Design of Propulsion System for 9 PAX Electric Aircraft

Power Converters and Safety Considerations

BSc Thesis

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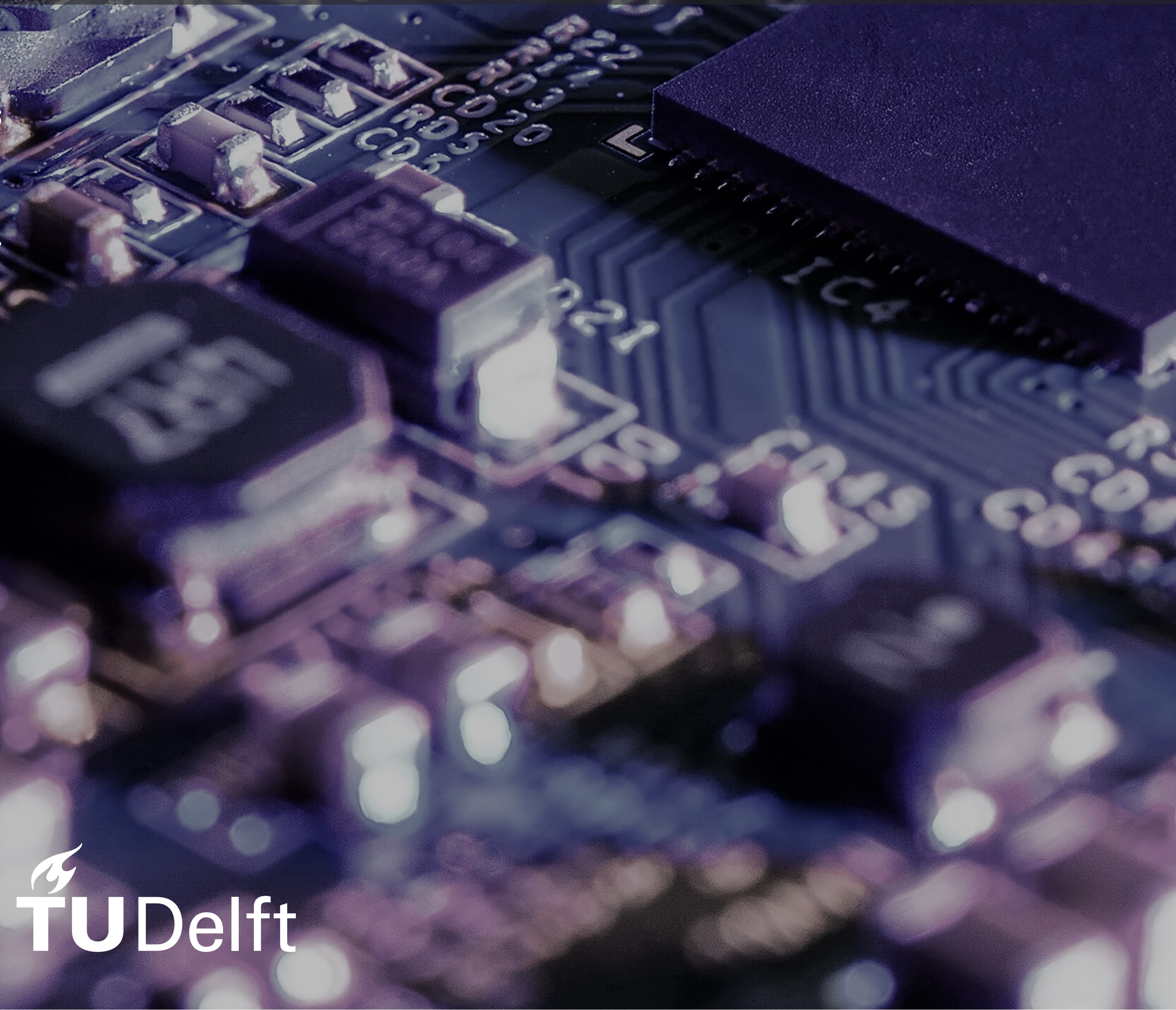
Delft University of Technology



TU Delft

Design of Propulsion System for 9 PAX Electric Aircraft

Power Converters and Safety Considerations

by

Joop Sluimer and Steven Zhou

to obtain the degree of Bachelor of Electrical Engineering
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TU Delft

Preface

This thesis was written for our Final Bachelor Project, proposed by the supervisors and based on the *2022 IEEE/AIAA ITEC+EATS Student Design Competition of a High-Voltage/ High Power Distribution Propulsion System for Zero Emission Aircraft*. All us students are in our third and final year of the Electrical Engineering Bachelor. This thesis is one of three theses that together cover all parts of the competition. The competition requirements and expectations were used to divide the original project group of 6 people into smaller subgroups of 2: Electrical power distribution and E-motors, Power converters and Safety considerations for the electrical architecture, and Energy storage and transfer. The subgroup workloads and division were based on the points given per category in the competition expectations. All the theses provide discussion and make technical choices on components or subsystems to be used within the propulsion system. Guidelines and requirements from the competition were followed when making these decisions. In the end all subgroups contributed to designing of the high power distribution system. This thesis specifically focuses on the Power converters and Safety considerations of the distribution system. The achieved research and decisions made could not have been done without the help of our supervisors and the facilities of the TU Delft. We greatly appreciate the opportunity given to us to participate in this project and all the time spent by the supervisors aiding us.

Joop Sluimer and Steven Zhou
Delft, June 2022

Abstract

In order to slow down global warming, electrification of transportation is looked into more and more. The commercialization of electric cars was one of the first steps. Next the transportation industry will look to expand into electric aircraft too. The electric distribution propulsion system is one of the most important areas regarding the feasibility of electric aircraft. This thesis presents a design for an all-electric distribution propulsion system for the year 2038. More specifically, the power converters and safety considerations of the electric architecture will be compared and discussed in this thesis. Existing research was compared to derive optimal solutions for the aircraft requirements. Finally, the conclusion summarises the most important results obtained during the research process for this aircraft application.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
IEEE	Institute of Electrical and Electronics Engineers
AIAA	American Institute of Aeronautics and Astronautics
ITEC	IEEE Transportation Electrification Conference & Expo
EATS	Electric Aircraft Technologies Symposium
FAA	Federal Aviation Regulations
EASA	European Union Aviation Safety Agency
WIPS	Wings Ice Protection Systems
ECS	Environmental control system
FIT	Failure in Time
CO_2	Carbon Dioxide
DC	Direct Current
AC	Alternating Current
Si	Silicon
SiC	Silicon Carbide
GaN	Galium Nitride
WBG	Wide-bandgap semiconductor
IGBT	Insulated-gate bipolar transistor
MOSFET	Metal–oxide–semiconductor field-effect transistor
EMI	ElectroMagnetic Interference
2LC	Two level converter
3LTTC	Three level T-Type converter
3LNPCC	Three level neutral point clamped converter
3LANPCC	Three level active neutral point clamped converter
3LFCC	Three level flying capacitor converter
3LSNPCC	Three level Sparse neutral point clamped converter

1 Introduction

Electric transportation options are being explored more and more due to the limited amount of oil based jet fuels and their contribution to global warming due to the CO_2 emissions. With this in mind all-electric aircraft are being researched and developed for the future. For a feasible electrical architecture a combination of high efficiency and a high power density sources are required as well as a highly efficient distribution system for the various loads. Advances in battery technology, propulsion systems and weight reduction allows research for the future.

1.1. Thesis objective

The objective of this thesis is to design the distribution propulsion system for an all-electric aircraft for the year 2038. The design was based on requirements for the student design competition by the IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium [1]. The competition was attempted by a group of 6 Bachelor Electrical Engineering students from the TU Delft, the workload was divided into three subgroups that had to tackle different aspects of the competition:

- Electric motors and Power distribution’
- Energy storage and Transfer
- Power converters and Safety considerations

This thesis will cover the power converters and safety considerations taken for the all-electric aircraft presented. This will include a discussion on the different semiconductor devices and the suitability for the application, the different converter topologies, and ultimately an estimated mass for all the different converters. Furthermore, the different safety considerations throughout the propulsion system are discussed and appropriate safety devices are chosen for different applications throughout the system. The results discussed will be made based on existing research and devices, whilst taking the different environmental conditions of the aircraft into consideration.

1.2. Thesis structure

First the program of requirements are mention in chapter 2, which includes the requirements of the entire distribution system and the more specific requirements for this thesis. Chapter 3 includes an in depth discussion on the power converters, discussing the different semiconductor devices, environmental conditions, appropriate topologies and an estimated weight. Chapter 4 mentions the main failures, redundancies in case of failure, different protection devices to be used throughout the electrical distribution system, and concludes with the certification requirements of the FAA and EASA met by the system design. Chapter 5 reflects on the achieved work along with a discussion. Finally, chapter 6 concludes the thesis and mentions options for future work regarding the topics discussed in this thesis.

2

Program of Requirements

2.1. Intergroup requirements

This project is based on the design of a propulsion system for a 9 PAX all electric aircraft. The requirements for the propulsion system were divided into seven different categories, each given points for scoring in the competition that this project is based on [1]. The project was divided into three subgroup based on the points per category each with their own requirements. The requirements that have to be considered for the entire group are included below:

- Minimum cruise speed of 500km/h, target cruise speed of 550 km/h or greater.
- Speed at take-off 300 km/h.
- Capable of flight in known icing conditions.
- Meets applicable certification rules in FAA 14 CFR Part 23.
- Entry of service is 2040, technology within the propulsion system should be in service by 2038.
- Fulfill all safety considerations and high voltage issues management.
- Maximum take of weight (MTOW) of 5650 kg.
- Payload of 1000 kg (9 PAX + 1 crew + luggage) and manufacturer's empty weight (MEW) of 3000 kg excluding the propulsion system.
- Expected propulsion system of 1650 kg, if exceeded the payload capability is reduced.
- Total embedded power of 2000kW.
- Thrust: 4 E-motor, two per wing.
- 260 km design range mission including a 50 km backup reserve.
- 9000 m ceiling.
- Initial climb duration at sea level (ISA+ 18oF) maximum, requested electrical power 1150kW.
- Cruise duration of 28minutes including the descent of 16minute requested electrical power 515kW.

2.2. Intragroup requirements

The goal of this subgroup is to provide an appropriate design for the different power converters used throughout the propulsion system and discuss the safety considerations taken throughout the entire propulsion system. The requirements per category are listed below.

2.2.1. Power converters

- Converter general topology.
- The switch technology selection used within the converters
- Characteristics of motor drive: voltage switching frequency and current frequency.
- Estimation for the converter mass.

2.2.2. Safety considerations for the electrical architecture

- Provide a list of main failures and how the electrical distribution system is fault-tolerant.
- Describe how redundancies are provided in case of critical components failure, power cables segregation.
- Describe how critical faults propagation is mitigated.
- Describe protection components and what risks are addressed by these components.
- Give main certification requirements for the electric distribution, and how they are taken into account by your proposed solution.

3 Power Converters

The power converters is an electrical component responsible for changing the input electrical energy into a more desired form for the specific load following it. Both DC-DC converters for between different voltage lines and DC-AC inverters for the motors are discussed. The DC-DC converters are responsible for converting from 3 kV ($\pm$1.5 kV) to 800 V ($\pm$400 V), and from 800 V ($\pm$400 V) to 28 V ($\pm$14 V). Both high power converters for the motors and low power converters for the rest of the electrical system have to be considered. The DC-AC converter (inverter) has to be able to handle 575 kW at most during take-off, in order to supply the motors with 800 V on six-phase lines. Different topologies of the DC-DC and DC-AC converters are discussed in order to achieve the requirements. In figure 3.1, the placements of the different converters (non-isolated and isolated) can be seen within the propulsion system. The power semiconductor devices used are of great importance when realising the converters and thus will be compared. Furthermore, the voltage switching frequency is of great relevance when considering both efficiency and weight. Finally, an estimated weight will be provided for all the different converters.

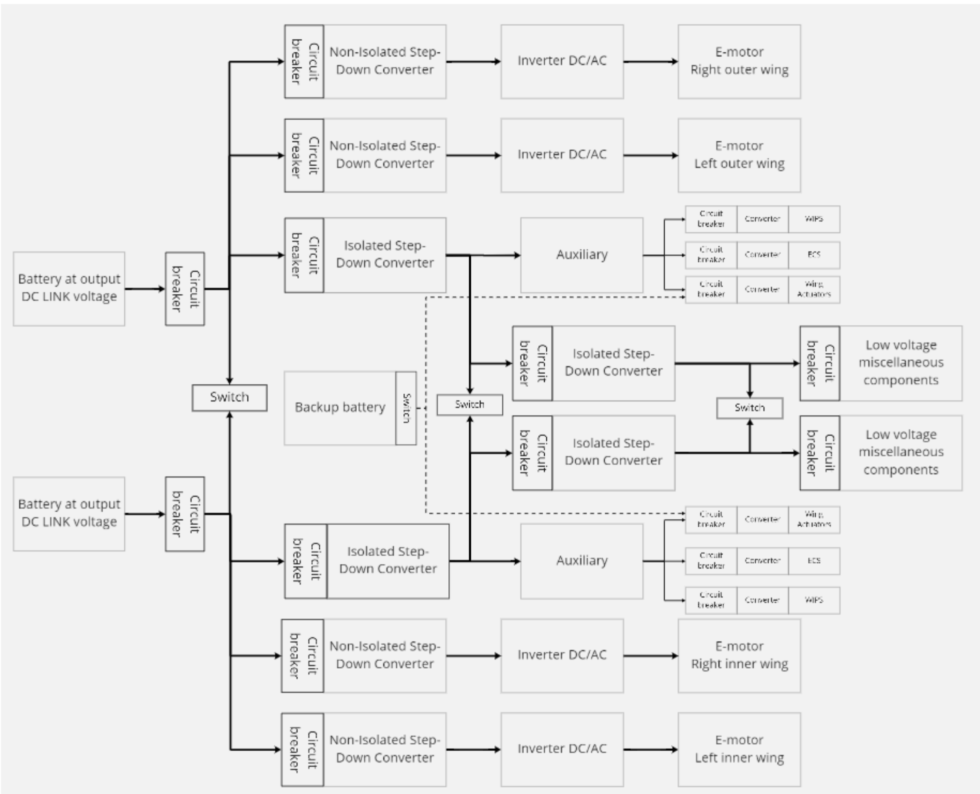


Figure 3.1: Schematics of the aircraft's propulsion system

3.1. Semiconductor technology

The most suitable semiconductor devices will mainly be determined on efficiency and voltage range at a specific switching frequency. Multiple sources were used to compare the most widely available semiconductor device materials: Si, SiC and GaN. The main advantage of using wide-bandgap semiconductors (WBG) like SiC and GaN over Si is the higher band gap. This means that they have lower intrinsic leakage currents and can operate at much higher temperatures compared to Silicon. Table 3.1 obtained from [2] directly shows their obtained material properties. Other advantages mentioned include a higher breakdown field, allowing them to operate at higher voltages. For the transistors of the same breakdown voltage, the WBG semiconductors would be much thinner, meaning smaller volume and higher power density. Furthermore, the switching capacity of semiconductor devices is greatly dependant on the saturation velocity and the electron mobility. GaN is the clear favourite for operating at high frequencies as the saturation velocity is 120% greater than that of Si and the electron mobility is 58% greater than that of SiC. GaN appears the best option purely based on material properties.

Property	Si	4H-SiC	GaN
Band gap energy E_g (eV)	1.12	3.26	3.43
Breakdown field E_c (kV/cm)	300	2200	3300
Saturation Velocity v_{sat} (cm/s)	$1x10^7$	$2x10^7$	$2.2x10^7$
Electron Mobility μ_n $(cm^2/V \cdot s)$	1300	950	1500

Table 3.1: Material properties of Si, SiC and GaN from [2]

However, comparing the material properties is not sufficient to justify a semiconductor material. When directly comparing all three semiconductor materials, as done in [2], it is clear that GaN again is a clear favourite in terms of power dissipation especially at high frequencies, as can be seen in figure 3.2. GaN has roughly 40% the average power dissipation compared to Si and SiC at 10 MHz, the difference is harder to tell at lower switching frequencies.

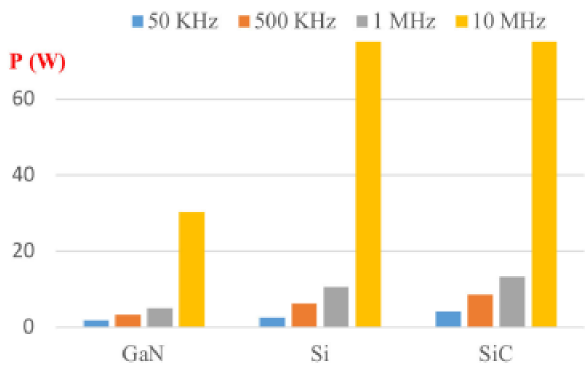


Figure 3.2: Average power dissipation of each transistor at different frequencies. Obtained from [2].

Toshiba has done comparisons of a Si IGBT and a SiC MOSFET under identical conditions [3]. The applied collector-to-emitter voltage for the IGBT and drain-to-source voltage for the MOSFET is 800 V, which is identical to the used voltage for the motor drive at sea level. Table 3.2 summaries the obtained results. At 25 °C the switching loss is reduced by 65% and at 150 °C a 76%. Power loss simulations were also done, resulting in a 66% reduction in power loss when comparing the SiC MOSFET to the Si IGBT. Considering both these reductions, SiC is a clear favourite in terms of efficiency compared to Si based semiconductors.

Temperature of testing (°C)	25	150
$E_{on} + E_{off}$ of IGBT (mJ)	2.46	3.48
$E_{on} + E_{off}$ of SiC MOSFET (mJ)	0.86	0.82
Reduction from IGBT to SiC MOSFET	65% reduced	76% reduced

Table 3.2: Switching loss of SiC MOSFET and Si IGBT obtained from [3]

Another comparison was done by [4]. From figure 3.3 it can be concluded that for similar voltage levels, the SiC MOSFET is more efficient compared to the Si IGBT over all the tested frequency ranges. Even though the comparison was done at a much lower power, higher power SiC modules exist that will later be evaluated.

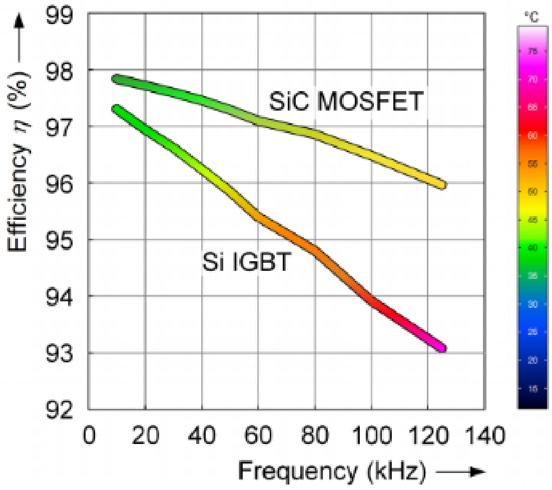


Figure 3.3: Measured efficiency at different switching frequencies. Obtained from [4].

Gallium Nitride based semiconductors are a much newer technology, and are currently only commercially available for low voltages, less than 700 V. The low output capacitance of GaN switches makes them especially suitable for high frequency applications because the weight and volume of passive components can be reduced. This is hugely beneficial for aircraft application, lower aircraft weight means less power required for take-off, cruise and descent. However, due to the lower voltage ratings GaN cannot be considered for the higher power converters. For the lower power converters, for instance for the cabin lights, it is the best option. Both being lighter and more efficient when compared to SiC and Si based semiconductors.

From these comparisons it can be concluded that SiC based semiconductors are the best option for the high and medium power converters, as they are both more efficient and also have a greater power density when compared to Si base semiconductors. Furthermore, a GaN based converter should be considered for the medium to low level conversion.

3.1.1. Environmental conditions and effect

When deciding an appropriate voltage level for the semiconductors in the aircraft application, different environmental conditions have to be considered. Humidity, air pressure and cosmic radiation limit the application of high voltage systems in aircraft. The effects are discussed in detail in [5].

Increases in humidity causes condensation of the devices, which can then cause short-circuits due to the moisture. These short circuits would have an effect on the insulation for cables and reduce the blocking voltage of semiconductors mainly. The environmental control system (ECS) is responsible for handling the humidity changes in the fuselage, dehumidifiers could also be considered for devices in the wings, however, are not discussed here.

When flying at higher altitudes the air pressure is decreased. According to Figure 3.5 from [5], the critical field strength drastically reduces at higher altitudes. The ECS is again responsible for handling the change of pressure at higher altitudes. However, in case of failure the electronic systems needs to remain operational under a lower critical field strength. Under normal conditions the ECS maintains a minimum air pressure of 760 hPa, which is equivalent to an altitude of 2.5 km. If the ECS were to fail the critical field strength would reduce from 25 $kVcm^{-1}$ at 2.5 km to approximately 12 $kVcm^{-1}$ at an altitude of 9 km. Clearance and creepage distances have to be considered in converter design to withstand the lower air pressures and thus lower critical field strength. According to figure 3.4 for an altitude of 9 km (approximately 30,000 ft) a breakdown voltage of 3 kV occurs at a distance of 4 mm, and for a breakdown voltage of 800 V at 0.06 mm. At a higher altitude a greater creepage and clearance distance is required to prevent breakdown. Alternatively potting of certain parts of the electric system can be done, which will add more weight to the aircraft. This make this solution not as desirable, but it is still a good solution to keep in mind.

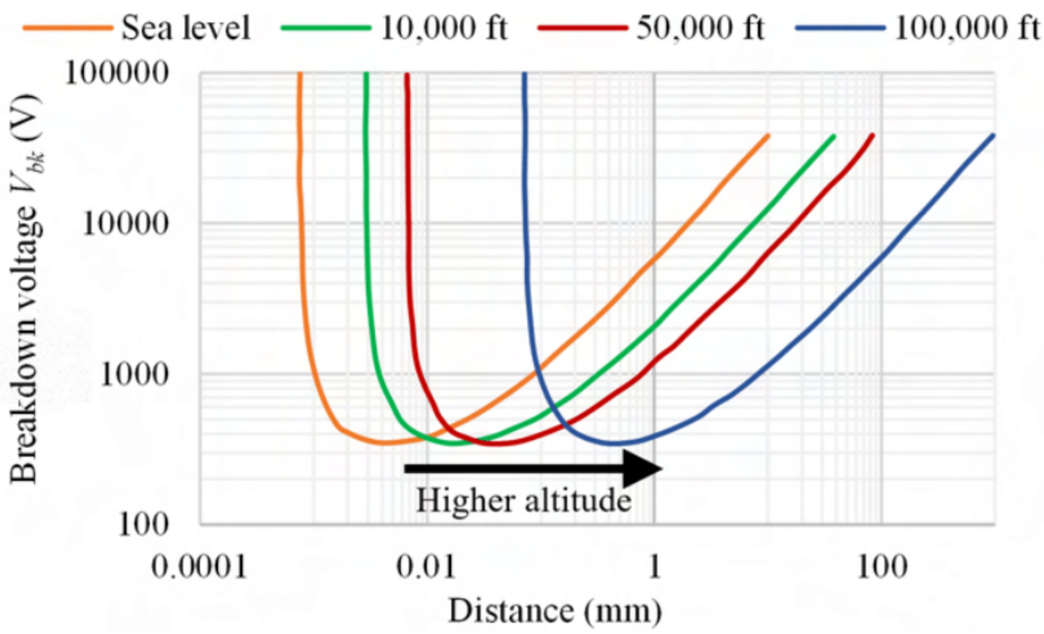


Figure 3.4: Paschen curve at different altitudes. Obtained from [6].

Finally, cosmic radiation can result in the most catastrophic failures and cannot be handled by a system like the ECS, thus a strong emphasis must be made when designing high voltage systems. Primary cosmic radiation consists of high energy particle radiation from outer space in the form of charged particles that have been accelerated to high speeds. This radiation does not reach the earth's surface due to the particle collision with molecules in the atmosphere. This collision causes a resultant secondary cosmic radiation consisting of photons and hadrons (neutrons, protons, and pions) most notably. As mentioned in [5] and [7] the collision between a high energy neutron and a Silicon nucleus can lead to a single event burnout, which can lead to a conductive channel being formed and spreading throughout the device. The channel causes a short-circuit in the device, which in turn will lead to self-heating and permanent damage to the device. This effect depends on the applied drain-to-source voltage on the device. Given that only a single event is needed the probability of failure depends on the availability of a high energy neutron, which in turn depends on the geomagnetic location and the solar activity. Figure 3.6 obtained from [5] is an example plot for the Failure in Time (FIT) rates for a 1.7 kV SiC MOSFET against altitude.

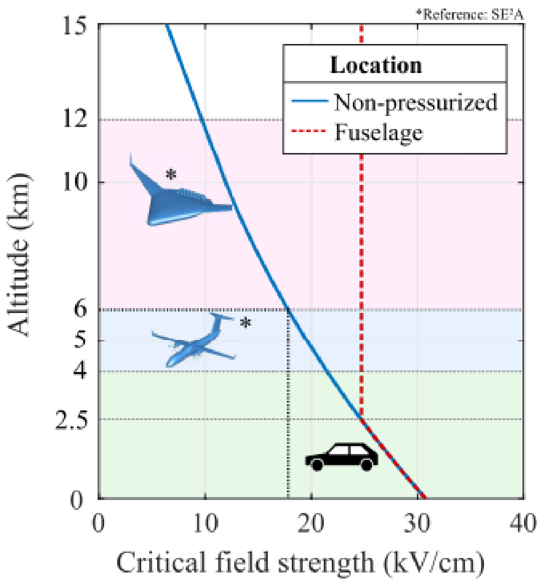


Figure 3.5: Critical field strength at different altitudes. Obtained from [5].

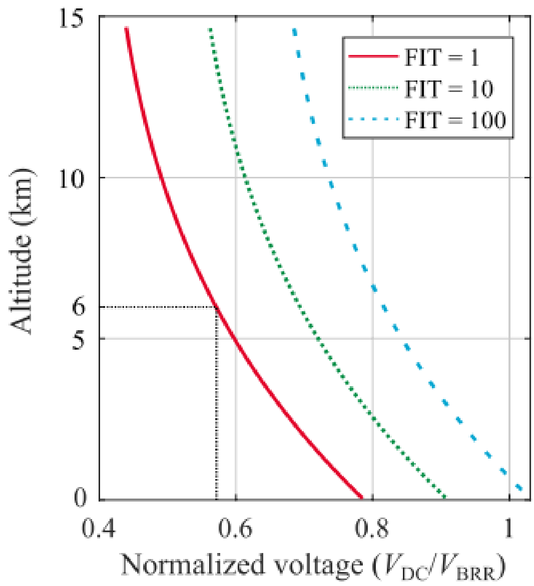


Figure 3.6: Reduction of drain-to-source source voltage at higher altitudes, obtained from [5].

From this plot and the aircraft maximum flight altitude of 9 km, it can be concluded that a safe estimate of 50% reduction of the rated drain-to-source voltage is needed for a FIT of 1 in 10^9 hours. This would suggest that a 1.7 kV rated SiC MOSFET at the flight ceiling of the aircraft should be considered as a 850 V rated MOSFET.

3.2. Converter topology

As mentioned before the system is split up into three different voltage levels: the 3 kV voltage level being the main voltage level coming out of the battery, the 800 V voltage level used for the motors and the auxiliary systems, like the WIPS, and finally, the 28 V voltage level used for the miscellaneous components, like lighting inside the plane. To achieve these different voltage levels, step-down converters are needed to be designed, both isolated and non-isolated variants. As seen in figure 3.1 the non-isolated converters are used for the motor and the isolated converters are used for the smaller systems. It is only needed to use the isolated converters for the smaller systems as they are closer to passengers and are likely to interact with it more, which is why it is needed to provide galvanic isolation as a safety measurement. This is not needed for the motors as the passenger are not directly interacting with it and by using a non-isolated converter it is also more efficient for the motor to use the battery power. The motor drive also has another safety measurement (a circuit breaker between it and the battery) built-in, so that it can protect itself from failures from elsewhere. Finally, it is needed to design inverters to convert DC- to AC-power for the motor as the aircraft uses synchronous motors to propel the aircraft forwards. The motors chosen for the aircraft application require an approximate 575 kW peak power continuously during lift-off.

3.2.1. Isolated converter topology

The isolated converters are designed in order to convert the high voltage level (±1.5 kV) into lower voltages (±400 V and ±14 V) suitable to power on the medium and low power systems. It will convert it first to ±400 V and then from that voltage level it will convert it to ±14 V, so the ±400 V lines should carry enough power to power the medium and the low power systems. Per bipolar line two converter will be used: one for the positive side and one for the negative side.
Many different topologies can be used to realise a step-down converter, but it is needed to design a converter with very high efficiency and lightweight. An overview of some of the topologies considered for this purpose can be seen in figure 3.7.

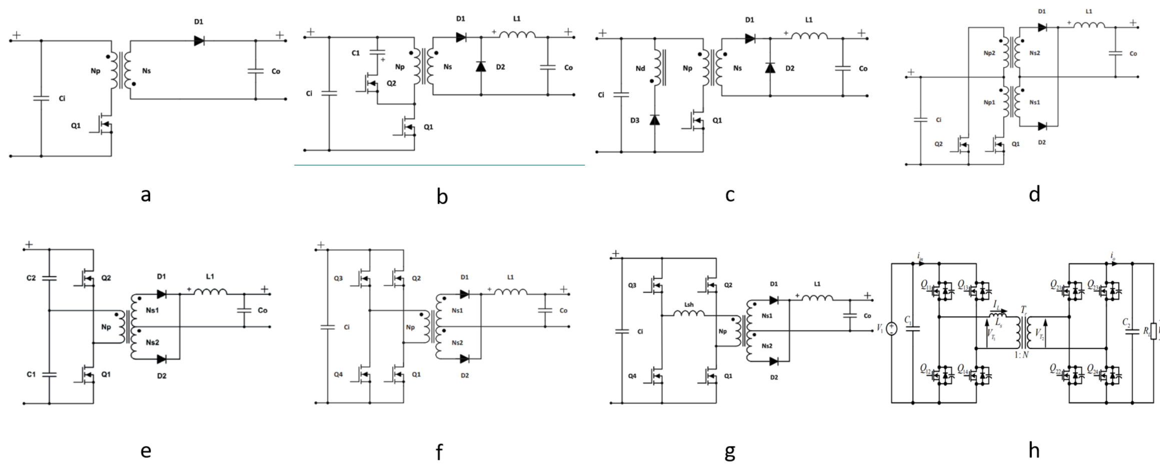
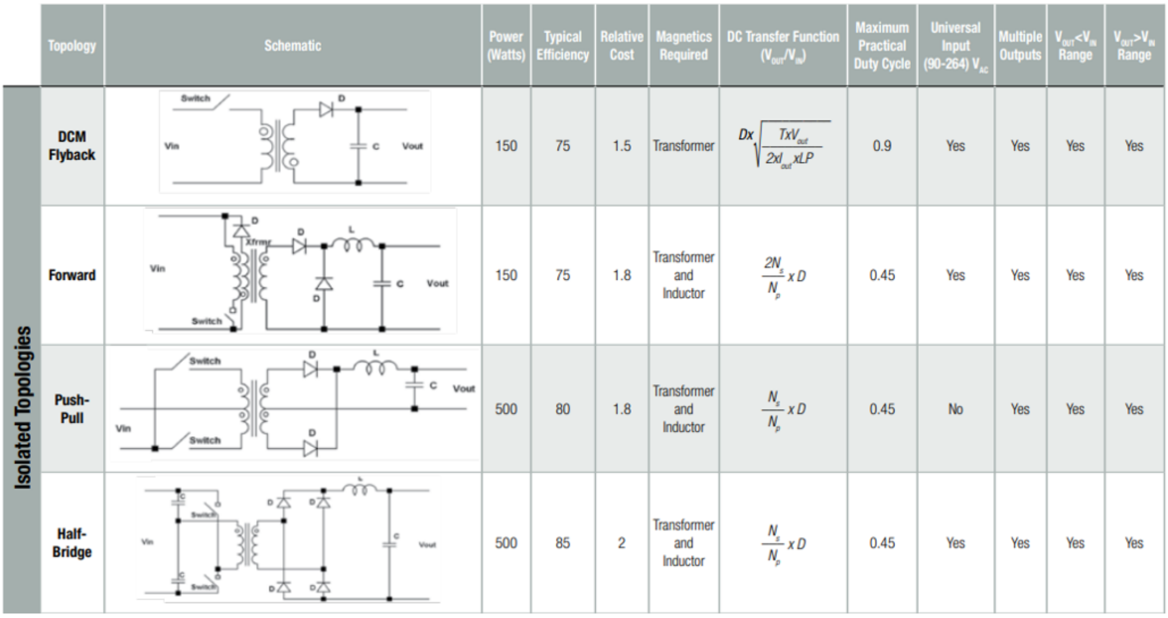


Figure 3.7: Schematics of a flybacyk converter(a), a active clamp forward converter(b), a single switch forward converter(c), a push-pull converter(d), a half-bridge converter(e), a conventional full-bridge converter(f), a phase shifted full-bridge converter(g) and a dual active bridge converter(h). Obtained from [8] and [9].

Starting from (a) the flyback converter, this topology is mostly used for low power conversions as it is very cheap to make, only one switch is needed, but it has high conduction losses and poor transformer utilization, which means that the efficiency is very low at high power and makes the transformer bulkier. It also has high input and output ripple currents, which is undesirable and needs extra capacitors to compensate for this. Moving onto the next two topologies, these are variants of a forward converter and these are mostly used in medium power conversions. These topologies also have a poor transformer utilization, which makes the efficiency also quite low and the transformer also bulkier. The push-pull converter can be used for high power conversion with high power density due to the full utilization of the transformer, but the voltage stress on the switches is quite high. This is can be as high as two times the input voltage, which is not really desirable. Looking at the last four topologies, these are all forms of bridge type topologies. The advantages of these type of topologies is that the voltage stress on the switches is equal to the input voltage, the transformer utilization is very good and the efficiency is very high relative to the other topologies as can be seen in figure 3.8 and figure 3.9.



Topology	Schematic	Power (Watts)	Typical Efficiency	Relative Cost	Magnetics Required	DC Transfer Function (V_{OUT}/V_{IN})	Maximum Practical Duty Cycle	Universal Input (90-264) V_{AC}	Multiple Outputs	$V_{OUT}<V_{IN}$ Range	$V_{OUT}>V_{IN}$ Range
Isolated Topologies: DCM Flyback		150	75	1.5	Transformer	$Dx\sqrt{\frac{TxV_{out}}{2xI_{out}xLP}}$	0.9	Yes	Yes	Yes	Yes
Forward		150	75	1.8	Transformer and Inductor	$\frac{2N_s}{N_p} x D$	0.45	Yes	Yes	Yes	Yes
Push-Pull		500	80	1.8	Transformer and Inductor	$\frac{N_s}{N_p} x D$	0.45	No	Yes	Yes	Yes
Half-Bridge		500	85	2	Transformer and Inductor	$\frac{N_s}{N_p} x D$	0.45	Yes	Yes	Yes	Yes

Figure 3.8: An overview of the flyback converter, forward converter, push-pull converter and half-bridge converter with their respective efficiencies. Obtained from [10].

	Forward	*Flyback*	*Full-bridge experimental*	**Full-bridge simulated*
High voltage high current (hard switched)	-	-	90% V_{in} = 150 V, P = 2.5 kW	87% V_{in} = 150 V, P = 2.5 kW
Low voltage high current (hard switched)	~80% (Ye et al., 2007) V_{in} = 12 V, I_o = 30 A	~80% V_{in} = 12 V, I_o = 30 A	> 84% V_{in} = 12 V, I_o = 30 A	86% V_{in} = 12 V, I = 30 A
Low voltage high current (soft switched)	~90% (Lee et al., 2007) V_o = 5 V, I_o = 20 A	~90% (Zhang et al., 1998; Zhang and Yan, 2009) V_o = 12.4 V, I_o = 20 A	> 95% (Wu et al., 2006) V_o = 50 V, I_o = 24 A	93% V_o = 50 V, I_o = 24 A

Figure 3.9: An overview of the efficiencies of the flyback converter, forward converter and full-bridge converter. Obtained from [11].

As the efficiency of the bridge type topologies is the best, it is needed to consider which type is the best for the aircraft. First comparing the half-bridge with the conventional full-bridge, it can be derived that the power losses from both topologies are around the same for a 200 kW converter as seen in figure 3.10. Although different current rated switches were used in figure 3.10, it still show an accurate representation of the power losses between the two topologies. The reason for the different switches, is that the current stress on the switches in the full-bridge is halved with respect to the half-bridge. As stated in [12], it reduces the power dissipation per switch with about 30% by using lower current rated switch in full-bridge than using higher current rated switches in the half-bridge. With this in mind the heatsink can be more lightweight and smaller in size. Another benefit of using a full-bridge over a half-bridge is that in a full-bridge two switches are used instead of two bulky capacitors which reduces the weight and size, and it is also cheaper to use switches instead of big capacitors as seen in figure 3.11.

Now looking at the different full-bridge topologies, the dual active bridge topology is ruled out as it not needed to make it bidirectional as the medium and low power systems will not provide power back to the overall grid/battery and with the added switches it will become more expensive, more difficult to control all the switches and bulkier with the added cooling elements to cool the extra switches. The choice is now narrowed down to two topologies which is the conventional full-bridge or the phase shifted full-bridge. The benefits of the phase shifted full-bridge is that zero-volt switching takes place by phase shifting the different switches from different legs and making the switching frequency constant. This zero-volt switching and constant switching frequency lead to a reduction of switching generated EMI, which also means that the EMI filters and magnetic components can be smaller and less complex. There is a reduction of the switching losses, but there is also an increase of the conduction losses on the primary side during the freewheeling time. Overall the efficiency is a bit higher due to the switching losses outweighing the conduction losses. Based on the benefit of having smaller components and better efficiency, the phase shifted full-bridge is chosen over the conventional full-bridge [13][14]. Depending on the transistor characteristics and ratings the amount of levels can be chosen, this is going to be determined in a later section.

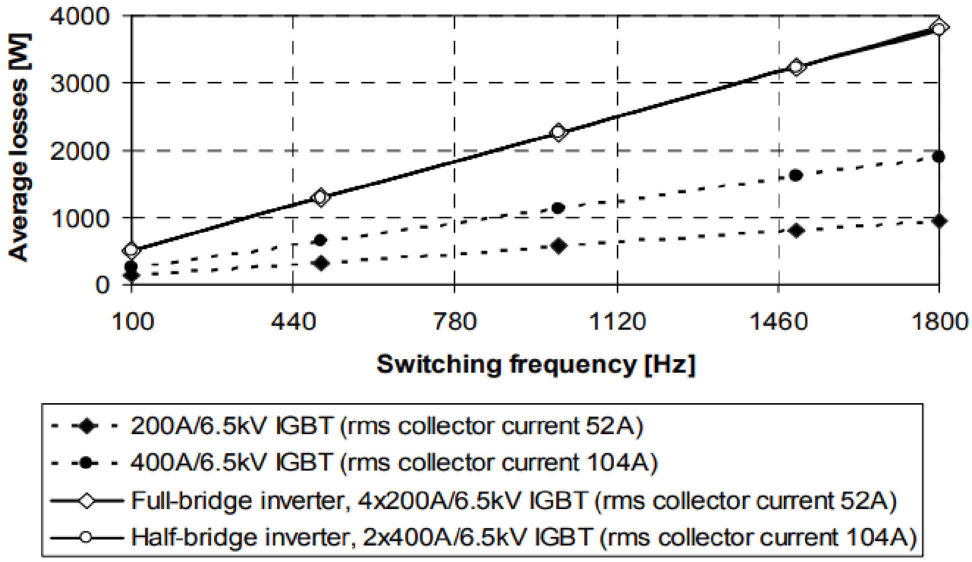


Figure 3.10: The power of losses of a 200 kW half-bridge and full-bridge converter. Obtained from [12].

	Forward (unidirectional)	*Flyback (unidirectional)*	*Half-bridge (unidirectional)*	*Full-bridge (unidirectional)*	*Full-bridge (bidirectional)*
*Active devices (560 V/52 A CoolMOS)	1 ($5.9)	1 ($5.9)	4 ($5.9 * 8 = 47.2)	4 ($5.9 * 4 = 23.6)	8 ($5.9 * 4 + 5.9 * 4 * 2 = $94.8)
Diodes (600 V/20 A)	2 ($2.39*2)	1 ($2.39)	2 ($2.39 * 2)	4 ($2.39 * 4)	--
**Isolation transformer	***1 ($100)	1 ($100)	1 ($100)	1 ($100)	1 ($100)
Filtering inductor	1 ($50)	Dispensable	Dispensable	Dispensable	Dispensable
****Capacitor	2 ($26.7 * 2 = $53.4)	2 ($26.7 * 2 = $53.4)	4 ($26.7 * 4 = $106.8)	2 ($26.7 * 2 = $53.4)	2 ($26.7 * 2 = $53.4)
Snubber	1 set ($10.3)	1 set ($10.3)	0	0	0
Total price ($)	($224.7)	($172.3)	($258.8)	($186.6)	($212.4)

Notes: *All the switches are 560 V/52 A CoolMOS. If other switches are selected, the cost will change. The diode is 600 V/20 A (average current) fast reverse recovery diode. All the prices are based on the quote for 5,000 pieces.

**The transformer price was not investigated. We assume all transformers have the similar price.

***For the forward-converter transformer, it needs another extra demagnetising winding therefore the price should be higher.

****500 V/100 μF film capacitors are used for long life time and high temperature.

Figure 3.11: An overview of the prices of the flyback converter, forward converter, half-bridge converter, full-bridge converter and dual active bridge converter. Obtained from [11].

3.2.2. Non-isolated converter topology

For the non-isolated converters, it is not needed to design them in a bidirectional way as a unidirectional one it sufficient enough for the aircraft motors. This is because the motors will not generate energy back into the system while it is flying in the air as they have to constantly draw power from the system to keep the right speed. This converter type will be used to convert $\pm$1.5 kV to $\pm$400 V that is needed for the motor and per bipolar line two converter will be used: one for the positive side and one for the negative side.

For this converter the choice came mostly down to two topologies: a simple, single buck converter or an interleaved buck converter, which is basically multiple buck converters working in parallel with some alteration to make it work. Although a simple buck converter is simpler to control and has fewer components, the preference goes to the interleaved buck converter because the current stress on the switches is lower (current gets divided into parallel branches) leading to lower heat production in the switches. Furthermore the converter reliability is higher, because the switches are fault tolerant. If one switch fails, it can turn of one of the parallel branches where the failed switch resides. The ripples at the input and output of the converter are also smaller and in turn smaller inductors and capacitors can be used. This is achieved due to ripple cancellation between the different branches [15]. Of course, the higher the amount of phases, the lower the ripple current and voltage, but there is also the trade off of having more switches and it is more difficult to control it. For this application, the focus is on making it reliable and compact, so the least amount of components and easy to control is desired. That is why it is dependant on the transistor characteristics and voltage and current ratings how many levels and phases the converter is going to have. The amount of phases and levels for this aircraft is determined in a later section.

In figure 3.12, the schematics of a simple buck converter, a two phase two-level and three phase three-level interleaved buck converter can be seen.

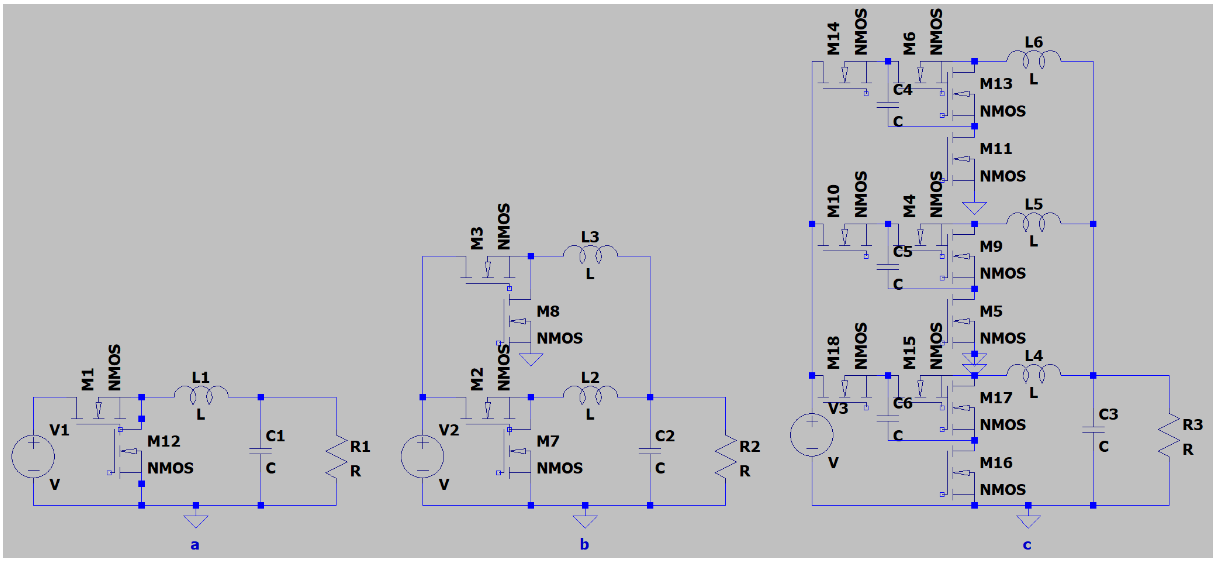


Figure 3.12: Schematics of a simple buck converter(a), a two phase 2-level interleaved buck converter(b) and a three phase three-level interleaved buck converter(c).

3.2.3. Inverter topology

The inverter designed is specifically for motor drive, in order to power the motors an approximate 550 kW has to be supplied at 800 V [16]. Different inverter topologies can be used to realise this demand. Comparing the conventional 2L converter and most widespread 3L topologies: T-Type converter (3LTTC), neutral point clamped converter (3LNPCC) (with SiC diodes), active neutral point clamped converter (3LANPCC), flying capacitor converter (3LFCC), and the 3L sparse npc converter (3LSNPCC) in terms of efficiency and power density to determine to most optimal for the motor application. The different topology schematics can be seen in figure 3.13.

An existing comparison was done by [17] for a 3 phase 800 V 7.5 kW variable speed driver. Even though the power is much lower than what is required for the aircraft motors, the comparison of topologies can still be used but different switches will have to be used to withstand the higher currents.

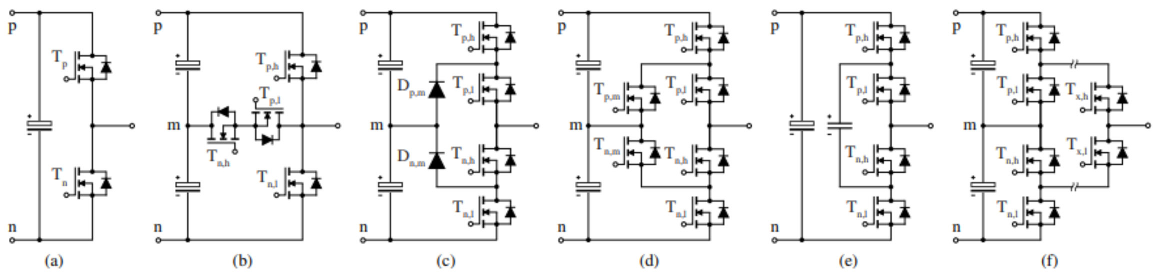


Figure 3.13: Schematics of a single-phase bridge leg of the (a) 2LC, (b) 3LTTC, (c) 3LNPCC, (d) 3LANPCC, (e) 3LFCC, (f) 3LSNPCC. Obtained from [17].

Starting with conduction losses. Considering the conduction losses have a purely resistive behaviour and are thus proportional to the square of the conducted current, the results in table 3.3 are obtained. The values were calculated with nominal operating conditions of the considered system in [17].

When calculating these values it was assumed that all the transistors per topology are active at the same time. This is not accurate in terms of inverter operation, however, due to high switching frequencies it can be assumed as a rough estimation. Alternatively, a conduction loss could be calculated per output voltage level, this was not done unfortunately.

In terms of conduction losses the 2LC is clearly favoured due to it having fewer components. From the 3L inverter selection, the 3LTTC is favoured again simply due the topology also having fewer components. The 3LNPC and 3LFCC inverters have identical switching losses. The 3LSNPCC has considerably greater conduction losses. No conclusion can be made at this point.

Topology	Peak current multiplier
2LC	0.50
3LTTC	0.65
3LNPCC	1.0
3LANPCC	1.0
3LFCC	1.0
3LSNPCC	2.26 or 2.79

Table 3.3: Factor proportional to conduction loss in case of equal applied current. The value for the 3LSNPCC depends on the area used [17], [18]

Furthermore, a performance comparison was done with all converter topologies. For a targeted semiconductor efficiency of 99.5% the results in table 3.4 were obtained. Out of all the 3L converters, the TTC and FCC have the lowest total semiconductor chip size and total RMS flux ripple for the targetted efficiency. The switching frequency used in the TTC to achieve this is more than double that of the FCC, if the same switching frequency was considered the TTC would require larger passive components for similar efficiencies and thus a heavier system, ultimately favouring the FCC topology.

Parameter	2LC	3LTCC	3LNPCC	3LANPCC	3LFCC	3LSNPCC
Switching frequency (kHz)	36	84	59	59	40	61
Total semiconductor chip area (mm^2)	75.9	146	213	231	166	186
total RMS flux ripple ($V \cdot ms$)	1.05	0.28	0.40	0.40	0.30	0.53

Table 3.4: Comparison of topologies for a semiconductor efficiency of 99.5% at nominal operation from [17].

Finally, the efficiency for a given volumetric power density was measured through an optimization procedure, where the Pareto-optimal designs are highlighted and all added to one plot, resulting in figure 3.14. As expected based on the previous two results, the 3LTTC has the best performance, closely followed by the 3LFCC. The difference in efficiency at 20 kW/dm^3 is roughly 0.02% notably.

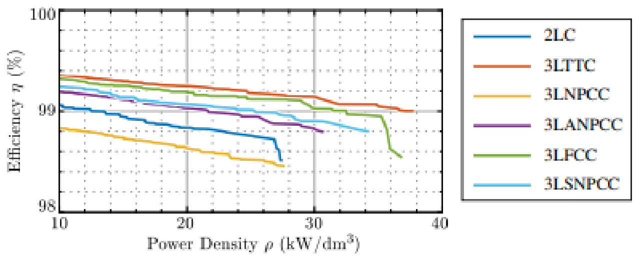


Figure 3.14: Overview of Pareto fronts of all topologies on the efficiency-power density plane. Obtained from [17].

The T-type converter results the best performance in terms of efficiency and volumetric power density, closely followed by the flying capacitor converter. However, due to the topology of the inverter the transistors in the T-type topology must have a much greater breakdown voltage. The Flying capacitor has two transistors in series between either the positive or negative and output, meaning half the required breakdown voltage per transistor. Especially considering the reduction of breakdown voltage due to cosmic radiation, as mentioned previously. The three level flying capacitor converter is a significantly more optimal topology for this aircraft application.

3.3. Switching frequency

The switching frequency is also important to be decided. Having higher switching frequencies can reduce the weight of passive components in converters. However, it comes at the cost of increased switching losses.

Comparing existing technology at different switching frequencies as seen in figure 3.15. From this graph it is clear that switching loss is proportional to the switching frequency. Given that the aircraft has a flight time of approximately an hour, continuous conduction is unlikely and lower switching on/off losses should be prioritised. The 50 kHz appears to be the best range for this aircraft application, given the low switching losses and very low power dissipation for all materials. SiC and GaN are again favourites, as concluded previously, given that both have an approximate 10% of switching loss when switching at 50 kHz. The switching frequency is discussed more in section 3.4.

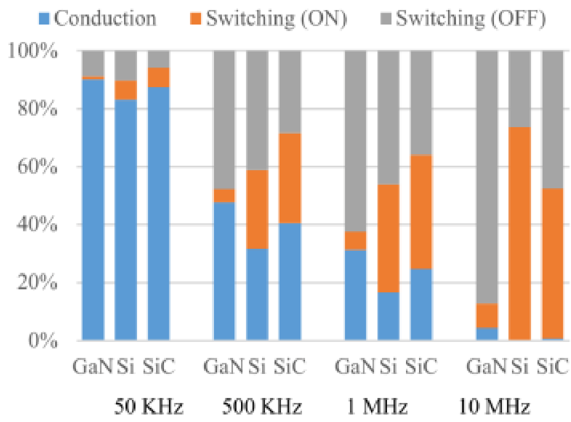


Figure 3.15: Percentage of losses for different frequencies and semiconductor materials. Obtained from [2].

3.4. Design with existing technology

Comparing existing technology and technology that is not yet commercially available allows for better designing keeping the future in mind. A currently available 1.7 kV SiC half-bridge module (CAB650M17HM3 from Wolfspeed) and a 3.3kV SiC half-bridge module from [19] are compared in table 3.5. For the motor a maximum power of 575 kW at 800 V is assumed during take-off. For a six phase motor application [16], this would then result in a current of 120 A through each transistor maximally.

Switch	1.7 kV/650 A SiC MOSFET	3.3 kV/400 A SiC MOSFET
$V_{breakdown}$ due to cosmic radiation (kV)	0.85	1.65
On-resistance at 40 per switch °C (mΩ)	1.56	9.2
Corresponding loss per switch (W)	22.5	132.5
Corresponding case temperature change (°C)	1.22	N/a
$E_{on} + E_{off}$ at 25 °C (mJ)	15	182*
Switching loss at 20 kHz switching frequency (W)	300	3640

Table 3.5: Comparison of 1.7 kV half-bridge module and 3.3 kV SiC half-bridge module . *Extrapolated from figure 11 in [19].

The 1.7 kV has 8% the switching loss and 17% the conduction loss of the 3.3 kV MOSFET. The switching loss comparison is not completely fair as the loss was found under different voltage conditions, however, these were the closest found and still provide an adequate comparison. Thus, the higher voltage rating is not necessary as even when taking the effect of cosmic radiation at 9 km altitude into account, the 1.7 kV MOSFET would be able to operate safely. Any lower voltage rating would not have a FIT rate of 1 (one failure in 10^9 hours). Furthermore, the 1.7 kV model mentions a clearance distance of 13.07 mm from terminal to terminal and 6.00 mm from terminal to heatsink, and creepage distance of 14.27 mm from terminal to terminal and 12.34 from terminal to heatink. All these values are greater than the minimum required distance for an altitude of 9 km, as mentioned in section 3.1.1, and thus safe to be used.

The value for the switching frequency, 20 kHz, was chosen in order to reduce the switching losses, passive component weight, and complexity of the EMI filter. The switching frequency also influences the number of poles in the motor [16]. Increasing the switching frequency by 50% to 30 kHz would increase the switching losses by 50% due to their linear relationship. Justifying a specific switching frequency has proven to be challenging, 20 kHz was chosen as an appropriate value based on the maximum switching frequency most commonly used in PWM for motor drive [20].

3.4.1. Isolated converter design

There needs to be two different isolated step down converters: one converter to step down from $\pm$1.5kV to $\pm$400 V and one converter to step down from $\pm$400 V to $\pm$14 V (for convenience these converters are going to be referred to as the medium and low converter, respectively, for this section). The medium converter supplies power to the medium powered systems, e.g. WIPS, but also to the low converter which in turn supplies power to the low powered systems, e.g. cabin lighting. Assuming that the maximum power that is needed for these systems is about 60 kW, which is split up over two power grids as the aircraft is working with two batteries and each power grid also consists of bipolar lines and per bipolar line two converter will be used: one for the positive side and one for the negative side, so in a normal situation 15 kW goes through one converter, but in case of failure of one battery or power grid, one power grid should be able to take care of this and the power through one medium converter becomes 30 kW. The current through the converter would be 20 A on the primary side and 75 A on the secondary side of the phase shifted full-bridge converter. With these values, the medium converter can be designed. As it is needed to be able to withstand 1.5 kV at the input and using the current technology of 1.7 kV SiC MOSFETs, the topology should be made into a three level, as seen in figure 3.16, as then the voltage over each switch will be only 750 V and this is within the degradation level of 850 V due to cosmic radiation. The 1.7 kV 225 A SiC half-bridge module from Wolfspeed (CAS300M17BM2) is selected to be used as the switches for the medium converter as it is able to withstand the voltage over it and current going through it. Further for the diodes on the primary side 1.7 kV 25 A SiC diodes from Wolfspeed (C5D25170H) are chosen and on the secondary side 1.2 kV 40 A diodes from Wolfspeed (C4D40120H) are chosen, which also needs to be used in parallel (2 minimal) to be able to withstand the current. In total there needs to be 4 half-bridge modules (CAS300M17BM2), 4 primary side diodes (C5D25170H) and 8 secondary side diodes (C4D40120H) to realise this converter. In the future there will be higher voltage and current rated MOSFETs/half-bridge modules and diodes, like the 3.3 kV rated half-bridge module discussed earlier, and by using these higher rated components, a standard 2 level full-bridge can be used instead, as seen in figure 3.7, which will decrease the amount of components and size of the converter.

Moving onto the low converters, assuming that the low powered systems need around 2 kW of power in total and likewise this is in a normal situation spread over two grids and two converters per bipolar line, but in case of failure of one battery or grid, one power grid should be able to provide this. One converter should be able to provide 1 kW of power, so the current through the primary side is 2.5 A and through the secondary side is 71.4 A. With the current technology, it is possible to realise such a converter using a standard 2 level full-bridge (from figure 3.7) instead of a higher level one as 400 V needs only switches with a minimum breakdown voltage of 800 V due to cosmic radiation. The 1.2 kV 78 A SiC half-bridge module from Wolfspeed (CAB016M12FM3) is chosen for this converter as it is able to withstand the voltage over it with the cosmic radiation degradation taken into account and it can easily withstand the current going through it. Further for the diodes the 650 V 50 A SiC diodes from Wolfspeed (C5D50065D) was chosen for the diodes on the secondary side, which also needs to be used in parallel (2 minimal) to be able to withstand the current. In total there needs to be 2 half-bridge modules (CAB016M12FM3) and 4 secondary side diodes (C5D50065D) to realise this converter.

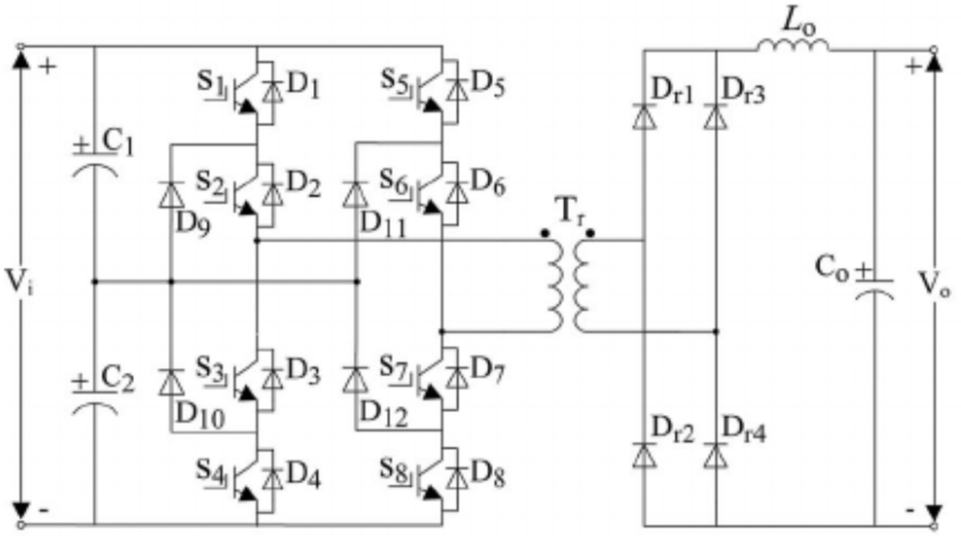


Figure 3.16: Schematic of a three level phase shifted full-bridge converter. Obtained from [21].

3.4.2. Non-isolated converter design

Assuming that the the motors get at most 1050 kW power and there are four motors on the aircraft, so about 287.5 kW per motor, but in case of motor failures or battery failures, the worst case scenario that is taken into account is that only two motors work. So at most 575 kW power goes to one motor, which is distributed along two lines (±1.5 kV), so the power per line is 287.5 kW. The voltage needs to be stepped down to 400 V, which will increase the current from 193.3 A to 725 A. It is needed to let the switches be able to withstand 1.5 kV at max and with the current technology of 1.7 kV SiC MOSFETs, it is needed to make the converter a three level converter as then the voltage stress on the switches will only be 750 V. With the future technology of 3.3 kV SiC MOSFETs or higher rated switches, only a normal 2 level converter can be used which reduces the size and cost by a bit. By making it a two phase three level interleaved buck converter, as seen in figure 3.17, the current stress on the switches will be 362.5 A and with these values a switch can be chosen: the 1.7 kV 380 A SiC half-bridge module from Wolfspeed (CAS380M17HM3) seems like a good suit for this application as it is able to withstand the voltage over it and current through it. In total there needs to be 4 half-bridge modules (CAS380M17HM3) to realise this converter.

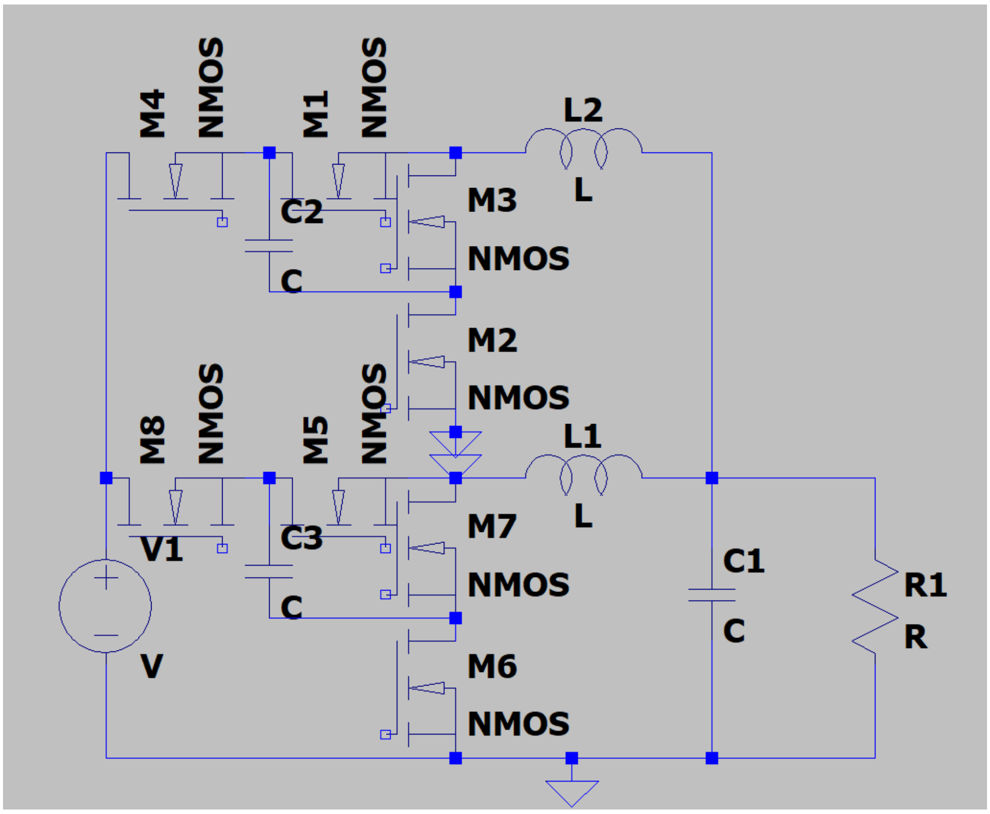


Figure 3.17: Schematic of a three phase three level interleaved buck converter

3.4.3. Inverter design

It is needed to convert DC power into AC power for the synchronous motor and this inverter will provide this conversion. As mentioned before the assumed maximal power that goes to the motor is 575 kW at ±400 V or 800 V and due to the synchronous motor being a six phase motor, it is needed to use two three phase inverters, so the maximal power provided per inverter is only 287.5 kW. As mentioned before a three level three phase flying capacitor converter is being used, as seen in figure 3.18 and the voltage stress on the switches using this topology will only be 400 V, so the switches have to be at least able to withstand 800 V due the degradation by cosmic radiation. Using equation 3.1, the line current can be calculated, which is 415 A with a power factor of 1 and line voltage of 400 V. The 1.2 kV 425 A SiC half-bridge module from Wolfspeed (CAB425M12XM3) meets the requirements for this converters as it is able to handle the voltage and current. In total there needs to be 12 half-bridge modules (CAB425M12XM3) to realise this converter.

$$P = \sqrt{3} \cdot V_{line} \cdot I_{line} \cdot pf \rightarrow I_{line} = \frac{P}{\sqrt{3} \cdot V_{line} \cdot pf} \tag{3.1}$$

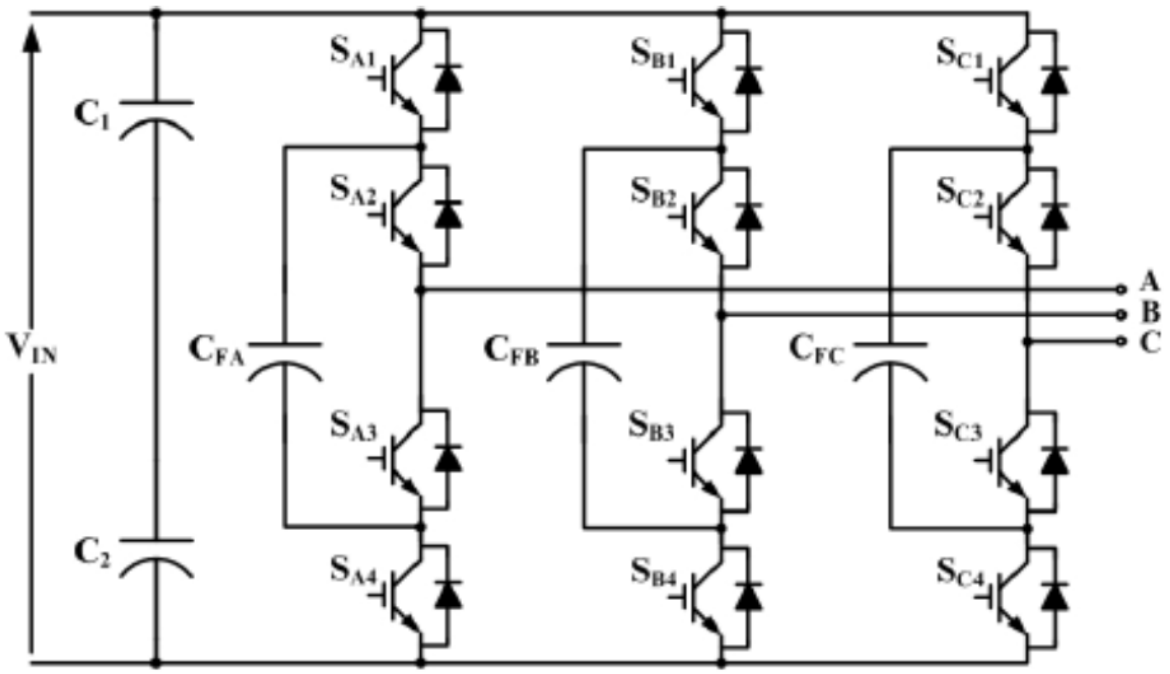


Figure 3.18: Schematic of a three level three phase flying capacitor inverter. Obtained from [22]

3.4.4. Component losses

These converters produce a lot of heat and this is mostly due to the switch losses and diode losses. The ambient temperature in the aircraft can become as hot as 200-250 °C [23][24]. Therefore, it is needed to provide sufficient cooling for these devices and for that we need to know how much heat gets produced. For the switches it is mostly the switching losses and conduction losses that contribute to the heat production and for the diodes it is mostly the conduction losses that contribute to the heat production.

The switching losses in switches is calculated as followed:

$$P_{sw,sw} = (E_{on} + E_{off}) \cdot f_{sw} \tag{3.2}$$

where:

- $P_{sw,sw}$ = Switching losses (W)
- E_{on} = Turning-on switching energy (J)
- E_{off} = Turning-off switching energy (J)
- f_{sw} = Switching frequency (Hz)

The conduction losses in switches is calculated as followed:

$$P_{sw,c} = R_{DSon} \cdot I_D \tag{3.3}$$

where:

- $P_{sw,c}$ = Conduction losses (W)
- R_{DSon} = On-state resistance (Ω)
- I_D = Drain current (A)

The conduction losses in diodes is calculated as followed:

$$P_{d,c} = V_F \cdot I_F \tag{3.4}$$

where:

- $P_{d,c}$ = Conduction losses (W)
- V_F = Forward voltage (V)
- I_F = Forward current (A)

In table 3.6, the varies losses per component (one module/diode) have been calculated for their converter use case at a very extreme situation (junction temperature of 150°C). This is a situation that is not expected to happen but has to be taken into account to assure that it can still operate with adequate cooling even in extreme situations: flying with only two motors (575 kW per motor), one battery failing and a very high junction temperature of 150°C. At lower temperatures the losses are much lower due to the on-resistances, switching energies and forward voltages being lower. In table 3.7, the total switch and diode losses of an individual converter at an extreme situation can be seen. These losses are based on the values in table 3.6 and the amount of switches and diodes. The losses for the 800 V inverter seems high compared to the other converter losses but when comparing it to the normal operation power of 287.5 kW, it is a loss of roughly 4% and thus appropriate.

Converter	Total switch and diode losses (W)
3 kV to 800 V isolated DC/DC converter	1225.6
800 V to 28 V isolated DC/DC converter	218.48
3 kV to 800 V non-isolated DC/DC converter	3878.4
800 V inverter	12,474

Table 3.7: Total switch and diode losses per converter at T_j = 150°C and $f_{sw} = 20$ kHz

3.5. Estimated total power converter mass

The estimated weights for all different power converters are included in table 3.8. The value obtained for the EMC/EMI filter is based on existing filters for similar ratings. Estimating the weight of each converter and inverter has proven to be more challenging, General Electric and Boeing have a goal specific power of 19 kW/kg and 26 kW/kg respectively, both for a continuous 1 MW power rating [25]. Alternatively, a different three-level inverter discussed in [26], has a specific power of 12 kVA/kg. A safe estimate for the specific power would then be 15 kW/kg. For a 287.5 kW application this would result in 19.2 kg per inverter. Increasing the specific power to 20 kW/kg would result in 14.4 kg per inverter. Considering that the weight difference is less than 0.6% of the total allowed propulsion system mass, the lower more reasonable estimation for specific power will be assumed.

Looking at the full-bridge DC-DC converters discussed in [27], [28] and [29], the specific power of these converters is 1.2 kW/kg, 5.9 kW/kg and 9.1 kW/kg. A safe estimate of the specific power would then be 5.4 kW/kg. For a 30 kW application this would result in 5.6 kg per converter and for a 1 kW application this would result in 0.2 kg per converter. Increasing the specific power to 9.1 kW/kg would result in 3.3 kg per converter for a 30 kW application and 0.1 kg per converter for a 1 kW application. For the two phase interleaved buck converter, the specific power of different converter are being looked at:

- A two phase interleaved boost converter with a specific power of 24.2 kW/kg [30].
- A three phase interleaved boost converter with a specific power of 21.4 kW/kg [31].
- A four phase interleaved buck converter with a specific power of 11.7 kW/kg [32].
- A two phase dual interleaved buck-boost converter with a specific power of 7.4 kW/kg [33].
- A six phase interleaved buck-boost converter with a specific power of 7 kW/kg [34].

Although the converters are of different types and phase, it still gives an indication of the specific power of a two phase interleaved buck converter. A safe estimate of the specific power would then be 14.3 kW/kg. For a 287.5 kW application this would result in 20.1 kg per converter. Increasing the specific power to 24.2 kW/kg would result in 11.9 kg per converter for a 287.5 kW application.

The different weight and quantity for each converter can be found in table 3.8, which also includes the total weight of all the converters in the systems.

Component	On-resistance (mΩ)	Drain/Forward current (A)	Switching energy (E_{on}&E_{off}) (mJ)	Forward voltage (V)	Conduction loss (W)	Switching loss (W)
Isolated $\pm$1.5 kV-$\pm$400 V						
CAS300M17BM2 (MOSFET)	14.5	20	6	-	5.8	120
C5D25170H (primary side diode)	-	20	-	1.9	38	-
C4D40120H (secondary side diode)	-	37.5	-	1.9	71.3	-
Isolated $\pm$400 kV-$\pm$14 V						
CCS020M12CM2 (MOSFET)	23	2.5	0.1	-	0.14	2
C5D50065D (secondary side diode)	-	35.7	-	1.5	53.55	-
Non-isolated $\pm$1.5 kV-$\pm$400 V						
CAS380M17HM3 (MOSFET)	5.4	362.5	13	-	709.6	260
Inverter						
CAB425M12XM3 (MOSFET)	4.7	415	11.5	-	809.5	230

Table 3.6: Switching and conduction losses of the components at T_j = 150 °C and $f_{sw} = 20$ kHz (losses are for one module or one diode). Obtained from the available datasheets from Wolfspeed (some values are extrapolation from the graphs in the datasheets).

Converter	Quantity	Estimated weight per converter (kg)
3 kV to 800 V isolated DC/DC converter	4	5.6
800 V to 28 V isolated DC/DC converter	4	0.2
3 kV to 800 V non-isolated DC/DC converter	8	20.1
800 V inverter	8	19.2
EMC/EMI filter	4	20 [35][36]
Total weight of all the converters in the system	-	417.6

Table 3.8: Estimated total weight of all power converter systems

4

Safety considerations for the electrical architecture

The safety of the electrical architecture is one of the most important things to consider when designing a propulsion system. Designing a system under perfect conditions without keeping failure in mind will lead to catastrophic failure putting individuals lives at risk.

4.1. Main failures and fault tolerance

In case of any failure the rest of the electrical architecture is expected to continue operating normally. Some of the main failures to be considered are mentioned in table 4.1.

Failure	Cause	Consequence	Risk
Battery thermal runaway	Fault or puncture in the battery	Heating cycle, eventually leading to an uncontrollable fire.	High
Motor overload	Excessive current drawn or insufficient torque	Damage to the windings, bearings and shaft.	Medium
Converter failure	Overheating and manufacturing defects	Damage to semiconductor technology.	Low
Common mode power failure	Maintenance errors, manufacturing defects or unforeseen operating conditions	Total power failure	Medium

Table 4.1: Main failures and consequences mentioned. Risk defined as either low, medium or high depending on the consequences and frequency of occurrence.

Preventing battery thermal runaway is very challenging, mitigating the consequences is a more viable solution. Different mitigation techniques are discussed in section 3.3.1 of [37]. Monitoring the battery such that measures can be taken against starting the runaway cycle should be employed to ensure safe operation. In the case of battery signs that could lead up to thermal runaway, such as battery deformation and increased internal temperature, the battery should be disconnected from the rest of the circuit. Disconnection could be achieved through circuit breakers or fuses.

In order to prevent damage to the different components in the electrical architecture, in case of failure, the faulty component should be disconnected from the rest of the system. The entire architecture was designed to be able to operate even with certain component failures. In case of any failure related to the motor subsystem, whether this is the converter, inverter or motor itself, this entire subsystem is disconnected. This way damage is mitigated from the rest of the system, and the non faulty components in the subsystem abstain from unnecessary damage. In case that a main line converter experiences failure, this converter is disconnected, but the second identical converter takes over the entire load. All the main line converters were designed to be able to withstand the entire load such that normal operation of the rest of the system can continue operating. This can be achieved by allowing the switches between the converters in figure 4.1 to conduct, such that the entire system operates through the remaining functioning converter. Further isolated converters are used for the subsystems to provide galvanic isolation, so that in case of failure the other systems and mainly the motors are protected.

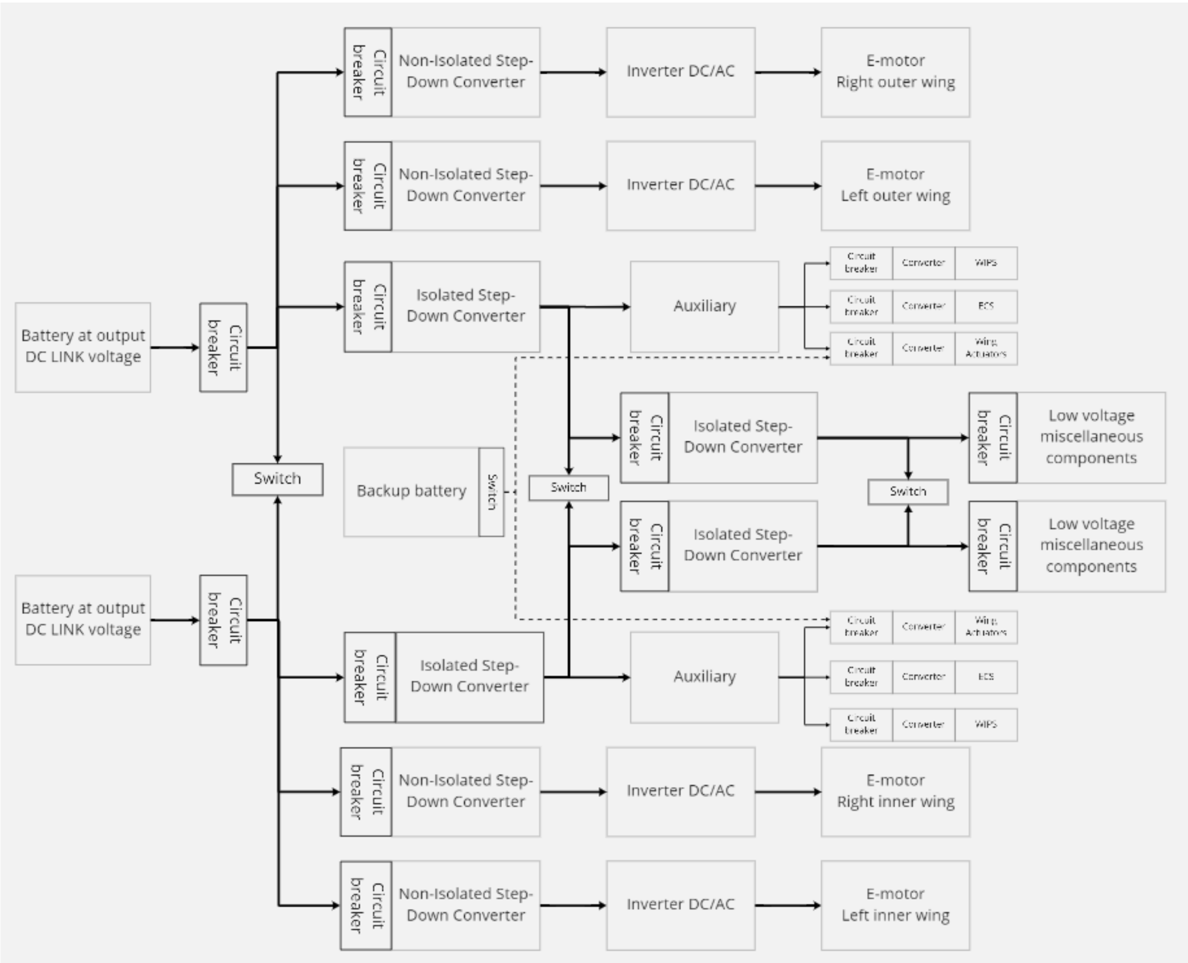


Figure 4.1: Proposed schematic of the entire electrical architecture

In case a failure has happened, it is required to locate the root of all the problems that have happened, so that they can be solved. This can be done using varies methods:

- Inspect the whole system looking for damaged parts, e.g. burn marks.
- Using heat sensors to detect abnormal temperatures (short circuits).
- Power on the system to check if there are components in the system that have been turned off or isolated by the protection devices.
- Take measurements of all the components to check for irregularities (e.g. too high currents).
- Using acoustic sensors or ultra high frequency sensors to detect partial discharges. Partial discharges emit high frequency electromagnetic waves and high frequency sound waves. By using a localization algorithm like Time Difference Of Arrival (TDOA) and the sensor inputs, the location of a partial discharge can be derived [38].
- Using high frequency current transformers (HFCT) to detect partial discharge, as a voltage is induced in the transformer when it detects a partial discharge [39].

- Using a corona camera to detect partial discharges as it can detect the amount of photons emitted by the partial discharge and with special software it can detect the partial discharge location [40].

These methods can also be incorporated in a routinely check up of the system to ensure that the system is working properly for flight and be able to spot early signs of failure.

4.2. Redundancies in case of critical component failure

Some of the most critical components regarding the electrical architecture include the main battery, the motors, the converters, and the wing actuators. In case of failure with any of these components it is still expected for the aircraft to function for the rest of the flight, with the worst case scenario resulting in an emergency landing.

Redundancies provided in case of battery failure include splitting the main battery into two separate batteries, such that if one fails the other battery can provide power for the entire system. In the scenario that both batteries fail, a small backup battery is present that is only used in this scenario to power the wing actuators, allowing for a safer immediate emergency landing.

The aircraft has four electric motors, two per wing. Alongside the decision to split the main battery into two separate ones, the decision was made to power the inner and outer motors on each wing separately with one of the two main batteries. In case one battery fails, the other can provide power for all four motors, or in case of insufficient power, fly with only two motors maintaining balance during flight. At this point it would be suggested to land at the nearest possible location due to only half the power being available for the electric system, thus not being sufficient to last the entire expected flight time. Furthermore, in order to maintain balance the batteries are located towards the centre of the fuselage between the wings. This symmetrical layout ensures that even in case of motor or battery failure balance is maintained, allowing the plane to continue flying.

In case the ECS fails, the people inside would experience discomfort, however, more concerningly, electronic equipment would no longer be able to operate normally under different environmental conditions. Humidity, air pressure and temperature can all effect the electronic equipment. At different altitudes the air pressure changes which would effect the critical field strength as can be seen per figure 3.5. Failure of the ECS was considered when choosing semiconductor technology for the power converters. Potting of electric systems and creepage and clearance distances were taken into consideration and only semiconductor technology where the values are greater than the minimum are considered, such that the semiconductors would operate normally at higher altitudes.

Furthermore, in case that the aircraft has to operate with only two motors, this could be the case with either a battery failure or a converter, inverter or motor failure. For this both the wires and system before each motor have to be handle a greater power compared to when all four motors are operating normally. This was taken into account during both design phases, chapter 3 and section 4.1 of [37], such that both can handle 575 kW maximally during take-off, instead of the expected 287.5 kW [16].

Finally, when designing the conductor radii, section 4.1 of [37], the conductor temperature was considered at 90 °C. This is a worst case scenario design decision as this temperature is much higher than normal operation, and could only occur with cooling failures.

4.3. Protection components used

Fault management technologies fall under three types of categories: Fault interrupters and isolators, Fault Current Limiters (FCL), and Fault Current Diverters (FCD). The functionality of the individual components per category are explained in [41]. Fault interrupters ensure the fault is interrupted and thereafter isolated by protection devices to maintain safe operation. Fault current limiters aid with the interruption process by limiting the energy reaching the fault, can be used to reduce the required ratings of electrical components. Finally, fault current dividers change the current direction to protect sensitive components.

For a DC aircraft application, only fault interrupters are considered. The other solutions either are not developed enough for aircraft application or add a lot of unwanted weight. Both limiting the faulty current or diverting the current does not solve the issue of the fault, interrupting and isolating the fault takes priority. The harsher environment of an aircraft has to be taken into consideration, therefore, solutions for grid applications are not necessarily applicable. The following sections will describe the fault interrupter technique options and relevance to an electric aircraft application.

4.3.1. Electromechanical (EM) circuit breakers

Interrupts faulty current by mechanically moving contact points apart. Some advantages include low conduction losses, galvanic isolation and being resettable. However, the weight of the motor drives have to be considered and during the breaking process arcing occurs. In AC systems the repetitive current zero crossing can be used to force the arc to zero, even for very high currents and voltages. This is not the case for DC systems, thus requiring arc chambers. The addition of the arc chamber has allowed for application in electrical vehicles already. Higher voltages applications, up to 3 kV, are already available [42]. The EM circuit breaker could be considered throughout the entire propulsion system, the weight of these circuit breakers have to be considered on the other hand. The existing circuit breaker from [42] are capable of handling 3 kV, weighing 23 kg but is not sufficiently rated in terms of current.

4.3.2. Solid-state (SS) power controllers

Based on controllable MOSFETs or IGBTs in order to the faulty current. Capable of interrupting DC current without arcing issues more rapidly and can also be used multiple times. It does not provide galvanic isolation, however. This could be an issue in terms of fault propagation due to faulty components not being completely disconnected from the rest of the system. Furthermore, SS interrupters have higher conduction losses during normal operation, meaning a less efficient system. Adding multiple SS based switches in series and parallel can be done in order to operate at higher voltages and currents during normal or faulty operation. Finally, higher voltage level SS power controllers are not available at the moment, due to low blocking voltages.

4.3.3. Hybrid circuit breakers

Combines the EM and SS technology for a rapid interruption with lower conduction losses and fault isolation. Normal conduction occurs through the mechanical circuit breaker with lower losses, only during the disconnecting process do the SS switches operate. This technology has already been applied for medium voltage transmission power systems. Different topologies can be realized for hybrid circuit breakers, allowing different possibilities for galvanic isolation, current capacity and weight. For aircraft application, even though it is considered newer technology and not yet commercially available, it could be used throughout the entire propulsion system.

4.3.4. Nonresettable circuit breakers

Include fuse or pyrofuse technology and breaks the circuit in case of too much current, the greater the current the quicker the circuit disconnects. Ensures fault interruption and isolation of subsystems to prevent fault propagation whilst being very light weight. They require replacing after breaking, considering that the entire propulsion system would ideally be checked in case of a fault, this is not much of a downside. One issue, however, is the fact that the circuit cannot be turned on. If for instance a battery short occurs and the breaking process takes too long, resulting in all other fuses in the system to also break. This could potentially lead to catastrophic consequences. Therefore, they should be used in combination with other current interrupting devices, as already widely used in the automotive industry.

4.3.5. In aircraft application

Throughout the proposed schematic protection devices are present. After the batteries and before the converters most notably. The circuit breakers after the battery have to be able to withstand much greater voltages and current than for instance the protection devices before the auxiliary components. Taking the advantages and disadvantages of each interruption device as well as the the confidence level, described in [41], for a target conceptual 5 MW aircraft at 1-3 kV: The fuse is the only technology with a high confidence level. Followed by the pyrofuse, solid-state interrupter and hybrid circuit breaker with medium confidence. The EM circuit breaker has a low confidence level. The criteria required for a high confidence level include at least: a high Technology Readiness Level (TRL) with feasible voltage or current ratings, technology is integrable without significant redesign of the systems, and the technology is already well adapted for reliable operation in harsh aircraft environment. If the technology does not meet sufficient of the criteria, it is either deemed at a medium or low confidence level, depending on the number of criteria met.

Throughout the propulsion system various current interrupting devices could be considered. After the batteries fuses or hybrid circuit breakers are the best options. They are the only devices being closely rated to the required peak current and voltage ratings of the propulsion system. Taking changing environmental conditions into account, no currently available fuses or hybrid circuit breakers are available. Both provide galvanic isolation in case of a battery failure. The hybrid circuit breakers tend to have lower forward resistances compared to fuses, leading to a more efficient system. However, this is at the cost of a lot more weight. The added weight is an acceptable trade-off to realise an overall more efficient design. Given a more efficient system, the battery would have to provide less power to account for the losses, thus allowing the battery weight to be reduced, compensating for the added mass of the hybrid circuit breaker.

The rest of the propulsion system has much lower current and voltage levels, thus more options could be considered. The reduced weight of fuses is desired. However, as mentioned previously the inability to reconnect components to the system could have catastrophic consequences. The low voltage auxiliary like cabin lighting could still make use of fuses, reducing the added weight, reconnecting the device of lower importance is unnecessary when considering the aircraft safety. When considering more important devices, the EM circuit breakers and SS power controllers both have great disadvantages that are accounted for in a hybrid solution. Therefore, future hybrid circuit breakers are the preferred solution. The low conduction losses, galvanic isolation and DC operation are desired throughout the propulsion system. Ensuring proper isolation and a greater efficiency at the cost of a slightly heavier system.

4.4. Main certification requirements

During the design process certain certification requirements have to be considered. Most of the requirements mentioned will only refer to the design process. Very little can be said regarding manufacturing and testing. The main requirements according to the EASA [43] and FAA [44] for an Electric and/or Hybrid propulsion system (EHPS) as well as how the requirement has been taken into account is mentioned in tables 4.2 and 4.3 respectively.

Section	Requirement	How its taken into account in the design
EHPS.15	The following effects, as a minimum, must be regarded as Hazardous EHPS Effects: 1. Uncontrolled fire; 2. Complete inability to isolate the components that could cause a hazard to the aircraft;	1. The most apparent source of uncontrollable fire is due to battery thermal runaway, mitigation techniques discussed in [37]. Insulation around the wires also aids heat isolation, minimizing heating surrounding components. 2. In case of any component failure, circuit breakers are able to isolate the component from the rest of the system. The rest of the system would be able to operate regardless of a component failure.

EHPS.40 Ratings and operating limitations	1. Ratings must be established for Take-off Power and/or Thrust and for Maximum Continuous Power and/or Thrust, as well as for Emergency Ratings if Emergency Ratings are intended to be used. 2. The Maximum permitted duration for the use of ratings other than Maximum Continuous Power and/or Thrust Rating must be established.	1. The maximum embedded power at one time is 2 MW, and 575 kW in case take-off occurs with only two motors. All power converters and wiring systems were designed to be able to withstand the maximum power during take-off. 2. The battery was designed such that the propulsion system can operate for the entire journey time. Take-off and thus maximum power was calculated to be 7.66 minutes.
EHPS.50 Materials	1. The suitability and durability of materials used in the EHPS must be established for the intended design conditions of the system. 2. The design values of the relevant properties of materials must meet or exceed the properties assumed in the design data over the lifetime of the EHPS.	1. For the power converters, wiring and battery different materials are discussed and compared. The most suitable material is chosen for each application. 2. Material properties were considered when designing the power converters, wires and batteries.
EHPS.90 EHPS Critical Parts	An Engineering Plan, the execution of which establishes and maintains that the combinations of loads, material properties, environmental influences and operating conditions, including the effects of parts influencing these parameters, are sufficiently well known or predictable, by validated analysis, test or service experience, to allow each EHPS Critical Part to be withdrawn from service at an Approved Life before Hazardous EHPS Effects can occur.	Throughout the design process, different environmental conditions, like cosmic radiation for semiconductor material for example, were considered. The operating conditions and effects influencing safety are known and taken account for.
EHPS.370 Electrical power generation, distribution and wiring	1. The electrical power generation, distribution and wirings of the EHPS for any sub-system, as applicable, must be designed and installed to supply the power required for operation of connected loads during all intended operating conditions. 2. Operation of connected loads must have no detrimental effects on the Electrical power generation, distribution and wirings.	1. During the design process the maximum power was considered throughout the system, this occurs during take-off. At all other times the power throughout the system is much less and thus the electrical architecture should be able to handle all operating conditions. 2. In case of any component failure, said component can be disconnected from the rest of the system. Ensuring no damage to the rest of the system. Under normal operation there are no expected consequences to the rest of the system.

EHPS.380 Propulsion Battery	If the EHPS contains a Propulsion Battery, the Propulsion Battery must be designed and constructed so as to provide the required power supply for the electric engine(s) of the EHPS in order for the intended aircraft application to perform its mission.	The battery was designed to provide enough power for the entire expected flight time. Even in case of battery failure, safety considerations like a backup battery have been considered to ensure a safe flight.

Table 4.2: EASA special conditions and requirements for electric/hybrid propulsion systems

Section	Requirement	How its taken into account in the design
23.2100 Weight and center of gravity.	• The applicant must determine limits for weights and centers of gravity that provide for the safe operation of the airplane. • The applicant must comply with each requirement of this subpart at critical combinations of weight and center of gravity within the airplane's range of loading conditions using tolerances acceptable to the Administrator. • The condition of the airplane at the time of determining its empty weight and center of gravity must be well defined and easily repeatable.	The weight for each subsystem was mentioned and considered during the design process. Trying to keep the entire distribution system under 1650 kg, as stated in the requirements proved to be challenging. The plane schematic designed and mentioned in [16] has taken balance and centre of gravity of the entire aircraft into consideration.

23.2105 Performance data.	• Unless otherwise prescribed, an airplane must meet the performance requirements of this subpart in - – Still air and standard atmospheric conditions at sea level for all airplanes; and – Ambient atmospheric conditions within the operating envelope for levels 1 and 2 high-speed and levels 3 and 4 airplanes. • Unless otherwise prescribed, the applicant must develop the performance data required by this subpart for the following conditions: – Airport altitudes from sea level to 10,000 feet (3,048 meters); and – Temperatures above and below standard day temperature that are within the range of operating limitations, if those temperatures could have a negative effect on performance.	During the design process of the power converters and energy distribution system the changing environmental conditions were considered. The semiconductor devices used within the power converters have their performance limited at higher altitudes due to cosmic radiation and change in air pressure for example. The peak altitude and larger temperature ranges were all considered.
23.2250 Design and construction principles	• The applicant must design each part, article, and assembly for the expected operating conditions of the airplane. • Design data must adequately define the part, article, or assembly configuration, its design features, and any materials and processes used. • The applicant must determine the suitability of each design detail and part having an important bearing on safety in operations.	Throughout the design process different materials and operating conditions were considered. Through the considerations, it was decided whether the materials were suitable for the application and thus also safe to use.
23.2260 Materials and processes	The applicant must determine the suitability and durability of materials used for parts, articles, and assemblies, accounting for the effects of likely environmental conditions expected in service, the failure of which could prevent continued safe flight and landing.	Throughout the design process of subsystems, different materials and their suitability to this aircraft application are discussed. The most likely different environmental conditions have also been considered during the design process and taken account for.

<table>
<tr><td>23.2430 Fuel systems.</td><td>

Each fuel system must -

Be designed and arranged to provide independence between multiple fuel storage and supply systems so that failure of any one component in one system will not result in loss of fuel storage or supply of another system;
Provide the fuel necessary to ensure each powerplant and auxiliary power unit functions properly in all likely operating conditions;

Each fuel storage system must -

Withstand the loads under likely operating conditions without failure;

</td><td>The battery system was designed to provide the needed energy for the entire flight mission in [37]. The environmental conditions and the battery lifetime were also taken into account to provide the best solution for this application.</td></tr>
<tr><td>23.2525 System power generation, storage, and distribution.</td><td>The power generation, storage, and distribution for any system must be designed and installed to -

Supply the power required for operation of connected loads during all intended operating conditions;
Ensure no single failure or malfunction of any one power supply, distribution system, or other utilization system will prevent the system from supplying the essential loads required for continued safe flight and landing; and
Have enough capacity, if the primary source fails, to supply essential loads, including non-continuous essential loads for the time needed to complete the function required for continued safe flight and landing.
</td><td>The propulsion system was designed with multiple component failures in mind. Most critical components like the batteries and converters consist of two components per application. Such that if one fails the rest of the system can still operate sufficiently. Even in the worst case that both batteries fail, a back-up battery is provided for a last resort emergency landing. The safety devices connected to the most essential components also have the ability to turn on again after disconnection, such that the device can be protected from another system failure first but then continue operating.</td></tr>
</table>

Table 4.3: FAA 14 CFR Part 23 applicable aircraft requirements

A lot of the requirements partially mention the assembly or testing of the aircraft, due to the thesis project being strictly on the design process, these requirements were not mentioned. All the listed requirements regarding the design process of the distribution system by both the FAA and EASA were met and thus the distribution system suffices the minimum safety requirements for certification.

5 Results and discussion

5.1. Intergroup results and discussion

It is first needed to summarize what the other two subgroups have researched and have achieved for the overall project to asses the work that has been done in this thesis.

The Energy Storage and Transfer subgroup has done research on the energy storage, wiring design and safety considerations for thermal runaway and arcing and partial discharges. They have design a Li-S battery with a high power density (600-650 Wh/kh) and the overall battery system for the aircraft and flight duration. The total mass of the battery system comes to around 1067 kg. Furthermore, they have designed a wiring system (e.g. conductor material, sizing and connectors used) that is able to withstand the workload that is required for the flight. The total mass of these wire system comes to around 284.5 kg. The in-depth research and design can be read in [37].

The Motors and Power Distribution for AEA subgroup has done research on the motors and the power distribution system in all-electric aircraft. They have designed the overall topology of the aircraft and the power distribution for the different systems. The total mass of different auxiliary systems (Wings Ice Protection Systems (WIPS), Environmental Control System (ECS) and Flight Control System (FCS)) have also been calculate to be 233 kg. Moreover, they have design the motor of the aircraft. Mainly the characteristics and technology of motor are of importance. The surface mounted permanent magnet synchronous motor (SPMSM) has been chosen for this aircraft. The total mass of one motor comes to around 153.7 kg which is including the power electronics, which comes down to 128.9 kg per motor if those are neglected. The total weight of the motors is given as 515.6 kg. The in-depth research and design can be read in [16].

The overall mass of the propulsion system is 2284.7 kg and including the different auxiliary systems the mass is 2517.7 kg. Looking back at the program of requirements in chapter 2, the mass exceeds the expected propulsion system mass by a lot and this means that the payloads needs to be reduced to compensate for the higher mass of the propulsion system. Although not all requirements were met, the overall project has achieved a functioning all-electric propulsion system for a small aircraft.

5.2. Intragroup results and discussion

Now looking back at the objectives of this thesis: designing different power converters used throughout the propulsion system of a 9 PAX electric aircraft and outlining safety considerations for the electrical architecture that needs to be taken into account for the propulsion system of a 9 PAX electric aircraft. Using the program of requirements, as stated in chapter 2, research and design choices were made to fulfill these objectives. An overview of the design choices will be provided now:

- Power converters:
  - The system is split up into three voltage levels: 3 kV (±1.5 kV), 800 V (±400 V) and 28 V (+14 V).

  - For the 3 kV (±1.5 kV) to 800 V (±400 V) non-isolated converter for the motors, a two phase three level interleaved buck converter is being used.
  - For the 3 kV (±1.5 kV) to 800 V (±400 V) isolated converter for the medium powered systems, a three level phase shifted full-bridge converter is being used.
  - For the 800 V (±400 V) to 28 V (+14 V) isolated converter for the low powered systems, a two level phase shifted full-bridge converter is being used.
  - For the 800 V (±400 V) inverter (DC-AC for the motors, two three level three phase flying capacitor converter are being used in parallel to create a six phase.
  - The semiconductor device used for the switches are silicon carbide based and most of the silicon carbide based switches are MOSFETs.
  - The breakdown voltage of switches are derated due to cosmic radiation to 50%, which was taken into account when designing the converters and choosing the switches.
  - For the 3 kV (±1.5 kV) to 800 V (±400 V) non-isolated converter for the motors, the 1.7 kV 380 A SiC half-bridge module (CAS380M17HM3) from Wolfspeed was chosen.
  - For the 3 kV (±1.5 kV) to 800 V (±400 V) isolated converter for the medium powered systems, the 1.7 kV 225 A SiC half-bridge module (CAS300M17BM2), the 1.2 kV 40 A diode (C5D25170H) and the 1.2 kV 40 A diode (C4D40120H) from Wolfspeed were chosen.
  - For the 800 V (±400 V) to 28 V (+14 V) isolated converter for the low powered systems, the 1.2 kV 78 A SiC half-bridge (CAB016M12FM3) and the 650 V 50 A SiC diode (C5D50065D) from Wolfspeed were chosen.
  - For the 800 V (±400 V) inverter (DC-AC) for the motors, the 1.2 kV 425 A SiC half-bridge module (CAB425M12XM3) from Wolfspeed was chosen.
  - The switching frequency is chosen to be 20 kHz.
  - The total mass of all the converters in the system is estimated at 417.6 kg, which is about 25 % of the total mass of the propulsion system.

- Safety considerations for the electrical architecture:
  - Four main failures have been discussed with possible measurements to combat these:
    - Battery thermal runaway.
    - Motor overload.
    - Converter failure.
    - Common mode power failure.
  - Several methods have been proposed in this thesis on finding the cause of failures.
  - Several redundancies have been taken into account in case of critical component failure:
    - The battery is splitted into two batteries.
    - The inner and outer motor on each wing is powered separately with one of the two batteries.
    - The aircraft is able to fly with only two of the motors.
    - The switch technology, creepage and clearance distances and potting of electric systems were taken into consideration in case of ECS failure.
    - The wires and systems are able to handle much greater power.
    - The conductor radii are designed for higher temperatures than normal operation.
  - With the usage of fuses and hybrid circuit breakers critical faults propagation can be mitigated.
  - The main requirements according the EASE and FAA have being discussed in this thesis.

The overall design of the converters is able to handle the required loads, even in extreme conditions and with failures, but what is still missing is the design using future technology. This is of course very difficult to do as it is unpredictable what the future technology can bring us, e.g. better breakdown voltages, better current ratings or even different semiconductors devices or materials. The usage of GaN based switches needs to be further researched as it is quite a promising solution, the limitation of breakdown voltage does not allow for it be used more throughout the propulsion system. When higher voltage rated GaN based switches are available the overall weight and efficiency of the system will improve drastically. Furthermore, the estimation of the losses and masses can be done in a more elaborated way as it is now based on only the datasheets of the switches and the existing converter models and this can be quite different from the actual converter when it is build and tested. Additionally, the motor characteristics were not fully researched as too much time was spent on the overall topology and design of the converters, but this needs to be researched further in order to fully design the aircraft.

Most of the safety considerations were made when designing the actual systems and have been discussed in their respective sections (also in the different subgroups theses [16][37]). Although the section was a bit unnecessary as most of the considerations were already thought about when designing the overall electric propulsion system and have been discussed before, it is still very important to have safety consideration as failures in an aircraft can have disastrous consequences.

6 Conclusion

The goal of this thesis was to provide appropriate power converter designs for an all-electric aircraft application following some requirements and discuss the safety considerations taken during the design process. The different semiconductor devices were compared, with the currently available technology SiC based switches are the most suitable for the application. Different environmental conditions were discussed and accounted for. The possible converter topologies were compared and the most suitable were chosen. Finally, a weight estimation was provided for all the different inverters, allowing for an estimated propulsion system weight. The safety considerations taken during the design process were first discussed via the main failures and fault tolerance of the system. Redundancies in case of component failure were also mentioned, to ensure even in case of failure the propulsion system is able to operate sufficiently. Different protection devices were described and their suitability was discussed for different applications within the distribution system. Finally, the certification requirements applicable were mentioned and how they were taken into account by the design.

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