreasing the temperature swings. To influence the junction temperature, the thermal control temporarily increases or decreases the losses in the desired chips [80]. At system level reducing stress from mission parameters may be used. Varying the current limit, the dc link voltage, the circulating current among parallel connected converters, and the circulating reactive power can control the junction temperature [81]. Selection of the switching frequency and modulation method can also be applied. On the hardware layer, parameters such as the gate voltage can be adjusted. Active thermal control is a possibility for reducing thermal stress, but commercial utilization has not yet been reported [3].

Active ripple-reduction and voltage compensator circuitry for capacitors has been developed. Temperature ripple and voltage ripple have been identified as the main stresses leading to failure [82].

Temperature management is going txo prove critical for the new WBG components due to higher operating temperatures and switching frequencies leading to greater power throughput. Hence cooling strategies may require upgrading and redesigning.

4. Roadmap for Reliability in MEA

The review of current power electronics reliability has opened several points for discussion in developing a road map for the future, as shown in Fig. 8.

The adoption of WBG devices is becoming more prolific (with devices already being used in some aircraft) and has raised the question of reliability.

Identifying stressors and subsequent failure modes within these devices is ongoing and part of the design cycle.

An advancement in accelerated aging tests such as power cycling and temperature cycling, to include, for example, vibration or humidity, may assist in finding complex failures. Currently, tests are targeted at extracting mutually exclusive failures. In real world applications this is not always the case, and failure maybe accelerated by a combination of stresses. On the other hand, for simply generating parameter variations, some accelerated tests may be unnecessarily complex, and a simpler alternative might be the so-called DC aging [83].

Following on from this, to produce an accurate assessment of stress that the unit under test may endure during its lifetime, the mission profile needs to be considered as closely as possible. For example, a unit for electrical braking on an aircraft may see little usage during the flight.

After take-off, being situated near the landing gear, it is subjected to extreme temperatures (more than −20 °C) during the flight. The device is then relied upon to undergo a power up, enduring a high start-up transient current and full operational temperatures approaching 100 °C as well as being subjected to excessive vibration for a short period

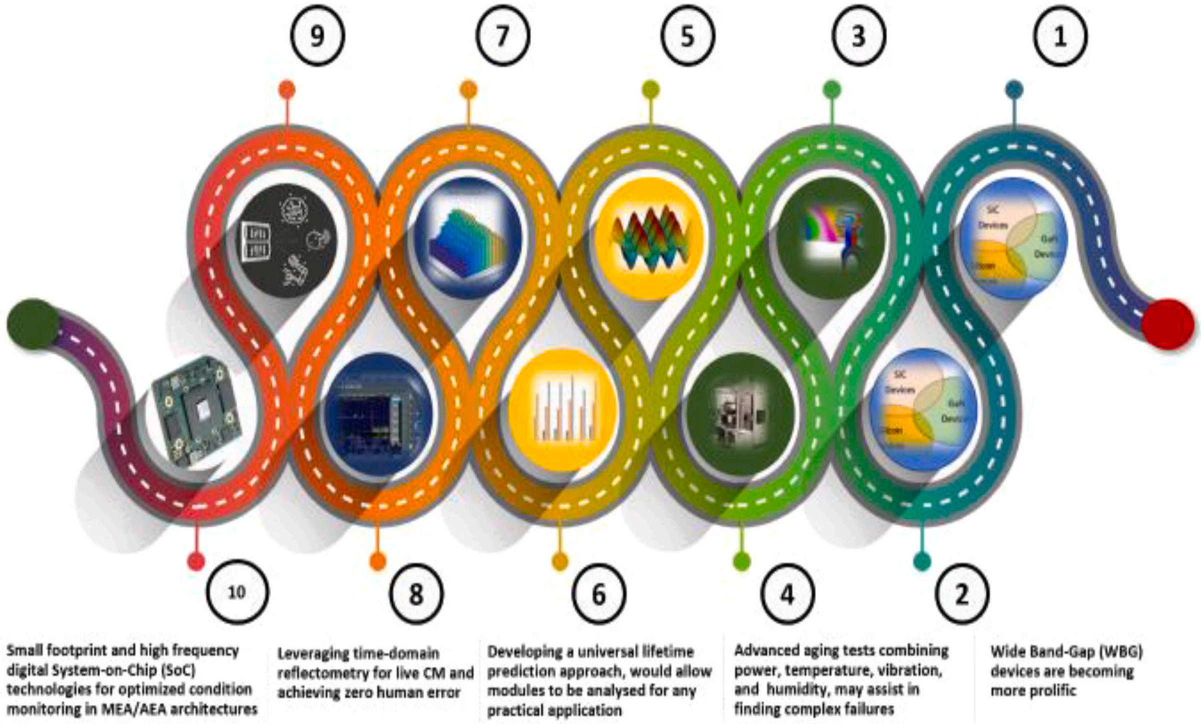

Fig. 8. Roadmap for reliability in MEA

of time whilst the aircraft lands.

Another problem that manifests itself in the accelerated aging processes is scalability. The lifetime prediction model for a lower rated device would not provide the same information about the aging of a higher rated device, even if they belong to the same family of components. This is particularly evident in WBG devices [84]. The methodologies used to provide reliability analysis of power devices are varied and often tailored to specific faults. Developing a universal approach, would allow modules to be analysed for any practical application, with the ability to scale models, so predictions for a lower rated device would provide the same information about the aging of a higher rated device in the same family of components. This may involve using advanced mathematical techniques to model the non-linearity in power devices, the major causes being the magnitude of the parasitic parameters, especially for wide bandgap devices [85,86]. Creating a universal approach, will allow access to the modules in any practical application.

Many of the direct measurement parameters relating to failure are not feasible to measure within a manufactured device unless some monitoring capability has been implemented by the manufacturer. CM then requires the addition of external circuitry and sensors. Opportunities to explore currently available sensors within a system (e.g. BIT) and use for CM become viable for legacy systems. For future devices, increased CM capability needs to be made available. Digital devices lead the way in embedding monitoring technology; however, we acknowledged the difficulties with implementing sensors in analogue power devices. Leveraging small footprint and high frequency power management System-on-Chip (SoC) technologies could provide an efficient and cost-effective way forward for CM of power paraphernalia in more and all-electric aircraft configurations. Some modern power semiconductor modules already incorporate temperature-sensitive resistive element (thermistor; NTC or PTC) soldered on the DBC substrate.

Measurement parameters such as $V_{CE,ON}$, RDS_{ON}, V_{th} exhibit problems due to the high voltages present, the complexity of the real time measurement equipment, calibration, resolution of the measurement and noise. This problem is escalated in SiC devices due to high operating temperatures [87]. Investigation into other secondary TSEP measurements such as the gate terminal, heat sink [88,89] would not only give universal access to all power electronic devices at the lower potential terminals, but it will also help in significantly reducing the complexity and voltage rating of CM hardware [85].

Other measurement techniques such as time domain reflectometry have been successfully used for live condition monitoring power MOSFETs, the dc bus capacitor and the load. Thus, avoiding measuring any electrical parameters leading to zero human error [90–92].

Finally, the use of machine learning techniques may be investigated to separate multiple failure modes in measured data such as bond wire failure and solder joint degradation, which both produce changes in V_{CE}. Unsupervised learning classifiers based upon pattern recognition such as K-Nearest Neighbour (KNN) and Principal Component Analysis (PCA) may be used to categorise failure modes [93,94].

Supervised learning techniques for fault detection may also be exploited to learn the condition of the system under various loading. Neural Networks can be used to categorise failure parameters as well as online monitoring of IGBTs to improve IGBT operation reliability [95].

5. Conclusion

The progressive replacement of traditional hydro-pneumatic power paraphernalia with electrical systems in aircraft has toughened the reliability requirements for power electronics. Especially, the demanding aircraft operational environment for power electronics such as varying temperature, fluctuating power stresses, gusts of vibration and shocks, electromagnetic interference (EMI), and cosmic radiations impact their performance and reliability over their lifetime. The combination of stressors like thermal cycling and mechanical vibration tend to aggravate their reliability degradation with solder cracking phenomenon whereas EMI can result in the device or the equipment malfunction altogether. In particular, power semiconductor modules, packages, and capacitors are found to be highly prone to failures during their lifetime. The bond wire lift-off and solder fatigue are examples of such failures, resulting from the mismatch of CTE.

It is argued that with an accurate understanding and analysis of the physics of failure (PoF) and finite element analysis (FEA) of power semiconductor devices (SiC and GaN-based) as well as the identification of key stressors' behaviour through accelerated testing may help improve manufacturing and connection technology. For example, sintering and low temperature joining can be employed as viable alternatives to solder. The wide bandgap devices with higher operating frequencies and temperatures, in particular, are finding their way into power modules and systems that can render highly dependable performance to various system applications within MEA. However, at the same time, the cooling issues may arise that require proper temperature management and improved implementation strategies.

In addition, utilising active methods like condition monitoring and prognostics, coupled with intelligent control, can help drive components while keeping their remaining lifetime in perspective. Temperature sensitive electrical parameters (TSEP) such as collector-emitter voltage and on-state resistance can be leveraged, for example, to monitor solder layer degradation/damage. Embedded sensor and time-domain reflectometry (TDR) based condition monitoring can be another viable reliability assessment.

A roadmap for an improved and robust reliability regime in MEA is put forth at the end. It outlines and lays emphasis on an in-depth reliability evaluation of WBG devices inter alia identification of stressors and corresponding failure modes, development of highly representative and scalable accelerated ageing tests (combining temperature, power, vibration, and humidity), and adoption of efficient machine learning techniques. These trends are reflective of the ongoing transition of power semiconductor devices from the traditional but mature (Si) to state-of-the-art and more efficient, still maturing, WBG devices e.g. (GaN and SiC).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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