Specific Power and Efficiency Projections of Electric Machines and Circuit Protection Exploration for Aircraft Applications

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***Abstract*- The purpose of this paper is to generate specific power and efficiency projections through the year 2050 for electric machines for aircraft applications. A general literature review was performed to identify the types of electric machines that are commonly used and which types have the biggest potential for future aircraft applications due to their high specific power and efficiency. A database with historical data was built to include parameters such as weight [kg], rated power [kW], specific power [kW/kg], RPM, efficiency, year, motor cooling type, application type and motor type to allow for trend identification and accurate projections. Once the data was gathered, multiple curve fits on the historical data were generated and extrapolated to produce the projections for specific power according to conservative, nominal and aggressive projection scenarios. A different process was followed for the efficiency projections due to the scattered nature of the data. A state of the art (SoA) value for efficiency was identified through literature review and was used to create the conservative, nominal and aggressive projections for the time frames of 2030, 2040, and 2050. The efficiency and the specific power projections of EMs for 2050 are 0.989 and 50kW/kg respectively. This paper will also be examining circuit protection as it is an additional component of electric powertrains.**

I. Introduction

Electric motors are used in electric or hybrid vehicles to convert electric power to mechanical shaft power. Their efficiency is indepedent of altitude which makes them advantageous compared to conventional combustion engines for aircraft. For electrified aircraft applications, high specific power and high efficiency are two of the most important requirements due to the stringent weight restrictions. There exists a rich historical data for electric machines designed for industrial applications, and other transportation systems. However, the use of electric machines in primary power systems in aircraft is a rather new concept, and thus there is a very limited amount of information available in literature.

In this paper, we present a collection of publicly available information on electric machines, and identify the ones suitable to be used in electrified aircraft propulsion systems. The goal of this work is to use this historical data to identify important trends, perform future projections, and eventually to inform system-level analysis of future electrified aircraft concepts.

To this end, a technical approach was formulated. Electric machines are a crucial component to a powetrain, and the most suitable ones for aircraft applications must be identified among a variety of options. First, types of electrical machines were explored to identify the advantages, disadvantages and characteristics of each type. Then, to project the specific power (SP) and efficiency of electrical machines, parameters such as cooling types, weight, power, efficiency, specific power and application were gathered to create a database of historical information. This database was then used to identify trends in specific power and efficiency. This paper presents the different trends identified and the specific power and efficiency projections generated through 2050. Finally, circuit protection devices with the potential to be used in electric powertrains for aircraft applications were explored. Projections for the efficiency and specific power of the circuit protection allow for more accurate benefit assessment and prediction of future electrified aircraft with less uncertainty. Due to the lack of documentation on historical and current data on efficiencies and specific power of circuit protection, projections of these properties could not be made.

II. Types of Motors

An initial review of the types of motors was performed to identify the types that are most appropriate for electrified aircraft applications. Some typical important characteristics of electric machines for any type of electric vehicle (EV) or hybrid electric vehicle (HEV) are high efficiency, a wide speed range, and most importantly, high specific power (HSP) and power density. HSP, i.e. high power-to-weight ratio, is crucial especially for aircraft applications as weight is a stringent constraint and thus can significantly affect the extent of electrification and diminish the fuel burn benefits.

This paper focuses on electric machines with high specific power. The HSP machines that were studied include permanent magnet synchronous machines (PMSM), induction machines (IM), and wounded field synchronous machines (WFSM) [1,2,5]. Superconducting electric machines are also considered HSP machines but are not in the scope of this paper, due to the early technological stages in aircraft applications. The following paragraphs provide a brief overview of the types of motors in more detail, data collection on the characteristics of EMs, curve fitting, and future projection steps of the technical approach followed in this paper.

A. *Permanent Magnet Synchronous Machines*

PMSMs are widely used in EV and HEV currently. They are widely considered to be the most attractive option for electric aircraft applications due to their high efficiency and HSP [3], but they are costly to manufacture, while also having a complex control system and less well-behaved failure modes than other motor types [1]. When compared to the other types of motors PMSMs have the highest efficiency, which makes them the most competitive motor type despite the higher cost. PMSMs are currently used in automotive applications and are considered to be the most appropriate option for aircraft applications as well [1-3].

B. Induction Machines

Three phase AC induction machines such as the squirrel cage IM have many advantages that render them appropriate options for both automotive and aviation applications [6]. One of the biggest advantages is that they have a long-life cycle and low maintenance and are therefore more cost effective than the PMSMs. IMs also have high efficiency, but it is approximately 1-2% lower than the efficiency of PMs [6]. One of the benefits of using an IM compared to the PMSMs is that they are significantly more affordable and due to their robustness very reliable. On the other hand, they are characterized by a much higher mass and volume as well as a high current at constant torque [6]. Finally, IMs also have a low torque density, which puts them at a disadvantage to PMSMs. Despite their disadvantages IMs used to be in high demand in the EV/HEV industry in the automotive world before PMSMs were introduced. Even in the aviation industry IMs are considered as a viable and attractive option due to their high efficiency, specific power and robustness[6].

C. Switched Reluctance Machines

SRMs are overall robust in nature and are therefore very suitable for high-speed applications [1,6]. They are also characterized by high specific power, although lower than that of the PMSM, but still higher than that of the IMs, as well as high power density [6]. These characteristics make them appropriate for aircraft applications, but they are complex in control, and they have ripple torque, which renders them not the best option when compared to the other EMs [1].

D. Wound Field Synchronous Machines

The WFSMs are a specific type of PM motor characterized by flexibility in applications and how simple and practical their autonomous control schemes are. Additionally, the WFSM have excellent fault mitigation capabilities and complete field controllability [6]. Unfortunately, they do have an inherent difficulty of implementation in high speeds and a comparatively lower power density than the other types of EMs, which does not make them suitable for aircraft applications [3]. Despite the current lack of technology, advancements are being made. NASA Glenn Research Center is currently working on a high efficiency Megawatt WFSM, which could have promising applications for electrified aircraft in the future [4].

E. Overall Electric Machine Comparison

The two main parameters that are crucial in identifying whether an electric machine is a competitive option for aviation applications is the specific power and the efficiency associated with it. As it has been mentioned in aviation weight is a major constraint and despite the fact that EMs are not the largest source of weight addition in an electric powertrain (the battery is), any reduction in weight of the electric powertrain makes electric propulsion more viable. To accurately understand which type of EM is the most appropriate for aircraft application an understanding of where the EM technology stands today and how it compares within different types of EM is crucial. Fig. 1. compares the mass and the power of EM that have been already built and tested, some that are currently being tested and some that are not yet built. It can be seen that the 2016 SoA on the figure shows a specific power of 2.2 kW/kg for oil cooled aircraft generators [2]. A drastic increase in SP is necessary to be able to support electrification in aircraft. It can be seen from the arrow that there is a shift of the EM towards lower mass and higher power and therefore a higher SP. The built and tested EM's, depicted with the green squares in Fig. 1., show higher masses and lower power capabilities, while the partially tested and not built ones show promisingly high power and low mass, with the vision being to reach 22 kW/kg for aircraft generators.

Additionally, apart from a high level comparison of the SoA EMs and future EMs it is also important to investigate in more detail the characteristics of specific types of EMs, such as the ones that were introduced in the previous section. Fig. 1. depicts a comparison of the different types of motors in terms of specific power vs rotational speed and cooling type. Fig 2. was generated from the database with all of the EMs that were collected for this paper. From Fig. 2. we can see that the PM motors have the highest available specific power of up to approximately 10 kW/kg for both air and liquid cooling types. PM motors can also be found to operate at a variety of rated RPM, which highlights their capability of operating in different conditions. IMs can be found to have higher speeds and relatively high SP. It is important to note that IM data was not as publicly available. Fig. 2 also depicts some unspecified and WFSM motors, which have a variety of SP, but not as high as it is observed for PMs. To sum up, Fig. 2 shows that the PM motors are capable of providing the highest SP out of all the EMs presented at a range of speeds and maintaining relatively high power. These characteristics indicate that PM motors would be the most appropriate type of motor for EV/HEV aircraft applications.

Table I [7] also provides a clear and detailed comparison between the different types of EMs that further highlight PM motors have the highest efficiencies and power densities, which can be correlated to SP. Taking into consideration the literature review that was performed and is shown in Fig. 1., Fig. 2. and the information that is listed in Table I PM motors seem to fit the HEV aircrraft applications best.

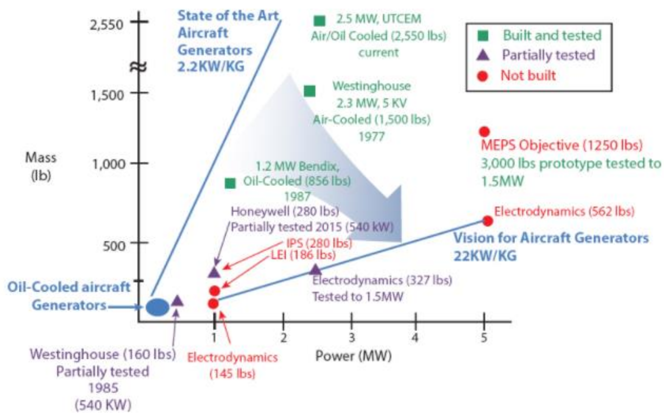

Fig. 1. EM Evolution [2]

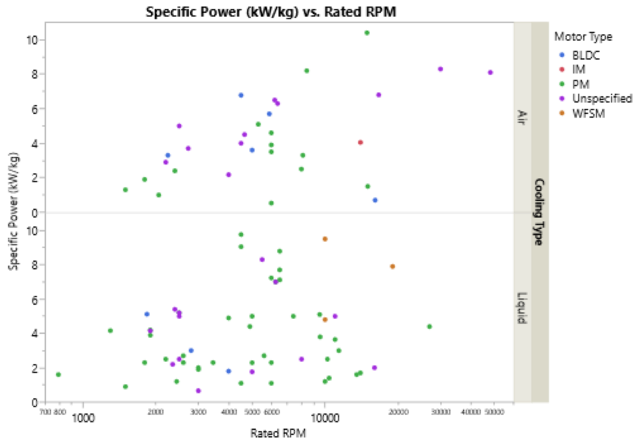

Fig. 2. EM Types Speed vs Power Comparison

TABLE I
EM TYPE GENERAL FEATURES COMPARISON [7]

Comparison of the main features of prototype and marketed PMSM, PM-assisted SynRM, IM and SRM technologies for HEV/EV applications.

General features	PMSM	PM-assist. SynRM	IM	SRM
Fault tolerance	✓	✓	✗	✓
Robustness	✗	✗	✓	✓
Reliability	moderate	moderate	high	moderate
Wide speed range[1]	✓	✓	✗	✓
Close loop control simplicity	✓	✓	✓	✓
Preferred torque control algorithms	FOC, DTC	FOC, DTC	FOC, DTC	DITC, ADITC, IDITC
Field weakening operation capabilities	✓	✓	✓	✓
Torque ripple	low	low	low	very high
Acoustic noise	low	low	low	moderate
Maximum power limitation by technology	virtually not[2]	virtually not[2]	virtually not[2]	yes[3]
Power conversion topologies	VSI	VSI	VSI	Asymmetric H-Bridge
Efficiency and power densities	**PMSM**	**PM-assist. SynRM**	**IM**	**SRM**
Typical efficiencies at constant torque region[4]	91.3–95.8%	87.0–93.0%	79.0–86.0%	85.1–89.0%
Power densities of current technologies (kW/l)[5]	3.3–10.2 kW/l	6.8 kW/l	2.5 kW/l	2.6–4.5 kW/l
Costs	**PMSM**	**PM-assist. SynRM**	**IM**	**SRM**
Overall technology costs	high	medium	medium	low
Relative material costs	10/10[6]	4.8/10[7]	5.9/10[6]	3.1/10[6]

III. OPPORTUNITIES FOR IMPROVEMENT

This section will cover potential improvements to electric machine cost, efficiency, and specific power. First, one of the main drawbacks of PMSM is its manufacturing cost. This is primarilly due to the fact that PMSMS use rare earth and heavy rare earth materials which can be very costly and have a higher cost of maintenance. A significant cost reduction can be achieved by using new magnetic materials that are non-rare earth and non-heavy rare earth. Additionally, the cost can be even further reduced by simplifying the existing cooling system [6].

The efficiencies that are currently available are also not as high as desired for electric aircraft applications. PMSMs have the highest efficiency of approximately up to 96%. By using high performance alloys and decreasing the copper and iron losses in all types of electric machines, the efficiency could be increased significantly [7].

As it has been mentioned before the specific power of the EM is one of the most important characteristics when an EM type is selected for electric aircraft applications. PMSMs were once again the best option in terms of specific power but the current SoA is not what it needs to be in order for electric aircraft to be as successful as they can be. An increase in specific power and power density can be achieve by increasing the operation speed for electric machines and adding high performance cooling for increased power [11]. There is still major advancements to be achieved in order for the EM specific power and power density to reach the technology levels that are required for electrified aircraft.

Some future technologies that will allow such advancements in EMs include advanced materials and advanced cooling techniques. In terms of the magnetic material new designs that do not include heavy rare-earth materials should be introduced [5]. An additional IM design, where rare earth magnets are introduced could make that type of EM more efficient and with a higher specific power, although it will increase the overall cost [1] and maintenance required. Finally, advanced thermal systems should be introduced as they could significantly improve the characteristics of the current SoA [6].

IV. SPECIFIC POWER AND EFFICIENCY PROJECTIONS FOR EM

A. Data Collection

To accurately project the specific power and efficiency of the motors an exploration of the advancements that have been made in the past is necessary to identify potential trends. A literature review was performed to collect as much information as possible on the HSP motors that could be applied in aviation and have been applied in the automotive industry. The data that was collected included: weight [kg], rated power [kW], specific power [kW/kg], RPM, efficiency, year, motor cooling type, application type and motor type. These parameters were used to further understand the potential trends in specific power and efficiency over the years. By looking at the different cooling types (air vs liquid) were also investigated by comparing power (kW) and SP (kW/kg). The PM motors have the highest SP overall and are mostly characterized by liquid cooling. Liquid cooling can be more effective for larger motors such as the ones used in aircraft, while air can be more effective for smaller EMs. Since PM motors are mostly characterized by liquid cooling the conclusion that they are the most appropriate EM for aircraft applications is further highlighted.

B. *Specific Power Projections*

Initially, the historical specific power data that was gather was plotted against time so that a trend could be identified. Fig 3. depicts the data that was collected while putting together the database of EMs. The specific power data that was collected for different years was plotted against the equivalent year [1,6,7,12-38].

To allow for variance in the projections three scenarios with the logistics fit were created, a conservative, a nominal and an aggressive one Fig. 4. The logistics equation that was chosen for the specific power projections takes into account a horizontal asymptote, L , an optimized growth rate, k, and the inflection point y0.

$$SP = \frac{L}{1 + e^{-k(y-y0)}} \quad (1)$$

The logistic equation in combination with the historical data were used to find the projections of specific power for a conservative case with an inflection point of 2020, a nominal case with an inflection point of 2030 and an aggressive case with an inflection point of 2040. The logistical equations were then used to find specific power values up to year 2050 as seen in Fig. 5. Table II shows the asymptote, growth rate and respective inflection point that were used to find the specific power for each condifence level. Each of the inflections points represent years at which the technology advancements would slow down, and it simulates an S curve, Fig. 5. The three projection curves were then plotted against not only the historical data that was gathered, but also projected values of the NRC 2016 report [8] as depicted in Fig. 5. and Fig. 6. The historical data that is shown in Fig. 5 and Fig. 6 represent an adjusted maximum value for each of the years that data was collected for. After examining the data points of specific power for each of the years the adjusted maximum was calculated by multiplying the maximum value with the ratio of the maximum over the median value for that year. This allowed for a single point for each year, rather than multiple entries per year.

TABLE II
SPECIFIC POWER PROJECTION CURVE PARAMETERS

Confidence Level	Asymptote, L	Growth Rate, k	Inflection Point, y_0
Conservative	16.3	0.1411	2020
Nominal	37.8	0.1213	2030
Aggressive	94.3	0.1134	2040

TABLE III
EFFICIENCY PROJECTION CURVE PARAMETERS

	Conservative	Nominal	Aggressive
k	0.01	0.025	0.045

TABLE IV
SPECIFIC POWER AND EFFICIENCY PROJECTIONS

Timeframe	Confidence Level	Specific Power (kW/kg)	Efficiency (%)
SoA	—	6	0.96
2030	Conservative	9.2	0.963
	Nominal	13.2	0.968
	Aggressive	16.1	0.974
2040	Conservative	10.8	0.967
	Nominal	20.4	0.975
	Aggressive	33	0.983
2050	Conservative	11.3	0.970
	Nominal	24.3	0.980
	Aggressive	50	0.989

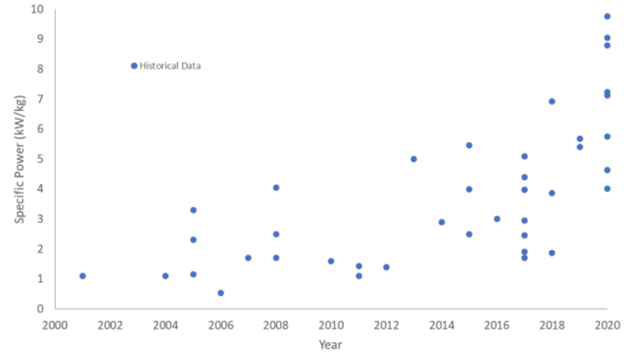

Fig. 3. Historical Data [1,6,7,12-38]

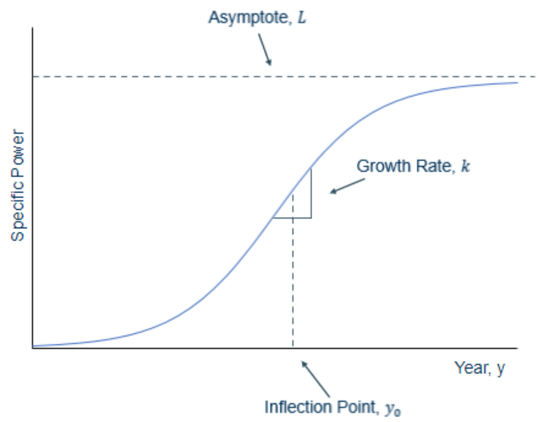

Fig. 4. Example Logistics Curve

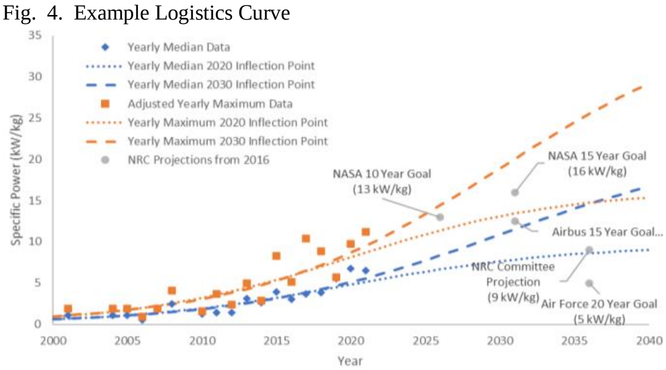

Fig. 5. Logistics Curve Projections with Original Data [1,6,7,12-38]

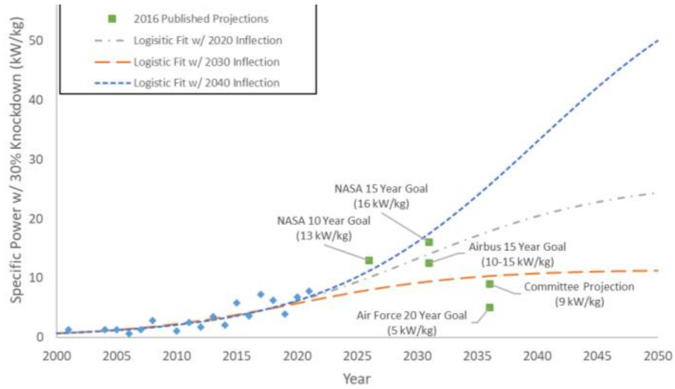

Fig. 6. Logistics Knockdown Factor Projections [1,6,7,12-38]

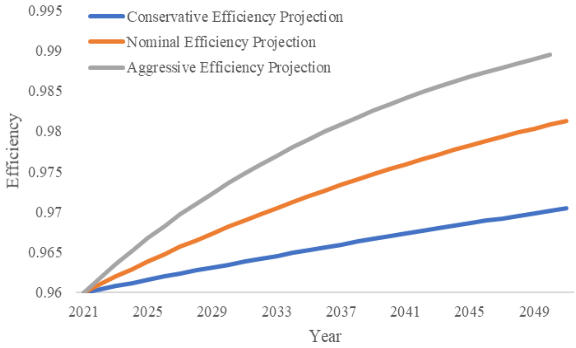

Fig. 7. Efficiency Projections

In Fig. 5 none of the projected curves fall in line with any of the projected values of the NRC. Seeing that the projected values were generated by maximimizing the R^2 that was generated by using the logistic equations and the historical data an additional consideration had to be defined. A 30% knockdown factor was applied to the historical data to account for additional weight to account for a smaller breakdown voltage at high altitude. The final projections calculated then coincided with NASA's 10- and 15-year goals [8], as it can be seen in Fig. 6.

C. *Efficiency Projections*

The efficiency data that was collected for the EMs were extremely scattered and therefore an accurate curve fit was not identified. A different approach to the projections was followed for the efficiency of EMs. By examining the SoA efficiencies that are currently available for aircraft applications a SoA efficiency of 0.96 was used as a starting point for the future projections. A fit that converged at a maximum efficiency of 1 was then applied using equation 2. Where k is a constant value that was adjusted to imitate the conservative, nominal, and aggressive projections. The parameter k also represents the yearly improvement rate, or the reduction by k precentage of the losses. The equation was then used to project the efficiency values through year 2050.

$$Efficiency = 1 - (1 - Efficiency_{SOA}) * (1 - k)^{Year-2021} \quad (2)$$

Fig. 7. depicts the three projections, conservative, nominal and aggressive through year 2050. The k values that were used to achieve the depicted efficiencies are summarized in Table III.

V. Circuit Protection Devices

Circuit protection devices are an additional component of an electric propulsion powertrain for aircraft applications. They are used to protect against overcurrent and overvoltage of the powertrain. Furthermore, they are used to prevent any chance ignition of surrounding fuel or oil which can lead to accidents. Additionally, they can handle many switching operations so that the maintenance requirements of the power train can be minimized. Just like any other component in the power train, circuit protection devices also should have low weight and high specific power.

There are multiple types of circuit protection devices that could be used in electric aircraft. The vacuum circuit breaker (CB) is applicable for high voltage AC power distribution [9]. The solid-state circuit breaker (SSCB) is the current state of the art for aircraft with voltage requirement up to 270Vdc, but for voltage requirements that are higher the technologies are not readily available [9]. One major disadvantage of the SSCB is that the on-state resistance is higher than the mechanical circuit breakers that are available. The high on state resistance leads to an overall lower efficiency and creates the need for more cooling weight. Not considering the higher cooling weight due to the decreased efficiency SSCB are characterized by low weight [9]. CBs with an arc chamber were then considered, which is another SoA option for application up to several MW. It has low on state resistance but a very complex geometry and therefore added weight. One major disadvantage is that hot plasma circulates within the arc chamber, which decreases the overall protection against explosions [9]. A hybrid CB is also an attractive option for electric aircraft as it is a combination of SSCB and CB with arc chamber, the two SoA options for aircraft applications [9-10]. The low on state resistance of the CB with the arc chamber makes a great cooling system for the SSCB. Furthermore, the switch off process carried out by semiconductors makes the heavy and complicated arc chambers unnecessary [9-10]. This concept of hybrid CB is still under development and there is not enough data to create efficiency and specific power projections.

When looking at the entirety of the electric powertrain is important to also quantify which components will affect the total weight. Batteries are the most significant component of the powertrain and therefore their projections of efficiency and specific power are the most impactful. Followed by EMs and power electronics such as converters and inverters. Circuit protection, although significant, has a minimal effect on the overall weight, efficiency, and specific power of the overall powertrain.

VI. Conclusions and Future Work

In conclusion, three projections for each of the timeframes in question were generated. A conservative, nominal, and aggressive value for specific power and efficiency for 2030, 2040, and 2050 for EMs can be found in Table IV. To create the projections for SP a logistics fit with inflection point on years 2020, 2030, and 2040 were generated as it was seen in Fig. 6. For the efficiency projections a curve fit could not be generated due to the scattered nature of publicly available data. Due to this any curve fit that was applied to the data produced a very low R^2 error indicating the inaccuracy of the curve fit. Therefore, an initial point of efficiency as a SoA was selected based on the literary research and projections were generated based on that initial point. The most aggressive projection for 2050 yielded a maximum specific power of 50 kW/kg and an efficiency of 0.989.

Due to the scattered nature of the efficiency data for EMs the efficiency projections that are presented are somewhat arbitrary seeing that only a single point was used to generate them. Further data identification is necessary to be able to fit a curve to historical data. Possible separation of the data in application type, cooling type, or motor type could produce fruitful results, but in the scope of this paper the limited available data did not allow for such investigations.

In terms of the circuit protection devices, a literature research was performed to identify the most appropriate device for aircraft applications. A hybrid CB was identified as the most appropriate option for electric aircraft due to the combination of all advantages of the SSCB and the CB with the arc chamber. Unfortunately, since the hybrid CB is not technologically ready, historical data on specific power and efficiency were unavailable. Efficiency and specific power projection for up to 2050 were not produced for hybrid CB due to that lack of historical data. As this technology evolves further, projections on efficiency and specific power should be revisited and quantified.

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