Received: 30 December 2022 | Revised: 17 March 2023 | Accepted: 14 April 2023

IET Electrical Systems in Transportation

DOI: 10.1049/els2.12078

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Reliability analysis of multilevel and matrix converters used in more electric aircraft

Aanchal Verma[1] | Aditya Singh[1] | Kyadsandra Anand Kumar[2] | Ram Khelawan Saket[1] | Baseem Khan[3]

[1]Electrical Engineering Department, Indian Institute Technology (Banaras Hindu University) Varanasi, Uttar Pradesh, India

[2]Division of Electrical Engineering, CSIR-National Aerospace Laboratories, Bengaluru, Karnataka, India

[3]Department of Electrical and Computer Engineering, Hawassa University, Hawassa, Ethiopia

Correspondence

Ram Khelawan Saket and Baseem Khan.
Email: rksaket.eee@iitbhu.ac.in and baseem.khan04@gmail.com

Funding information

Science and Engineering Research Board, Grant/Award Number: EEQ/2021/000177

Abstract

This paper presents the current scenario related to the application of power electronics converters in aviation industries, major challenges and their reliability aspects. Recent developments in power electronics have given a major breakthrough in the aviation industry. These developments are not only limited to the more electric aircraft (MEA) but also in the field of electric propulsion, popularised as electric propulsion aircraft (EPA). The aircraft requires a well-established protection scheme of these converter topologies. The overall reliability of aircraft solely depends on its protection and fast mitigation of any fault if occurs in the cruise time. This paper aims to provide a comprehensive analysis of power converters applications in MEA and EPA. Further, a review of various topologies of Power Converters and their reliability assessment is also described in detail. The physics of Failure of switches, their lifetime estimation and thermal cycling have also been discussed. Finally, the reliability assessment of different topologies and their comparison has been discussed for overall performance enhancement of the MEA and EPA.

KEYWORDS

Electric Propulsion Aircraft, More Electric Aircraft, Multilevel and Matrix Converters, Reliability Analysis

1 | INTRODUCTION

The electric revolution in transportation is already well underway, and the aviation sector is ready to embrace major change. The advantages of switching to electric aircraft in terms of safety, maintenance, noise pollution and environmental impact are without dispute. The development of electric aircraft that satisfy societal needs and win public approval and trust, however, still faces a number of technological obstacles [1]. Hundreds of initiatives are being investigated to advance greater electrification, from applications for long-haul flights to urban air mobility. Power electronics, which is at the core of every aircraft's construction, are essential in the modern age of transportation. Gas turbines in civil aeroplanes supply both the secondary power needed for all onboard systems and the primary power for the engine thrust [1–3]. More electric aircraft (MEA) has been established to gradually replace the hydraulic, mechanical and pneumatic sources with their electric equivalents in order to enhance the secondary power system's controllability and overall performance [4–7]. Electrical drives make it possible to implement the concept of MEA, facilitating the generation and conversion of renewable energy at a low cost and with high efficiency [1, 8]. Electrical drives can be found in the energy generation system for a typical MEA onboard system, which includes starter-generators/generators and energy consumption loads for the wing ice protection system, fuel pumps, flight control system and environmental control system. Systems with electricity can be more efficient overall, lighter and cheaper while still being reliable when compared to those without [1, 9–12].

Over the past few decades, the movement towards MEA has taken huge progress. The usage of secondary power in civil aircraft has traditionally been divided into three broad categories: electrical, hydraulic and pneumatic power. Manufacturers are increasingly turning to electrical solutions for conventional secondary hydraulic and pneumatic power systems. However, a lot of reliability problems still need to be fixed, notably in the field of power electronics, before complete electrification can be seen. For power electronics, the operational environment in aerospace is challenging. High temperature variations, vibrations, dust, humidity, electromagnetic interference and cosmic radiation may result in component failure and ultimately put the aircraft's safety in jeopardy. Semiconductors, capacitors, electromechanical, electromagnetic, sensors and auxiliary devices are the parts that make up a power electronics system. Failure of these components not only puts the aircraft in danger but also costs money in maintenance and downtime. The analysis of lifetime expectations and the underlying causes of these failures in terms of major stresses and component failure mechanisms should be done. The most crucial factors for the entire aviation industry are the volume, weight, reliability and performance of electric machines and power electronic converters [2]. The performance of the MEA system can be enhanced by reducing the complexity and expense of the electrical machine and drive design and control approaches. The three categories of machines that have been researched fall into three categories: induction machines, permanent magnet synchronous machines (PMSM) and switched reluctance machines. By recommending advanced machine design and control techniques, fault tolerance is increased. However, there do exist some limitations associated with each methodology and there will always be some degree of trade-off between system complexity, cost and the performance of the motor drive system. The usefulness of these suggested techniques is also connected to how the corresponding power electronic devices operate and what their properties are. The electric actuators and protection devices are the crucial parts of the MEA electric power distribution system. Reliability and stability analysis is required to be done through modelling, analysis and control of such essential components preventing the system's performance from drastically declining [13]. In modern electric aeroplanes, the majority of flight control wing surface actuators, whether in manual or autopilot mode, is electro hydrostatic or electromechanical. Their reliability is critical for aircraft safety; even a single actuator failure might have disastrous repercussions. Converter reliability has always been a significant hurdle to the use of power electronics in many applications, which is why, in the last few years, substantial progress has been made to increase power inverter's reliability, for example, on variable speed drives, rectifiers, dc-dc converters, power supply units and telecommunication and data frameworks. As a result, many techniques and design methods for increasing converter reliability have been presented, with redundancy remaining one of the more appealing ways because of the increased fault-tolerant capabilities it provides. However, carrying a duplicate for every system, on the other hand, adds more weight to the plane and diminishes its efficiency. Electric drives in aeronautical applications must have high efficiency as well as high power density. The power density is achieved by enhancing components performance, exposing them to significant environmental, mechanical, and thermal stress, which may jeopardise power electronic systems reliability. Due to their safety-critical nature, aerospace subsystems should achieve extremely high reliability criteria. As a result, in aircraft drive systems, reliability must be a primary design goal in order to meet the increasing demands of reliability and power density. High temperatures, temperature cycles, vibrations, moisture, dust, electromagnetic interference and cosmic solar radiation pose a threat to the reliability of these components. There are many works of literature available that compare the efficiency, power density and weights of the power electronic devices used in MEA and all-electric aircraft (AEA). However, there is minimal literature comparing the reliability of these advanced power electronic devices. A comparative study of the converters mentioned above based on component-based reliability is necessary for future electric aircraft safe operation. The concerns of reliability and safety are still questionable.

2 | POWER ELECTRONICS CONVERTERS APPLICATION IN AVIATION

Each aircraft architecture is made up of both Alternating Current (AC) and Direct Current (DC) electrical systems, irrespective of the level or type of electrification. As a result, power electronic converters are essential for an all-electric or MEA's operation because they ensure proper power distribution throughout the electrical networks. Usually, it is required that converters need to have their electrical ratings (voltage, current, and power) changed according to the type of aircraft [1]. For instance, DC/AC converters are used for low power electric drives for the non-propulsive loads in MEA. Apart from their application in MEA, in as electric propulsion aircraft (EPA), DC/AC converters are applied to provide propulsion power that can go to the megawatts. As the power level goes up to megawatt, the dc-link voltage also achieves an approximate value of thousands of volts. Therefore, the power electronics converter design utilised in MEA, EPA and AEA must be able to translate by changing topology selection, component or cooling system. Different power converters available in the literature are discussed as follows.

2.1 | AC/DC converters

Electric aircraft use AC-DC converters commonly known as rectifiers connected to ac mains bus to transfer AC supply to DC-grid. They frequently appear in MEA, hybrids and turbo-electric setups. These setups have multiple generator shafts connected to the engines rectifiers and are not required in AEA since their powertrain does not consist of DC storage networks in contrast to MEA. Because there were no regenerative energy sources, and energy storing solutions are prohibited. Only unidirectional topologies are thought to be suitable for aircraft [1]. To get the bidirectional power flow, Dual Active Bridge Converters [14] are popularly used. Key duties of an aircraft active rectifier include distortion-free generator current in the AC side with low total harmonic distortion (THD), high generating side power factor and regulated DC-bus voltage [15]. Transformer rectifier units are used for converting to significantly high voltage levels. Galvanic isolation among 115V AC (230V AC) and 28V DC networks is also achieved by Transformer rectifier units. On the other hand, for the low voltage ratio, auto-TRUs are specifically used in aviation. Auto-TRUs convert 115V AC (230V AC) to 135V DC (or 270V DC) in Boeing 787 and Airbus 380 [16]. The magnetic component's size, weight and price might be decreased as a result. Active rectifier topologies had been researched through the years, and control strategies had been thoroughly reviewed [15, 17]. Power-train systems, such as hybrid and turbo-electric, have an in-house power generator that is firmly attached to the main engine. Input AC voltage with variable voltage or frequency for the AC-DC converter is used [15].

2.2 | DC/AC converters

Both MEA and EPA frequently use DC/AC converters, widely known as inverters. Although various inverter topologies, such as Z-source inverters, current source inverters, and multilevel or multiple phase inverters have been proposed for aircraft applications. The most popular and commonly used inverter is the voltage source inverter (VSI). More electric aircraft inverter applications include electro-mechanical actuators, electro-hydraulic actuators and more recently engine starting generators [18]. Electric propulsion aircraft mandates the use of inverters to power propulsion motors, which are typically PMSM. Power density is crucial in EPA, much like with other power electronics, necessitating sophisticated inverter design and packaging. For their Magnus eFusion aircraft, siemens is said to have utilised a 13 kW/kg silicon (Si)-based inverter and created a new 63 kW/kg silicon carbide (SiC) inverter. Since next-generation wide bandgap aviation propulsion inverters are still being developed, aircraft frequently use inverters from automotive applications [1].

2.3 | AC/AC converters

Aircraft are made lighter by reducing their weight and volume. Hence the gearbox between the generator shaft and engine is removed in some electric aircraft. Now, two different AC buses are required first is variable frequency bus ranging from 360 to 800 Hz and the second one is fixed frequency bus at 400 Hz with a regulated voltage equal to or less than variable frequency bus voltage. This is achieved by deploying AC-AC converters. Converter topologies such as matrix converters and back-to-back (BTB) converters are primarily used in Ref. [19].

2.4 | DC/DC converters

In the powertrain of MEA, the propulsion motor is controlled by a three-phase VSI. This inverter also needs to be bidirectional in order to support regenerative braking. Previously, because of simple technicality and straightforward management, the basic type of three-phase six switches VSI is the most common inverter topology utilised in the aviation sector. Multi-level VSI had been chosen for MEA requirements, when the DC voltage level rises. It has a higher voltage threshold, lower THD along with Ghigher efficiency, reduced voltage stress dv/dt and lower common mode voltage stress [20]. For secondary loads like avionics, conventional commercial aircraft only have one 28V DC bus. Therefore, DC/DC converters are not required in ordinary aeroplanes. However, a second DC bus has been added to military aircraft. An extra High Voltage Direct Current (HVDC) bus is required in EPA and MEA to accommodate the higher number of electrical sub-equipment. DC/DC converters are therefore more in demand in the aviation sector for obtaining lower voltages as 28V DC from existing HVDC buses having higher voltages as 135V (or 230V) [21]. Cascading of faults are prevented in DC/DC converters by galvanic isolation to make its operation safer. Dual Active Bridge Converters is well popular soft switching technology with high efficiency and better power density for energy conversion [22].

2.5 | Multilevel and matrix converter application in electric aircraft

Back-to-Back converters are gaining huge demand and craze for their application in MEA. Although conventional indirect and direct matrix converters have high power density, the output voltage regulation for a wide range is not possible and has control only over the input current and that too for a certain limit [1]. But the elimination of the dc-link capacitor gives more reliability to the direct and indirect AC-AC converters as dc-link capacitors are more prone to failure. Also, it makes the converters lighter and smaller in volume. Hence these converters are widely applicable in MEA [23]. Three-phase matrix converter is used to feed the permanent magnet motor which runs at a very high speed in aircraft. In direct matrix converters, nine switches are implemented which are configured by the anti-series connections of Insulated Gate Bipolar Transistors (IGBTs) in three phases. In order to reduce harmonics associated with the converter switching frequency, an input (Inductor Capacitor) LC filter is often needed. Nevertheless, the absence of large intermediate dc-link capacitors or inductors allows for excellent power density and dependability.

A starter/generator (S/G) system for aircraft is presented in Ref. [24] with an indirect matrix converter (IMC). The S/G system of aircraft needs bidirectional power converters for the variable speed constant frequency or variable speed variable frequency operation [25]. The constant voltage constant frequency system is also used in the present scenario, but it does not match the high reliability, power and efficiency. To achieve this, IMC can be used to feed the S/G system in two different configurations [24]. Indirect matrix converter consists of two power stages which are achieved by the interconnection of Rectifier and inverter circuits. The rectifier stage is current source-based and the inverter stage is voltage source-based. The S/G system can be connected to either the current-source rectifier (CSR) side or the current-source converter side. But the disadvantage of the voltage source converter (VSC) side is that it may face over-current fault problems. Hence for healthier operation, an S/G system connection on the CSR side is a good practice. Also, it gives better control of power and speed from this side [26]. Current-source rectifier stage used bidirectional switches, but VSC used unidirectional switches. Indirect matrix converter has the advantage that it performs power conversion and works as DC-AC converter without using a dc-link capacitor. Additionally, it is feasible to connect IMC to More Electric Power trains by the battery energy storage system. This feature is not applicable in direct matrix converter.

However, as the dc voltage level has increased, multilevel VSI has become more popular for MEA applications because of their benefits of withstanding higher efficiency, higher voltage, lower dv/dt, reduced overall harmonic distortion and common-mode voltage stress. Now a days, SiC plus Si-based Metal Oxide Semiconductor Field Effect Transistor (MOSFET) and IGBT-based modules are very popular. With the help of this hybrid employment of SiC and Si-based semiconductor module, a three level neutral point clamped (NPC) converter has been developed, and the specific power and nominal efficiency of 12kVA per kg and 99% are demonstrated for the hybrid electric propulsion drive system. Figure 7 depicts the circuit topology of the three-level active neutral point clamped (ANPC) inverter. Silicon carbide MOSFETs operate at far higher frequencies as compared to Si-based IGBT modules. To limit line to line and line to ground over current fault, this feature is helpful. Additionally, in MEA, cascaded H-bridge converters (CHB) are gaining interest because of their modular design. These converters give high quality output waveforms with reduced THD [27, 28]. Multilevel CHB is used in AEA, powered by the battery. Since Multilevel CHB needs an isolated DC supply, hence all individual battery packs can be utilised as separate dc sources. An inverter for propulsion must also be fault-tolerant in addition to being efficient and power-dense. A novel study direction may be opened by the use of fault-tolerant motor drives in aircraft electric propulsion systems, which have been extensively studied in the literature [29]. Multilevel converters are exclusively used in MEA for the electric starter/generator because of their high power quality [30].

3 | LIFETIME ESTIMATION OF IGBT

Due to the sinusoidal input or output waveforms, during power converter operations, semiconductors used in converters suffer cyclic power losses, particularly in electric drive and machine applications [31]. Because the material properties (such as the coefficient of thermal expansion) of the semiconductor substrate, insulators and base plate metal vary, repeated power losses and the ensuing heat cycles cause cyclic fatigue strains in power modules. The semiconductor's mean junction temperature promotes chemically induced thermal ageing. To predict the reliability of the power modules made up of power semiconductors devices, three methods are available in the literature. The first method is based on the constant failure rate and can be easily implemented by the MIL-HDBK-217F. The second method is based on Accelerated lifetime testing, which gives the prediction of future failure based on the previous failure data. The third method is based on the Physics of failure (PoF), which is basically based on thermal, mechanical and environmental stress. Because the thermal mechanical stress lifetime models based on PoF are obtained by modelling, the stress strain deformations. It gives physical insight into the mechanisms that cause bond wire fatigue in semiconductors. Statistics have not been included in the PoF analysis. The physics of the failure method is very accurate and gives insight into depth analysis, but its use is limited to the lack of detailed information on materials and geometries of semiconductor devices.

4 | EFFECT OF COSMIC RAYS ON LIFETIME OF SEMICONDUCTORS

Cosmic rays have been linked to power electronic system failures since the early 1990s [32–34]. High energy particles known as cosmic rays are the result of cosmic occurrences outside of our Solar System. Thus cosmic rays may come into contact with molecule nucleons in the troposphere or in the upper atmosphere. Due to these collisions, many particles with high energy enter the earth's atmosphere. The failure likelihood varies with device technology and operating conditions; however, some secondary particle types, primarily neutrons, have a modest but definite risk of causing damage to a semiconductor device's blocking capabilities. The numerical probability of failure of the power electronic system, caused by cosmic rays, cannot be determined, but with familiar application conditions and renowned device technology, this probability is calculable. Because cosmic ray breakdowns are unpredictable and have a continuous failure rate, they increase the chance of failure of the associated power electronic systems [35]. Thus in the early stage of design, it is vital to consider the impact of cosmic rays. Specially, four trends in the power semiconductor sector make this need more worrisome: First, a general increase in product reliability over the course of their intended lifetime causes attention to move to failure modes with lower failure rates. Second, higher dc-link voltages are becoming more common. For instance, in Photovoltaic systems, the occurrence of high dc-link voltage due to low loading and low switching over voltage is even more blatantly obvious. Since cosmic ray failure rate increases exponentially as reverse bias voltage increases, hence dc increase in dc-link voltage will lead to an increase in cosmic ray failure rate. Similar effects will result from the trend towards low-inductive packaging, as lower inductance will result in less switching over-voltage, and a constant rated blocking voltage of semiconductor devices allows higher voltage at dc-link. At last, due to the increased particle flux, installations at high altitudes are more vulnerable to failures due to cosmic rays.

5 | TEMPERATURE PROFILES OF ELECTRIC AIRCRAFT

Temperature is the main factor that affects the lifetime of an IGBT or converter switches. For the analysis of temperature stress on the semiconductors devices and capacitors, thermal simulation is required, which is done by the foster thermal impedance network [36]. Junction temperature, case temperature and ambient temperature of the IGBT module depend on the switching losses and conduction losses. In Ref [36], IGBT module F3L400R07ME4 B22 from Infineon is used. For switching loss and voltage drop, the values are taken from the data-sheet.

$$P_{sw\_IGBT} = f_{sw}(E_{ON} + E_{OFF})\left(\frac{I}{I_{ref}}\right)^{K_i}\left(\frac{V_{off}}{V_{ref}}\right)^{k_v} \quad (1)$$

$$P_{cond} = V_{ce_{on}}.I \quad (2)$$

$$t_{jIGBT}(t) = P_{losstot-IGBT(t)}.Z_{th-IGBT(j-c)(t)} + T_c(t) \quad (3)$$

Results obtained by thermal simulation are used for the reliability analysis. Equivalent series resistor modelling of the capacitor is shown in Figure 1. For the temperature stress analysis of the capacitor, hot spot temperature estimation is used which is done by Equivalent series resistor modelling of the capacitor. The rms current flowing through the capacitor is responsible for the loss occurred in it. The current is fed into the thermal network modelled for the capacitor and used to calculate the hot spot temperature of the capacitor. The DC-link rms current of 3-L NPC converter is given in Ref. [36].

$$I_{Crms}^2 = \frac{3Im^2M}{4\pi}\left(\sqrt{3} + \frac{2}{\sqrt{3}} \cdot \cos(2\phi)\right) - \frac{9}{16}(I_m M)^2\cos^2(\phi) \quad (4)$$

The mission profile of an aircraft consists of five parts namely:

1. Take-off
2. Climb
3. Cruise
4. Descend
5. Landing

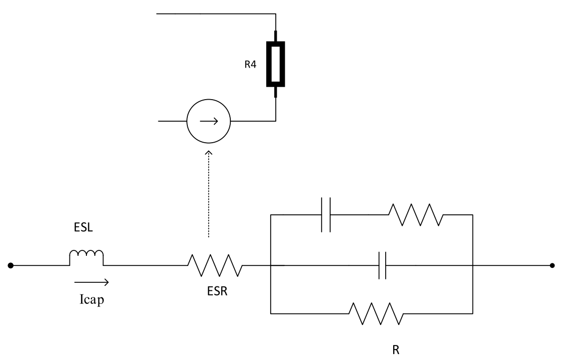

FIGURE 1 Equivalent series resistor (ESR) modelling of capacitor.

The ambient temperature range in the above-mentioned mission profiles varies as shown in Figure 2:

- Take-off and Climb - 15°C–30°C.
- Cruise - 05°C to (−) 40°C
- Descend and Landing - 25°C to 40 °C

5.1 | For IGBT

Based on Figure 3, if it is assumed that power electronic components operate on 540V DC, it can be inferred that the average junction temperature range is:

- Take-off and Climb–100 °C–110 °C
- Cruise–40 °C–50 °C.
- Descend and Landing–100 °C–110 °C.

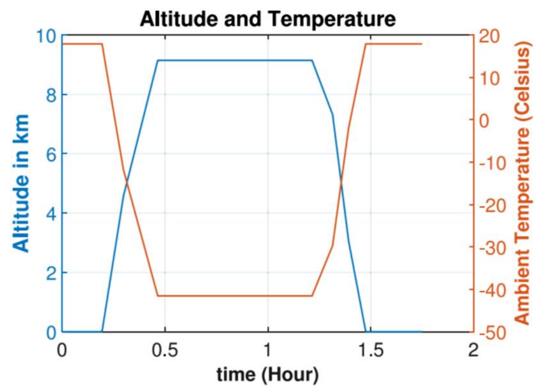

FIGURE 2 Temperature and altitude variation during flight [37].

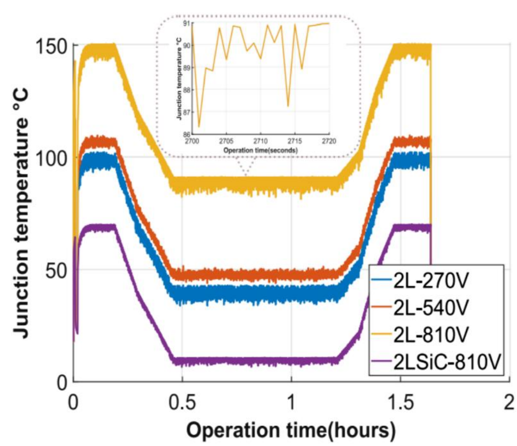

FIGURE 3 Insulated Gate Bipolar Transistor junction temperature variation [37].

5.2 | For capacitor

From the capacitor temperature variation as shown in Figure 4, if it is assumed that the power electronic components operate on 540V DC, the average junction temperature range can be assumed to be

- Take-off and Climb - 26 °C–28 °C.
- Cruise - (–) 32 °C to (–) 33 °C.
- Descend and Landing - 26 °C–28 °C.

Temperature effects can be further subdivided into two stress components. In electronics, it is known that both increased junction temperature and cyclic temperature can cause stress. The thermal cycle of the junction can be further separated into junction temperature cycles elicited by junction temperature and ambient temperature cycles elicited by element self-heating. It is difficult to ignore thermal stress due to their pervasive nature, particularly thermal cycles because of its own losses. In aviation, the issue may be exacerbated by the location of the unit. Mounting the power electronics inside a pressurised structure has its own host of concerns with the cooling system (often forced cooling is required).

6 | RELIABILITY ESTIMATION OF CONVERTERS USED IN PROPULSION OF AIRCRAFT

The use of multi-level power converters has increased recently in a number of high-voltage industrial and commercial sectors and power plants. A number of different converter architectures, including imbricated cells inverters, converters using flying diodes and conversions using NPC and ANPC architectures, have also been proposed and ultimately developed. A converter is referred to be "multilevel" if it has the ability to produce a stepped output waveform by selectively combining many discrete voltage levels. In actuality, this typically consists of a number of various DC sources that are integrated at the output node through complex switching procedures [24]. Multilayer inverters seem to be more suitable for Electric Aircraft Propulsion drives due to advantages like improved nominal power and low switching losses, better DC-bus voltage withstanding capabilities (ex. 1–4 kV), lower electromagnetic interference and output voltage harmonics and lower electromagnetic interference.

The reliability of each of a power converter's individual parts determines the device's overall reliability. The main premise is that the reliability of an electronic device is influenced by the circuit architecture, DC-bus capacitors, AC inductors and semiconductors. It was expected that the impact of each control system-related component and auxiliary circuit (sensors, contactors, digital controllers, gate drivers, etc.) on total reliability would be minimal. These components can age relatively slowly, increasing their life, because they were not put through the same intense temperature cycles as the power stage devices.

The component failure rate that is calculated using Mil-HDBK-217-F [27] is shown in the Table 1.

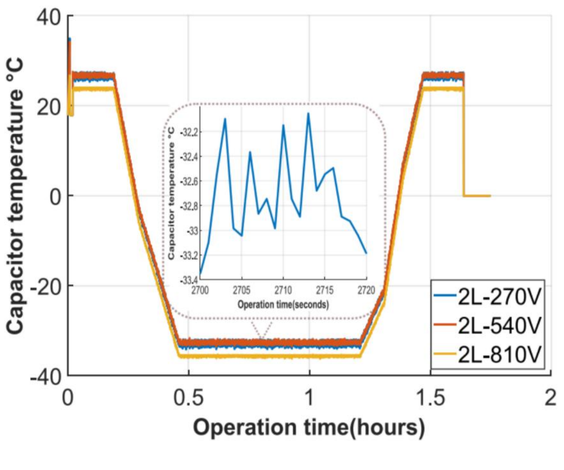

FIGURE 4 Capacitor temperature variation [37].

6.1 | 3-Level neutral point clamped converter

The NPC converter is made up of three legs that are required for the proper operation of the system. Two clamping diodes (Dc_1 and Dc_2), Two capacitors (Cap_1 and Cap_2) and four IGBT switching devices ($IGBT_1$,.., $IGBT_4$) make up any one of the legs as shown in Figure 5. When one of these elements fails, the converter fails as well. As shown in Figure 6, the NPC electronic converter may be represented by a series combination of 24 sub-systems.

To enhance the fault-tolerance ability of three level NPC topology [38] have examined the combination by introducing a fourth Flying capacitor (FC)-based leg as illustrated in Figure 7. The fourth leg outlet (O) is linked to the NPC converter's NP by an LC filter, which serves to reduce the impacts of the required dead times voltage transition from FC to NPC and back. Further, it has been proven that the Hybrid NPC converter fully handles the initial open circuit and short circuit faults happening in a few of the 12 switching devices of the NPC components from a fault tolerance standpoint.

TABLE 1 Failure rate of components.

Components-profiles	Take-off and climb	Cruise	Descend and landing
Capacitor	$3.357 . 10^{-3}$ failure/year	$1.090 . 10^{-4}$ failure/year	$3.357 . 10^{-3}$ failure/year
Diode	$1.333 . 10^{-2}$ failure/year	$2.9 . 10^{-3}$ failure/year	$1.333 . 10^{-2}$ failure/year
IGBT	$11.34 . 10^{-2}$ failure/year	$5.1096 . 10^{-2}$ failure/year	$11.34 . 10^{-2}$ failure/year

Abbreviation: IGBT, Insulated Gate Bipolar Transistor.

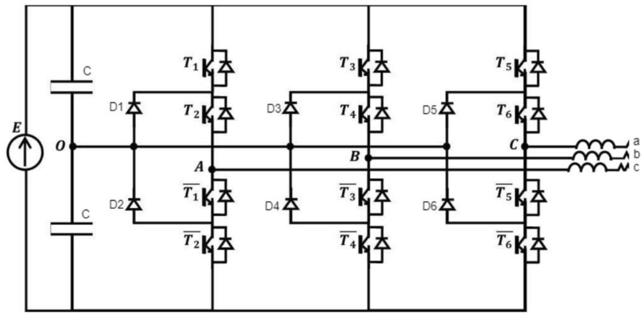

FIGURE 5 3-level neutral point clamped (NPC) converter [38].

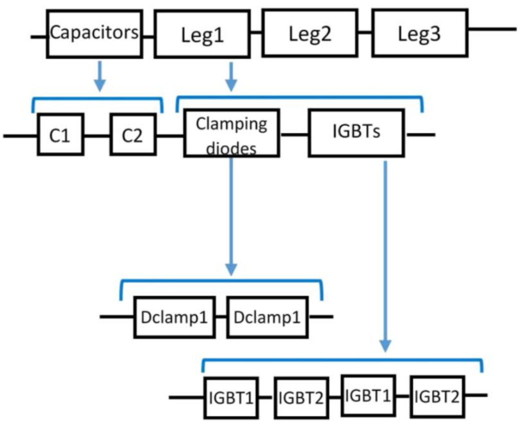

FIGURE 6 Reliability block diagram of 3-level neutral point clamped (NPC) converter.

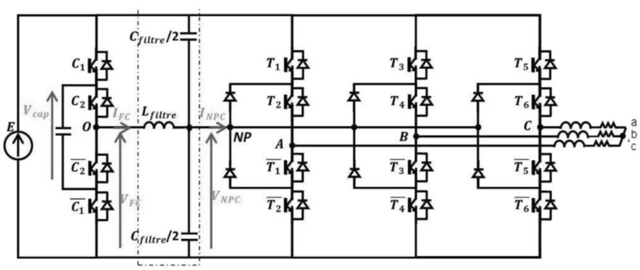

FIGURE 7 Hybrid 3-level Flying capacitor (FC)-NPC converter [39].

According to the authors in Ref. [39], this hybrid inverter may work in two post-fault states.

The FC leg and its elements are essential to a healthy functioning in the hybrid FC-NPC converter, whereas two out of the three legs are necessary for a healthy operating condition in the NPC component. In reality, if one of the three legs has a switching malfunction, the converter can still function due to the hardware and software reorganisations. As illustrated in Figure 8, the FC leg is represented with a series connection of 1 FC and four IGBT switches. The FC-based leg has a two-out-of-three association with the 3 NPC-based legs.

The hybrid FC-NPC three-level converter's reliability diagram is illustrated in Figure 9.

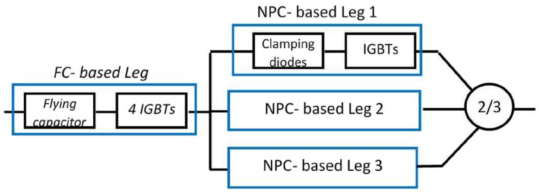

FIGURE 8 Reliability block diagram of the 3-level Flying capacitor (FC)-NPC converter.

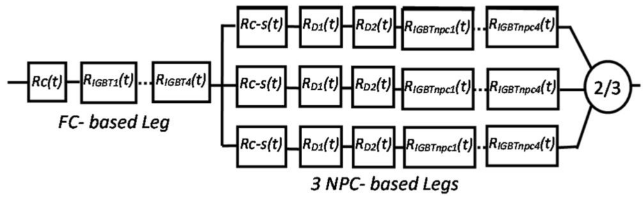

FIGURE 9 Detailed reliability block diagram of the studied 3-level Flying capacitor (FC)-NPC converter.

For a normal NPC converter: As each leg constitutes of four IGBTs and two Diodes, the reliability of an individual leg is given by

$$R_1(t) = e^{-(4.\lambda_{IGBT}+2.\lambda_D)t} \tag{5}$$

Using the series connection, the NPC converter reliability may be calculated as

$$R_{NPC}(t) = e^{-(12.\lambda_{IGBT}+6.\lambda_D+2.\lambda_C)} \tag{6}$$

For the FC-NPC converter: The NPC component of this fault tolerant converter's reliability for the hybrid converter is evaluated and stated $R_1(t)$.

$$R_1(t) = 3.e^{-(8.\lambda_{IGBT}+4.\lambda_D)} - 2.e^{-(12.\lambda_{IGBT}+6.\lambda_D)} \tag{7}$$

We must include the FC component reliability in the calculation for the four-leg FC-NPC converter. As a result, Figure 10 the hybrid converter's reliability is determined by

$$R_{FC-NPC}(t) = .e^{-\left(4.\lambda_{IGBT}+.\lambda_{Cf}\right)}.\left[3.e^{-(8.\lambda_{IGBT}+4.\lambda_D)} - 2.e^{-(12.\lambda_{IGBT}+6.\lambda_D)}\right] \tag{8}$$

Now

Putting in Values of failure rates.

6.1.1 | Neutral point clamped converter

$$R_{NPC}(t) = e^{-(12.\lambda_{IGBT}+6.\lambda_D+2.\lambda_C)} \tag{9}$$

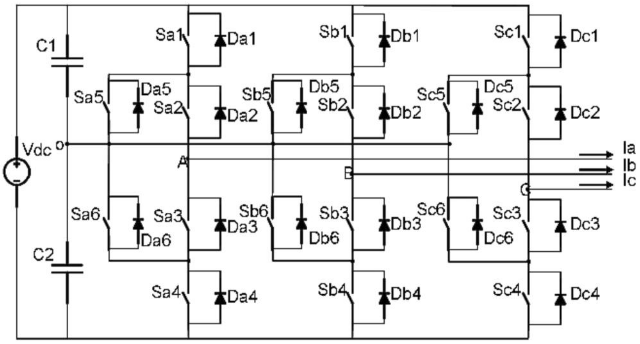

FIGURE 10 Hybrid 3-level Flying capacitor (FC)-NPC converter [40].

6.1.2 | Hybrid neutral point clamped converter

$$R_{FC-NPC}(t) = e^{-(4.\lambda_{IGBT}+\lambda_{Cf})t}.\left[3.e^{-(8.\lambda_{IGBT}+4.\lambda_D)t} - 2.e^{-(12.\lambda_{IGBT}+6.\lambda_D)t}\right] \quad (10)$$

Figure 11 shows the reliability comparison between hybrid NPC and conventional NPC.

6.2 | 3-Level active neutral point clamped converter

An ANPC Converter is very similar to a neutral clamped converter in terms of structure. The passive diodes on each leg are replaced with active switches for better control.

For a normal ANPC converter:

As each leg constitutes of just six IGBTs, the reliability of an individual leg is given by

$$R_1(t) = e^{-6.\lambda_{IGBT}.t} \quad (11)$$

Using the series connection, the ANPC converter reliability may be calculated as

$$R_{ANPC}(t) = e^{-(18.\lambda_{IGBT}+2.\lambda_C).t} \quad (12)$$

Now, putting in Values of Failure Rates.

6.2.1 | Active neutral point clamped converter

$$R_{ANPC}(t) = e^{-(18.\lambda_{IGBT}+2.\lambda_C)t} \quad (13)$$

The reliability function of the ANPC converter at different temperature is shown Figure 12.

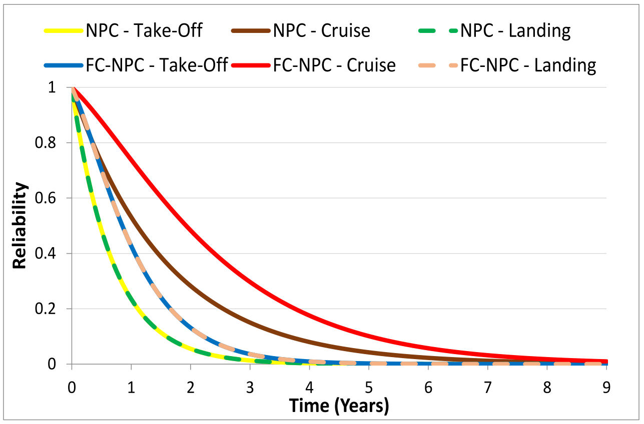

FIGURE 11 Reliability comparison between hybrid neutral point clamped (NPC) and conventional NPC.

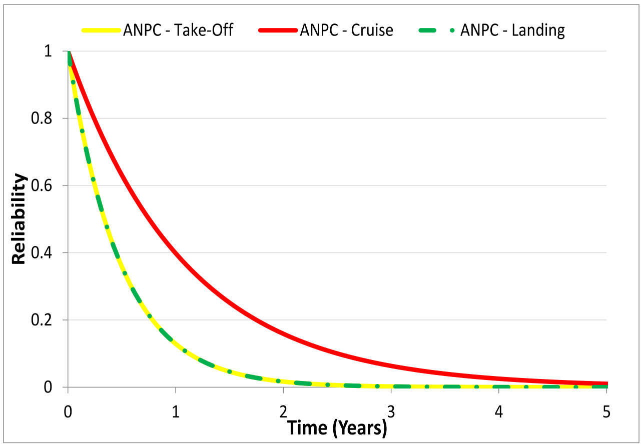

FIGURE 12 Reliability graph of active neutral point clamped (ANPC) topology.

The functioning of three-level ANPC (3L-ANPC) converters under equipment failure circumstances is examined, and fault tolerant techniques are proposed to enable continued functioning of 3L-ANPC inverters for both short- and open-failure scenarios for the singular device failure. If a de-rating is permitted for drive systems in fault tolerant functioning, the findings reveal that 3L-ANPC inverter has superior reliability than 3L-NPC inverter, despite using more semiconductors.

6.3 | Cascaded H-bridge

A five-level cascaded h-bridge (CHB) multi-level converter consists of eight IGBT switches and two capacitors per leg.

The reliability equation for H-Bridge is

$$R_{H-Bridge}(t) = e^{-(24.\lambda_{IGBT}+6.\lambda_C).t} \quad (14)$$

Figure 13 shows the reliability graph of CHB topology.

6.4 | Five-level flying capacitor-clamped converter and five-level diode-clamped converter

A 5-Level FC-clamped (Flying capacitor-clamped (FCC)) converter and five-level diode-clamped converter have eight IGBTs, 10 capacitors and eight IGBTs, four capacitors and six diodes respectively on a single leg.

6.4.1 | Flying capacitor

$$R_{FlyingCapacitor}(t) = e^{-(24.\lambda_{IGBT}+30.\lambda_C).t} \quad (15)$$

The reliability function of 5-Level FCC converter at different temperature is shown in Figure 14.

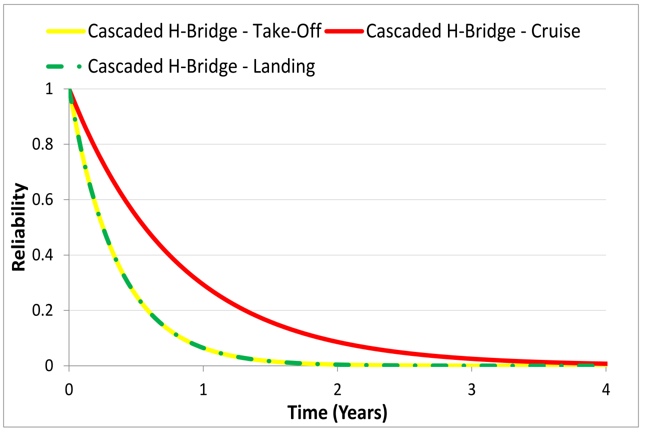

FIGURE 13 Reliability graph of cascaded H-bridge converters (CHB) topology.

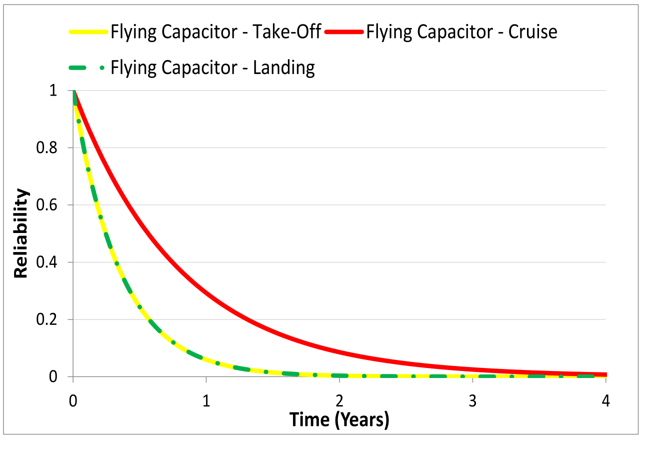

FIGURE 14 Reliability graph of the flying capacitor (FC) clamped inverter.

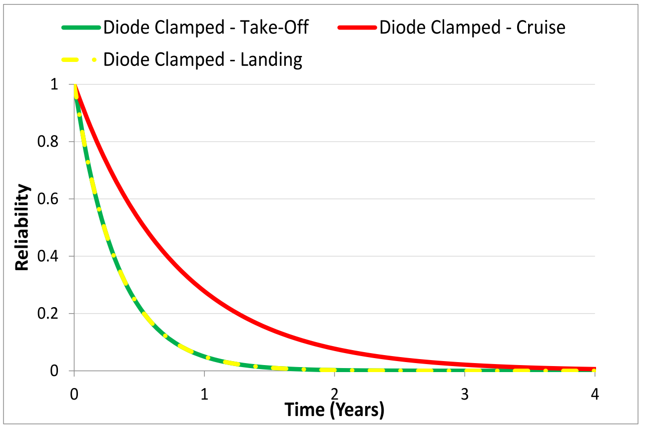

FIGURE 15 Reliability graph of diode clamped inverter.

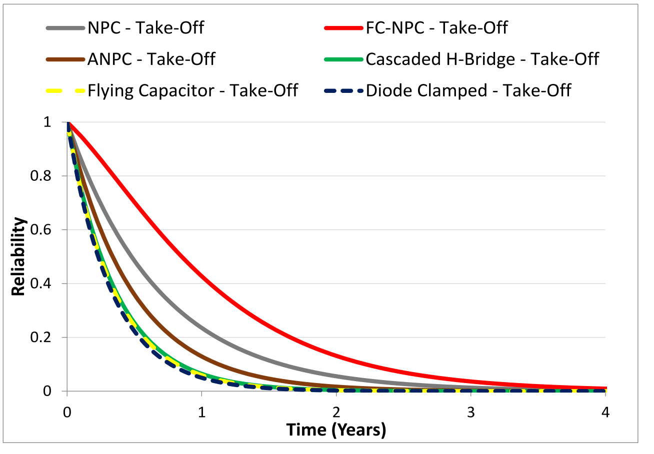

FIGURE 16 Reliability comparison graph of different multilevel inverter topology during take-off.

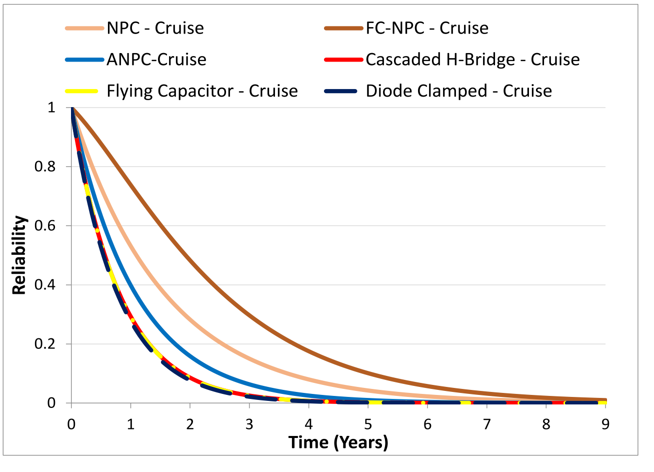

FIGURE 17 Reliability comparison graph of different multilevel inverter topology during cruise.

6.4.2 | Diode clamped

$$R_{DiodeClamped}(t) = e^{-(24.\lambda_{IGBT}+18.\lambda_D+12.\lambda_C).t} \quad (16)$$

The reliability function of the diode clamped converter at different temperature is shown in Figure 15.

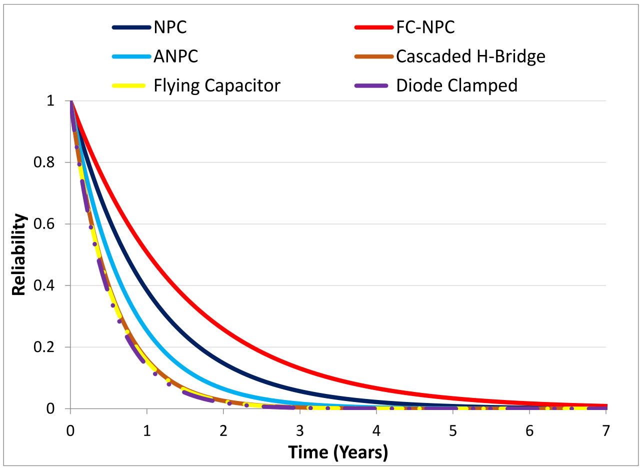

FIGURE 18 Overall Reliability comparison graph of different Multilevel Inverter Topology.

7 | RESULTS

The reliability function for various multi-level converter topologies and temperature profiles is described in the previous sections. According to the plots, cruising has a better reliability than takeoff and landing. This is because junction and ambient temperatures are lower at higher altitudes. The comparison plots of all the topologies are now included in this section. Figures 16 and 17 show the reliability comparison graph of different multilevel inverter topology during take-off and cruise.

The overall reliability comparison graph of different multilevel inverter topology is shown in Figure 18 and data is given in Table 2. A combined reliability graph can be drawn by computing the average failure rate, assuming that the aircraft spends 60% of the flying time in the Cruise profile and 20% of the total flight time for each take-off and landing.

8 | CONCLUSION

The schematic arrangements of multilevel matrix converter are illustrated in this study for the fault tolerance ability enhancement and reliability estimation of the overall propulsion system. The graphical descriptions of the reliability issues related to different inverter topologies are comprehensively presented in the comparative graphs. The FC-NPC converter

TABLE 2 Overall reliability data of different multilevel inverter topology.

		Reliability of converter topologies					
S.No.	Time in year(s)	NPC	FC-NPC	ANPC	Cascaded H-Bridge	Flying capacitor	Diode clamped
1	0	1	1	1	1	1	1
2	0.5	0.576402	0.7124824	0.4830235	0.3777623	0.3690475	0.3496754
3	1	0.3322392	0.5076312	0.2333117	0.1427044	0.136196	0.1222729
4	1.5	0.1915033	0.3616783	0.112695	0.0539083	0.0502628	0.0427558
5	2	0.1103829	0.2576895	0.0544343	0.0203645	0.0185494	0.0149507
6	2.5	0.0636249	0.1835992	0.0262931	0.007693	0.0068456	0.0052279
7	3	0.0366735	0.1308112	0.0127002	0.0029061	0.0025263	0.0018281
8	3.5	0.0211387	0.0932007	0.0061345	0.0010978	0.0009323	0.0006392
9	4	0.0121844	0.0664039	0.0029631	0.0004147	0.0003441	0.0002235
10	4.5	0.0070231	0.0473116	0.0014312	0.0001567	0.000127	7.816E-05
11	5	0.0040481	0.0337087	0.0006913	5.918E-05	4.686E-05	2.733E-05
12	5.5	0.0023334	0.0240168	0.0003339	2.236E-05	1.729E-05	9.557E-06
13	6	0.0013449	0.0171116	0.0001613	8.445E-06	6.382E-06	3.342E-06
14	6.5	0.0007752	0.0121917	7.791E-05	3.19E-06	2.355E-06	1.169E-06
15	7	0.0004468	0.0086864	3.763E-05	1.205E-06	8.693E-07	4.086E-07
16	7.5	0.0002576	0.0061889	1.818E-05	4.553E-07	3.208E-07	1.429E-07
17	8	0.0001485	0.0044095	8.78E-06	1.72E-07	1.184E-07	4.996E-08
18	8.5	8.557E-05	0.0031417	4.241E-06	6.497E-08	4.369E-08	1.747E-08
19	9	4.932E-05	0.0022384	2.048E-06	2.454E-08	1.612E-08	6.109E-09

Abbreviation: FC-NPC, Flying Capacitor-Neutral Point Clamped.

emerges as the most reliable topology of multilevel three-phase inverters from the reliability assessment on various temperature profiles during a flight. This topology is followed by the conventional NPC with fault tolerance control activation as compared to ANPC topology. Similar reliability profiles may be seen in the CHB, diode clamped and FCC topologies. The NPC, its additional hybrid versions and the ANPC inverter are the only alternatives for today's current MEA applications since they provide 4.5 times of the reliability for the same installation cost. The overall comparative reliability data of different multilevel inverter topologies for propulsion applications are illustrated in Table 2. The reliabilities of FP-NPC, NPC and ANPC are 71.25%, 57.64% and 48.30% respectively, for the operation of the 0.5 years duration. After a year of operation, the propulsion system reliability of the above topologies drops to 50.76%, 33.22% and 23.33%, respectively. Finally, FP-NPC topology has high reliability for proportion applications.

AUTHOR CONTRIBUTIONS

Aanchal Verma: Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualisation; Writing – original draft; Writing – review & editing. **Aditya Singh**: Conceptualisation; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualisation; Writing – original draft; Writing – review & editing. **Kyadsandra Anand Kumar**: Investigation; Methodology; Resources; Software; Supervision; Validation; Visualisation; Writing – original draft; Writing – review & editing. **Ram Khelawan Saket**: Investigation; Methodology; Resources; Software; Supervision; Validation; Visualisation; Writing – original draft; Writing – review & editing. **Baseem Khan**: Investigation; Methodology; Resources; Software; Supervision; Validation; Visualisation; Writing – original draft; Writing – review & editing.

ACKNOWLEDGEMENTS

The authors thank the Science and Engineering Research Board for financial support under the sponsored research project sanction order No. EEQ/2021/000177. Science and Engineering Research Board is a statutory body of the Department of Science and Technology, Government of India. The authors also express special thanks to the Electrical Engineering Department, Indian Institute of Technology (Banaras Hindu University), Varanasi (India) for providing research facilities and laboratory environment to execute the research work.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ORCID

Baseem Khan https://orcid.org/0000-0002-5082-8311

REFERENCES

1. Dorn-Gomba, L., et al.: Power electronic converters in electric aircraft: current status, challenges, and emerging technologies. IEEE Transa. Transp. Electrif. 6(4), 1648–1664 (2020). https://doi.org/10.1109/tte.2020.3006045
2. Madonna, V., Giangrande, P., Galea, M.: Electrical power generation in aircraft: review, challenges, and opportunities. IEEE Trans. Transp. Electrif. 4(3), 646–659 (2018). https://doi.org/10.1109/tte.2018.2834142
3. Giangrande, P., et al.: Considerations on the development of an electric drive for a secondary flight control electromechanical actuator. IEEE Trans. Ind. Appl. 55(4), 3544–3554 (2019). https://doi.org/10.1109/tia.2019.2907231
4. Wang, C., et al.: Power quality improvement using an active power sharing scheme in more electric aircraft. IEEE Trans. Ind. Electron. 69(4), 3588–3598 (2021). https://doi.org/10.1109/tie.2021.3076401
5. Cano, T.C., et al.: Future of electrical aircraft energy power systems: an architecture review. IEEE Trans. Transp. Electrif. 7(3), 1915–1929 (2021). https://doi.org/10.1109/tte.2021.3052106
6. Kostakis, T., et al.: Demonstration of fast-acting protection as a key enabler for more-electric aircraft interconnected architectures. IET Electr. Syst. Transp. 7(2), 170–178 (2017). https://doi.org/10.1049/iet-est.2016.0065
7. Tariq, M., et al.: Aircraft batteries: current trend towards more electric aircraft. IET Electr. Syst. Transp. 7(2), 93–103 (2017). https://doi.org/10.1049/iet-est.2016.0019
8. Buticchi, G., et al.: On-board microgrids for the more electric aircraft—technology review. IEEE Trans. Ind. Electron. 66(7), 5588–5599 (2018). https://doi.org/10.1109/tie.2018.2881951
9. Calzo, G.L., et al.: Converter topologies comparison for more electric aircrafts high speed starter/generator application. In: 2015 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 3659–3666. IEEE (2015)
10. Cao, W., et al.: Overview of electric motor technologies used for more electric aircraft (mea). IEEE Trans. Ind. Electron. 59(9), 3523–3531 (2011)
11. Saket, R.K.: Reliability evaluation of defence support systems. In: Innovations in Defence Support Systems-2, pp. 241–286. Springer (2011)
12. Saket, R.K., et al.: Biorhythmic analysis to prevent aviation accidents. In: Innovations in Defence Support Systems-2, pp. 207–240. Springer (2011)
13. Ni, K., et al.: Electrical and electronic technologies in more-electric aircraft: a review. IEEE Access 7, 76145–76166 (2019). https://doi.org/10.1109/access.2019.2921622
14. Kheraluwala, M., et al.: Performance characterization of a high power dual active bridge dc/dc converter. In: Conference Record of the 1990 IEEE Industry Applications Society Annual Meeting, vol. 2, pp. 1267–1273 (1990)
15. Singh, B., et al.: A review of three-phase improved power quality ac-dc converters. IEEE Trans. Ind. Electron. 51(3), 641–660 (2004). https://doi.org/10.1109/tie.2004.825341
16. Blaabjerg, F. (ed.): Chapter 24 - power electronic systems for aircraft Control of Power Electronic Converters and Systems, pp. 333–368. Academic Press (2018)
17. Friedli, T., Hartmann, M., Kolar, J.W.: The essence of three-phase pfc rectifier systems—part ii. IEEE Trans. Power Electron. 29(2), 543–560 (2014). https://doi.org/10.1109/tpel.2013.2258472
18. Sarlioglu, B., Morris, C.T.: More electric aircraft: review, challenges, and opportunities for commercial transport aircraft. IEEE Trans. Transp. Electrif. 1(1), 54–64 (2015). https://doi.org/10.1109/tte.2015.2426499
19. Kolar, J.W., et al.: Review of three-phase pwm ac–ac converter topologies. IEEE Trans. Ind. Electron. 58(11), 4988–5006 (2011). https://doi.org/10.1109/tie.2011.2159353
20. Benzaquen, J., He, J., Mirafzal, B.: Toward more electric powertrains in aircraft: technical challenges and advancements. CES Trans. Electr. Mach. Syst. 5(3), 177–193 (2021). https://doi.org/10.30941/cestems.2021.00022

21. Chen, J., Wang, C., Chen, J.: Investigation on the selection of electric power system architecture for future more electric aircraft. IEEE Trans. Transp. Electrif. 4(2), 563–576 (2018). https://doi.org/10.1109/tte.2018.2792332
22. Buticchi, G., et al.: A pv-inspired low-common-mode dual-active-bridge converter for aerospace applications. IEEE Trans. Power Electron. 33(12), 10467–10477 (2018). https://doi.org/10.1109/tpel.2018.2801845
23. Wheeler, P., et al.: A matrix converter based permanent magnet motor drive for an aircraft actuation system. In: IEEE International Electric Machines and Drives Conference, 2003, vol. 2, pp. 1295–1300 (2003). *IEMDC'03*
24. Lei, J., et al.: Aircraft starter/generator system based on indirect matrix converter. In: IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, pp. 4840–4846 (2014)
25. Zhang, Z., et al.: Overview and development of variable frequency ac generators for more electric aircraft generation system. Chin. J. Electr. Eng. 3(2), 32–40 (2017)
26. Friedli, T., et al.: Comparative evaluation of three-phase ac–ac matrix converter and voltage dc-link back-to-back converter systems. IEEE Trans. Ind. Electron. 59(12), 4487–4510 (2012). https://doi.org/10.1109/tie.2011.2179278
27. Buccella, C., et al.: A cascade multilevel configuration for commercial transport aircraft. In: 2018 AEIT International Annual Conference, pp. 1–5 (2018)
28. Patel, V., Buccella, C., Cecati, C.: Analysis and implementation of multilevel inverter for full electric aircraft drives. Energies 13(22), 6126 (2020). [Online]. https://doi.org/10.3390/en13226126 https://www.mdpi.com/1996-1073/13/22/6126
29. Mirafzal, B.: Survey of fault-tolerance techniques for three-phase voltage source inverters. IEEE Trans. Ind. Electron. 61(10), 5192–5202 (2014). https://doi.org/10.1109/tie.2014.2301712
30. Chiang, G.T., Itoh, J.-i.: Dc/dc boost converter functionality in a three-phase indirect matrix converter. IEEE Trans. Power Electron. 26(5), 1599–1607 (2011). https://doi.org/10.1109/tpel.2010.2088139
31. Zhou, D., Wang, H., Blaabjerg, F.: Mission profile based system-level reliability analysis of dc/dc converters for a backup power application. IEEE Trans. Power Electron. 33(9), 8030–8039 (2018). https://doi.org/10.1109/tpel.2017.2769161
32. Kabza, H., et al.: Cosmic radiation as a cause for power device failure and possible countermeasures. In: Proceedings of the 6th International Symposium on Power Semiconductor Devices and Ics, pp. 9–12 (1994)
33. Zeller, H.: Cosmic ray induced breakdown in high voltage semiconductor devices, microscopic model and phenomenological lifetime prediction. In: Proceedings of the 6th International Symposium on Power Semiconductor Devices and Ics, pp. 339–340 (1994)
34. Matsuda, H., et al.: Analysis of gto failure mode during dc voltage blocking. In: Proceedings of the 6th International Symposium on Power Semiconductor Devices and Ics, pp. 221–225 (1994)
35. Scheuermann, U., Schilling, U.: Impact of device technology on cosmic ray failures in power modules. IET Power Electron. 9(10), 2027–2035 (2016). https://doi.org/10.1049/iet-pel.2015.1003
36. Harikumaran, J., et al.: Reliability analysis of aircraft starter generator drive converter. In: 2019 IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference (COBEP/SPEC), pp. 1–6 (2019)
37. Harikumaran, J., et al.: Failure modes and reliability oriented system design for aerospace power electronic converters. IEEE Open J. Ind. Electron.Soc. 2, 53–64 (2021). https://doi.org/10.1109/ojies.2020.3047201
38. Schweizer, M., Friedli, T., Kolar, J.W.: Comparison and implementation of a 3-level npc voltage link back-to-back converter with sic and si diodes. In: 2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1527–1533 (2010)
39. Shaik, T., Bezawada, S., Reddy, B.N.: A Novel Approach of Active Npc (Anpc) Multi Level Inverters for Fault-Tolerant Operation
40. Rodriguez, J., Lai, J.-S., Peng, F.Z.: Multilevel inverters: a survey of topologies, controls, and applications. IEEE Trans. Ind. Electron. 49(4), 724–738 (2002). https://doi.org/10.1109/tie.2002.801052

How to cite this article: Verma, A., et al.: Reliability analysis of multilevel and matrix converters used in more electric aircraft. IET Electr. Syst. Transp. e12078 (2023). https://doi.org/10.1049/els2.12078