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Review

Commercial Aircraft Electrification—Current State and Future Scope

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Abstract: Electric and hybrid-electric aircraft propulsion are rapidly revolutionising mobility technologies. Air travel has become a major focus point with respect to reducing greenhouse gas emissions. The electrification of aircraft components can bring several benefits such as reduced mass, environmental impact, fuel consumption, increased reliability and quicker failure resolution. Propulsion, actuation and power generation are the three key areas of focus in more electric aircraft technologies, due to the increasing demand for power-dense, efficient and fault-tolerant flight components. The necessity of having environmentally friendly aircraft systems has promoted the aerospace industry to use electrically powered drive systems, rather than the conventional mechanical, pneumatic or hydraulic systems. In this context, this paper reviews the current state of art and future advances in more electric technologies, in conjunction with a number of industrially relevant discussions. In this study, a permanent magnet motor was identified as the most efficient machine for aircraft subsystems. It is found to be 78% and 60% more power dense than switch-reluctant and induction machines. Several development methods to close the gap between existing and future design were also analysed, including the embedded cooling system, high-thermal-conductivity insulation materials, thin-gauge and high-strength electrical steel and integrated motor drive topology.

Keywords: more electric aircraft; electrical machine; actuation; power generation; propulsion; aircraft electrification

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1. Introduction

The electrification of aircraft systems has seen a continuous upward trend in recent years. This revolution not only offers reduced emissions, but also unlocks the potential for more energy-efficient aircraft with newer architecture. In the aerospace industry, electrification is moving towards the two concurrent technology trends: higher electric technologies, which are equipped with more electric equipment than the traditional mechanical, hydraulic or pneumatic sources of power; and all-electric technologies. It is also possible to observe a disruptive transition towards hybrid and full-electric propulsions. These conventional systems were powered using aircraft engines, where a variety of mechanisms were used to extract the power. Pneumatic power is generated using air bleed systems in the engine compressor, whereas electric and hydraulic systems receive their power through an engine gearbox using mechanical transition.

In an MEA, the complexity of the systems has largely increased together with a large increase in capacity, speed and range. Conversely, a standard pneumatic system has many drawbacks such as low efficiency; heavy, complex pipes; and ducting running through aircraft. Hydraulic systems often suffer from high maintenance cost and a lack of reliability. Leakage problems are also commonly seen in these traditional systems, which are difficult to locate and largely time-consuming to repair. Disruption to normal operation will ground the aircraft, leading to passenger and operator inconvenience as well as generating costs. However, any of the shortcomings inherent in mechanical, pneumatic, or hydraulic systems are not seen on a carefully designed electrically powered system. They are more efficient, light and relatively flexible. As the aircraft technologies evolve from secondary to primary power systems, a higher power electrical machine with increased power density and low weight is essential. This will form a key enabler for low-environmental-impact air travel. Several concepts and architectures have been introduced and assessed by organisations around the world, namely, Boeing, Airbus, Rolls-Royce, NASA, DLR and ESAero.

With the increasing demand for power-dense and lightweight electric motors in MEA, the key subsystems that are currently electrified include propulsion, power generation and actuation. Studies have shown several potential benefits are associated with replacing or augmenting the traditional fuel-based propulsion system, including reductions in aircraft emissions, fuel burn and noise. It was identified that power generation and storage are the two greatest hurdles faced by electrically powered aircraft designs in conjunction with achieving good aerodynamic efficiency and reduced weight. The replacement of hydraulic actuators to electrically powered actuation systems is also becoming quite common in many commercial aircraft.

This paper reviews the current state-of-the-art of MEA technologies, identifies any trade-offs between conventional and electrically powered systems, and analyses different machine topologies and key development areas including weight reduction, thermal management and material advancement [1,2].

2. Evolution of More Electric Aircraft

The idea of electrification in aircraft emerged in 1940, where the Boeing B-29 Super fortress implemented different levels of electrification that included actuators for landing gear. For non-propulsive commercial aircraft, the electrical system only emerged in 1967 where Boeing 737 introduced various electrical avionics and cabin equipment.

In 1980, Airbus A320 introduced 'Fly by Wire' system technology that significantly reduced weight, offering additional space for other components in the aircraft. In addition to that, agility, controllability, accuracy, reliability, efficiency and torque density were also improved by this technology [3].

Another key milestone was when Airbus A380 implemented the hybrid electro-hydraulic actuation system along with electrically actuated thrust reverser, followed by the Boeing 787, which was the first large commercial aircraft to have electrically powered environmental control system as well as electric brakes and de-icing system. A change in trend from constant frequency generation derived from generator and speed gearbox to variable frequency generator with power electronics has also been seen in the recent days [1,2,4]. An overall view on how power ratings of on-board electrical generators have varied from 1940s to 2010s can be observed in Figure 1. As displayed in the diagram, a gradual increase in the power rating of aircraft machines can be seen from 1950 to 2020.

2.1. More Electric Aircraft

The More Electric Aircraft uses advances in electrical systems and machine technology to improve the efficiency using lower power consumption and reduced size and weight. This enables aircraft to implement bleed-less engines with simplified architectures and lighter electrical subsystems. The main benefits offered by MEA include:

- Better reliability;
- Improved volume and weight of subsystems;
- Improvement in the system power efficiency;
- Better maintainability;
- Rapid and cost-effective insertion of technology;
- System level optimisation and new capabilities.

Figure 1. Power rating of short- to medium-range aircraft (red) and medium- to long-range aircraft (green) [5].

These benefits of MEA will lead to improved fuel consumption, much lower emissions and a large reduction in the overall cost [1,2,6].

2.2. Aircraft Electrical Power Systems

Aircraft electrical power systems are self-contained networks of components made up of electrical generators, power electronics, actuators and energy storage devices. They can generate, distribute, store and use the electrical energy. Key aircraft subsystems required to make these technology advancements are categorised into four sections:

(a) Architecture and interconnect: propulsion, insulation, connectors, whole aircraft and protection.
(b) Electrical energy storage: energy storage, energy management, energy generation and infrastructure.
(c) Electrical machines: motors, generators, transformers, actuators and drivers.
(d) Power electronics: power conversion, switching, monitoring and control [2].

2.3. Aircraft Components That Are Electrified

With the increasing demand for lightweight, power-dense and efficient electric motors in MEA, there are three main aircraft architectures that are currently being electrified (Figure 2). The key aircraft sub-systems that will be focused in this paper includes, propulsion, power generation and actuation.

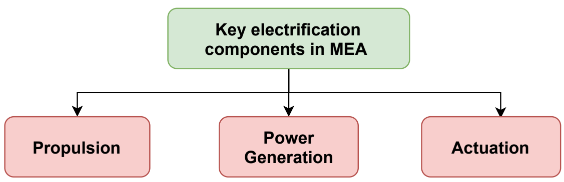

Figure 2. Key components to be electrified in a MEA.

3. Propulsion

Electric propulsion technologies have gained increasing attention in the recent years particularly for fully electric and hybrid electric architectures. This is due to the ever-growing specifications and demand for cleaner, quieter, more reliable and safer air travel [7]. One of the key drivers of the technology is optimisation of power density in these propulsion motors [8]. Studies have shown several potential benefits associated with replacing or augmenting the traditional fuel-based propulsion system, including improvement in the aircraft emission, fuel burn and noise. Using electrical power distribution to augment propulsion was one potential way to improve design freedom and future aircraft. Identifying a viable, efficient aircraft with electrified propulsion system is a complex process. A key challenge would be to obtain improvement in electrical power control components, distribution and conversion, to reduce the electrical system weight without compromising aircraft safety [9].

3.1. Requirements/Barriers of Electrically Propelled Aircraft

Electrically powered transmission are preferable due to the reliability, flexibility, lower drag and having the ability to shut down prime movers. The current envisaged electrically propelled aircraft has two technical barriers, one which is related to the electrical system and those are linked directly to the aircraft applications planned and are under construction. Some of the barriers are as follows:

- **Battery performance**—Reduced weight and good battery storage capacity are vital for hybrid and all-electric aircraft architectures. If batteries are not designed to be lightweight, the aviation industry will be forced to discontinue the use of batteries in their system. Currently the highest commercial battery energy storage has energy density range from 150 to 250 Wh/kg; however, an ideal energy density in these batteries would be at least 500 Wh/kg. In addition, to improve energy density, long battery life-cycles and better recharging speeds are also essential for battery-powered aircraft [10].
- **Battery safety**—Effective hazard containment systems for batteries to meet airworthiness and safety of public concerns are vital in aircraft systems.
- **Power density**—High power density, light and efficient motors and generators are essential for configuration that requires multiple distributed fans to obtain high-power propulsive efficiency. Hybrid/turbo-electric architectures will also require these types of generators/motors to convert the shaft power to electricity, in conjunction with lightweight gearbox to reduce the rotational speed of the turbine to a much slower rate suitable for the generator.
- **Power electronics**—To convert, switch and condition the power whilst maintaining minimum electrical and heat losses.
- **Light and safe high voltage distribution**—The large quantities of electrical power is transmitted from batteries/generators to motors that provide propulsion is done at high voltages to reduce the resistive losses [1,11,12].

3.2. Recent Developments in Electric Aircraft

Various pieces of research and developments have taken place in the recent days on more electric aircraft topologies. However, various smaller-scale full-electric aircraft have been successfully demonstrated worldwide. A few recent examples of successful manned electric aircraft can be observed in Figure 3.

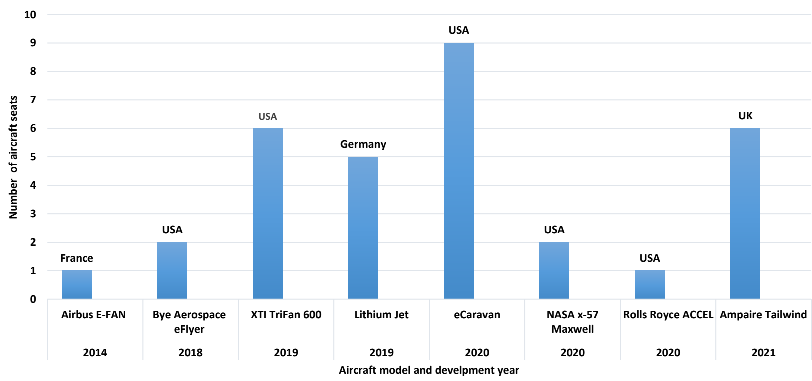

Figure 3. Recent developments in electric aircraft.

3.3. Electric Aircraft Propulsion Architectures

There are three broad aircraft architectures within the area of electric propulsion. These rely heavily on electric technologies such as motors, generators or batteries. The reduction in carbon dioxide emissions will be heavily dependent on the performance of the components and the configuration.

An overview of the propulsion architectures available can be observed in Figure 4. The three main areas of propulsion are hybrid electric, turbo electric and all-electric system. These three points can be further divided into different architectures which are explained in a later section.

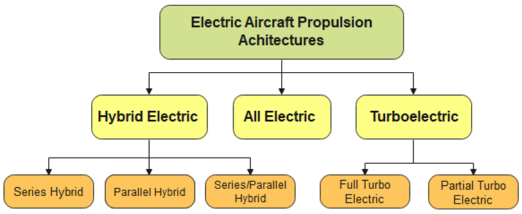

Figure 4. Overview of the different propulsion architectures.

1. **All electric**: Aircraft with small seats are feasible in the near future but for the development of a fully electric passenger aircraft, drastic improvements in drivetrains are required. All electric architecture uses the energy stored in the battery to drive one or multiple fans. This system will be heavily dependent on the weight and storage capacity of the battery [1]. Battery sources are the only source of propulsion power on battery-powered fully electric aircraft [11]. An example of a fully electric aircraft is the Airbus E-fan which was a two-seater electric flight launched in 2014 [13]. Fully electric propulsion architecture can be observed in Figure 5. As displayed in the diagram electric motor and battery forms the two main components in this system.

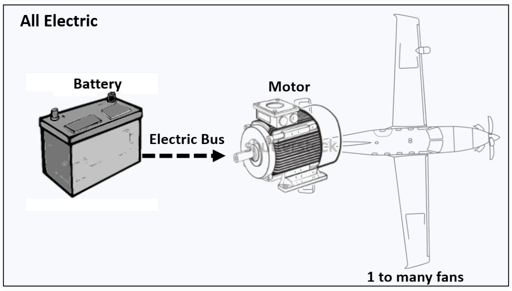

Figure 5. Fully electric aircraft propulsion architecture [11].

2. **Hybrid electric**: Hybrid-electric large aircraft concepts are proposed from mid-2030 based on the integration of traditional turbo engine into the propulsion system. Various level of hybridisation can be achieved and the degree of hybridisation (H) with respect to power and energy can be defined using Equation (1), where P_m is the electric motor power and E_b is the battery energy. The parameters H_p and H_e will be 0 on a non-electric aircraft and 1 in all-electric configurations. In turbo electric architectures, H_e is 0 as they do not carry stored energy while hybrid architecture have them greater than 0 [14].

$$H_p \quad = \frac{P_m}{P_{tot}} \times H_E = \frac{E_b}{E_{tot}} \tag{1}$$

In hybrid-electric propulsion systems, electrical power is produced using generators. These generator systems are bigger than motor systems due to the massive demand for larger-power electronics, to generate electrical power and torque. Some aircraft such as the Boeing 787 uses multiple smaller generators rather than one large generator to increase the flight-critical system's power system reliability [11]. More details on the configuration can be found in [14].

- **Parallel hybrid**: A battery-powered motor and a turbine engine is mounted on the shaft to drive the fan so that either of those can provide propulsion when required. As the internal combustion engine and the electric motor is mechanically connected to the propeller, they can contribute to the propulsion energy individually or simultaneously. It also has the advantage of only having two propulsion devices in comparison to series configuration making the overall system smaller and still achieve the same performance. However, the propeller's rotational speed is not always at the optimal speed of the engine; therefore, operation at engine's optimum region cannot be guaranteed. An example of parallel hybrid system can be seen in the SUGAR Volt's Subsonic Ultra Green Aircraft Research [9,11,15–18].
- **Series hybrid**: The benefit of series hybrid configuration is that the output power is not related to the power demand of the power train and the engine is fully decoupled from the propeller. Therefore, the engine can work at its optimal operating conditions even at different working environments. The lifespan of the engine can be lengthened and the fuel efficiency of the engine will remain high for this configuration. It also has major advantage of having the flexibility of locating the ICE-generator set due to mechanical decoupling. As there is a large power loss in the combustion and energy conversion, series hybrid architecture suffers from power system efficiency. Another drawback of this configuration is the need of three propulsion devices namely, generator, motor and engine making it more expensive and bulky. It also cannot make use of the engine and motor's maximum combined potential power as it is not mechanically connected to the load.
- **Series/parallel hybrid**: This configuration is a mixture of series and parallel configurations. The structure of this architecture makes the power distribution very flexible whilst allowing the motor and engine to operate in the optimum region. Series architecture requires the most complex gearing or clutch mechanism and energy management but it is the most advanced hybrid propulsion system available.
  Overall, the series-parallel is the most complex configuration amongst the three hybrid options; however, series configuration enables the engine to operate at its best operating condition [11,19,20]. Overview of the hybrid architectures can be observed in Figure 6. The components displayed in the diagram is an approximate representation of electrical machine images, it is much more advanced in reality.

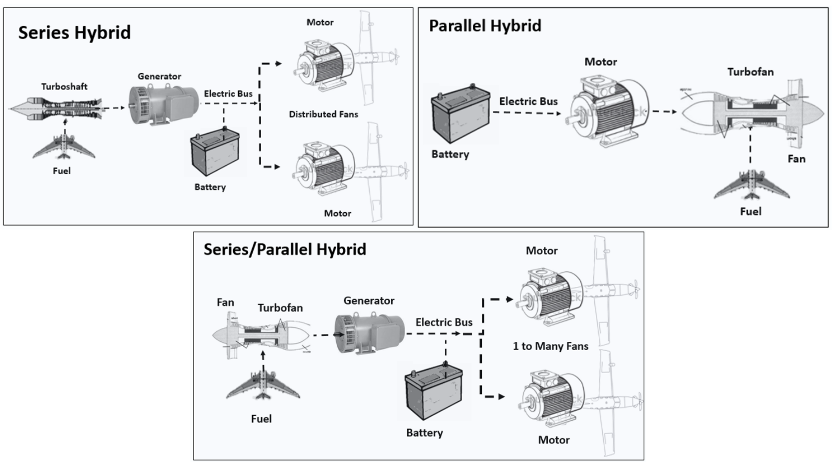

Figure 6. Overview of series, series/parallel and parallel hybrid architectures [21].

3. **Turbo electric**—The turbo electric concepts are largely dependent on electrical power system technology advances. These technologies include: power electronics for converting; conditioning and distributing power; generator systems for electrical power generation; energy storage motors and high power aircraft distribution system for circuit protection. Full or partial turbo electric configurations are not reliant on batteries at any phase of the flight for propulsion energy. It has the advantage of gaining a higher propulsive efficiency as it provides the designer more freedom with the location and number of propulsive fans. An example of a turbo electric development can be seen in distributed open rotor aircraft concept by Rolls-Royce for regional aircraft.
    - **Full turbo electric**: It uses gas turbine to drive the generator which powers the electric motors that drive the fans.
    - **Partial turbo electric**: This system is an alternative to the full turbo electric configuration, where it uses the electric propulsion to provide part of the propulsive power and the rest are provided by a turbofan which is driven using a gas turbine. The NASA STARC-ABL is an example of a partial turbo electric system. This architecture or some other variant of turbo electric system are likely to be the first options for electric propulsion systems in regional or single-aisle aircraft configurations. It is also likely to be first application that can make a significant impact in aviation carbon emission [9,11,14,15]. An overview of a labelled turbo electric architecture can be seen in Figure 7.

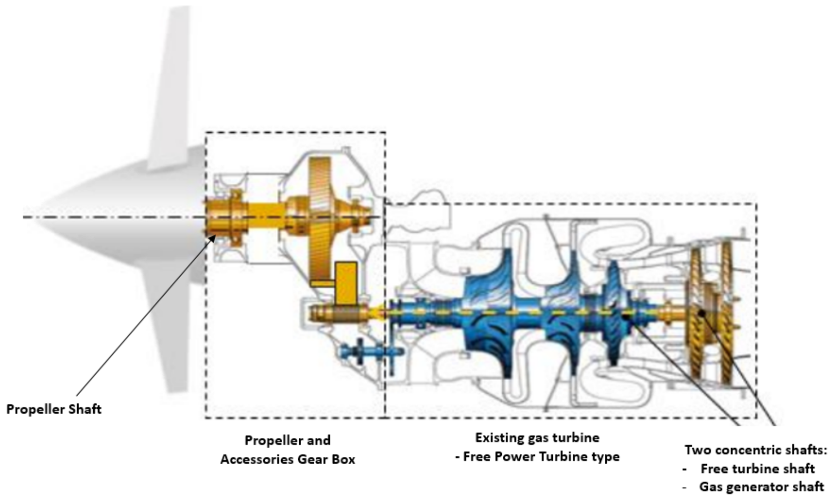

Figure 7. Turbo electric aircraft architecture [22,23].

Each of these power train architectures can be applied in various aircraft designs. Commercial aircraft generates electrical power for non-propulsive loads and mechanical shaft power for propulsive loads. Advanced propulsion design are closely related to maturation of technology therefore, any development in the technology assumptions should be explored simultaneously. For example, The size of the aircraft with all-electric solution implemented will be closely coupled with assumptions of advancement in the battery technology [6,9,21].

3.3.1. Distributed Electric Propulsion System

Distributed electric propulsion (DEP) system is another concept that has been seen in the recent years. It uses multiple motor-driven propulsors that do not share mechanical power source or mechanical driveshaft with the components that produces power. The propulsors will be combination of devices that generates thrust such as, fans or electrically-driven propellers. The power source in DEP system will be a combination of energy storage devices such as capacitors or batteries and electrical power producing devices such as, electric generator or fuel cells. NASA studied one of the earlier DEP concepts on turbo electric distributed propulsion which consists of multiple light-weight and highly-efficient motor. An example of a DEP system can be observed in Figure 8 [24–26].

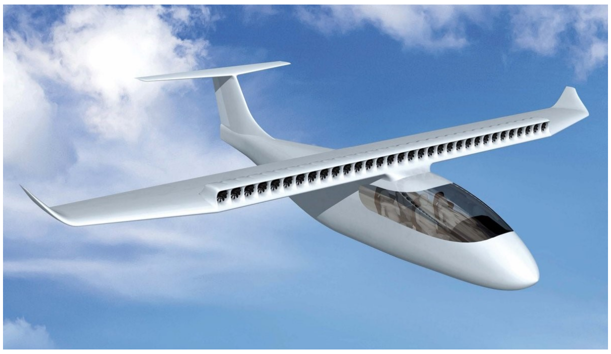

Figure 8. Distributed electric propulsion creating higher bypass ratio and lift wing [26].

3.3.2. Aircraft Propulsion Architecture and Motor Topologies

For the development of zero emission aircraft the only serious obstacle is the low energy storage capacity. Various methods of electrical energy supply already exists to provide the on-board propulsion power; however, the ideal means of achieving aircraft propulsion is by using electric motors. High speed motor designs will become a requirement for commercial aircraft in the near future. Two useful measures for determining the most suitable motor design include specific power (kW/kg) and specific storage energy (Wh/kg). Until recently, electric motors in aerospace applications were mostly used to power the on-board systems instead of being the primary propulsion mechanism [8,27–29].

Various architectures and concepts have been introduced and discussed by organisations across world, namely, Airbus, Boeing, NASA, Rolls-Royce, DLR, Bauhaus Luftfahrt and ESAero [14]. Some of the main propulsion architectures currently used in different aircraft systems can be seen in Table 1. Some data is not available at this point of time, as it is an on going development area. The power capability and specific power of different propulsion architectures can be observed in Table 2. The studies assumed various levels of component performance and electrical energy storage, depending on the assumed rate of technology development and time frame of interest. There are some missing data at this point in time on Tables 1 and 2 but with more advancement in research and technology those details could be filled in coming years.

Table 1. Aircraft electric propulsion timeline for different users [11].

Name	Time Frame	Propulsion Architecture	Component	Component Power	Component Performance
Boeing	2030-40	Parallel hybrid	Motor	1.3–5.3 MW	3–5 kW/kg
NASA N3X	2030-40	Turbo-electric	Generator Motor	30 MW 4 MW	>10 kW/kg
NASA	2030-40	Parallel turbo-electric	Generator	1.45 MW	13 kW/kg
STARCABL	-	Electric	Motor	2.6 MW	-
Airbus	2015-25	Hybrid Electric	Generator Motor	-	-

Table 2. Aircraft propulsion motor requirements [11].

	Electric System			Battery
	Aircraft Requirement	**Power Capability (MW)**	**Specific Power (kW/kg)**	**Specific Energy (Wh/kg)**
Regional/ Single-aisle	Parallel hybrid	Motor: 1–6	>3	>800
	All electric	Motor: 1–11	>6.5	>1800
	Turbo electric	Motor: 1.5–3 Generator: 1–11	>6.5	- -
General aviation and commuter	Parallel hybrid	Motor < 1	>3	>250
	All electric	Motor < 1	>6.5	>400
	Turbo electric	Motor < 1 Generator < 1	>6.5	- -
Twin-aisle	Turbo electric	Motor: 1.5–3	10	-
	Parallel hybrid	Not studied	-	-
	All electric	Not feasible	-	-

The most common motor topology used in unmanned aircraft electrical propulsion is the Brushless DC (BLDC) motor designs, which is quite similar to the AC synchronous motors with the primary difference of rotor position sensing and back-EMF waveform. BLDC motors are suitable for power drive application and has the capability to with stand torque ripple. They also have the following characteristics, high power density, low cost Hall Effect probes for controlling the commutation and concentrated full pitched winding. The two types of AC motors namely, permanent magnet (PM) and wound-field motor are also common topologies used in aircraft propulsion. Wound-field motor topology is generally undesirable for aerospace on the grounds due to susceptibility to arcing and reduced component reliability; however, permanent magnet synchronous motors (PMSMs) are preferred over BLDC motors as they offer better control and field weakening capabilities. Due to the superior power density, PM machines are also widely adopted in aerospace industry particularly in hybrid-electric architectures [30].

Induction motors (IM) are also extensively used in terrestrial application because of their manufacturing simplicity and lower cost due to the exclusion of rare-earth magnets. The stator windings on an induction machine are identical to synchronous machines; however, induction machines cannot match the PM machines when considering the power density. Performance restrictions are also seen in induction machine due to the rotor induction heating effects imposing thermal limitations [11]. Some key performance indicators against different machine topology can be observed in Figures 9 and 10 and Table 3.

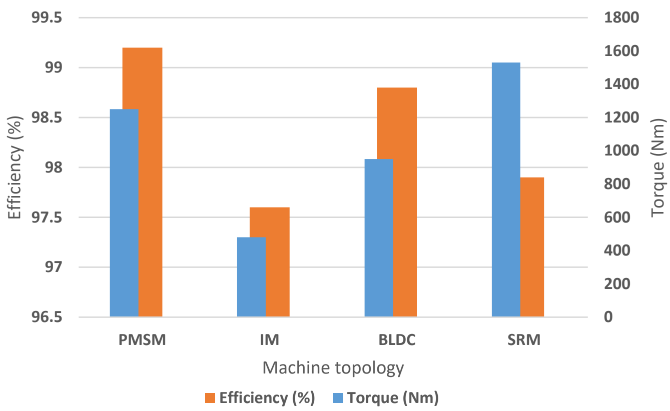

Figure 9. Propulsion machine topology comparison against different performance indicators.

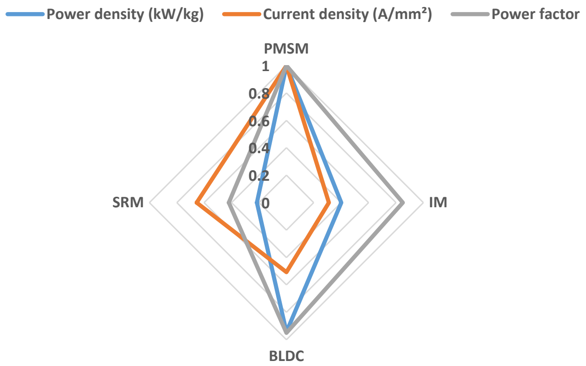

Figure 10. Key performance indicators per unit values with respect to PMSM.

Table 3. Comparison of key performance indicators for different propulsion machine topology.

Key Performance Indicators	PMSM	BLDC	SRM	IM
Weight (kg)	113.6	283.5	120.5	528.4
Speed (RPM)	11,500	15,000	9375	29,700

For commercial aircraft applications, electrical machine still needs to be developed to attain the required weight, specific power and reliability. The specific power of the machine is expected to improve by a factor of 5–10 from the current state of art. The efficiency of these machines should improve from 95% to 97/98%. High-power distribution cabling for MW class power system and circuit protection will also need to be developed. In order to obtain weight reduction and an increase in specific power the voltage of the aircraft power distribution should be improved. Development in material selection for magnets, conductors, bearing, insulator, thermally conductive materials and polymer composites could also aid in improvement of motor efficiency and power density [11]. Other than the advancements in propulsion components such as electrical machine, power electronics and batteries, a new development observed in the literature was the design of coreless PM propulsion machines by D.Lawhorn et.al. It offers low ripple, zero/negligible core loss, increased power/torque density and improved efficiency [6,31].

3.4. Power Generation

Having the constant increase in demand for performance optimisation and decrease in maintenance and operating cost have motivated aerospace industry to shift towards more electric solutions. It will utilise electrical power rather than the conventional mechanical, hydraulic or pneumatic power to improve performance and life cycle cost. As a result, a significant increase in electric power requirements on-board for aircraft can be seen. Power generation in aircraft are essential as batteries are not suitable to be the only source of power in an aircraft. This is due to the safety issues such as hazard and the significant weight associated with these batteries [32].

The main sources of power generation use Auxiliary Power Unit (APU) and turbo shaft generation. Secondary power systems are essential for the safe operation and comfort of the passengers. In a conventional aircraft the secondary power system combines mechanical, hydraulic and pneumatic power together. The total energy consumption of these systems forms approximately 5% of the total fuel burnt during the flight operation. With the advent of MEA the trend has shifted towards electrical power particularly in larger aircraft. For example, Boeing B787 traditionally had pneumatic bleed system which is not driven electrically [33,34].

3.4.1. DC Power Generation

DC power generation on aircraft was one of the early forms of power generation methods particularly used for ignition and communication systems. During these early days, the DC generators relied on wind-driven technologies and was most commonly mounted on the landing gear of the aircraft. However, the increased requirements for flight dynamics pushed the power generation industry towards engine driven generators. Low-voltage dc system that were successful in the past can no longer meet the higher requirements of current larger aircraft. For instance, the modern A380-800 that operates in 115 Vac has a total weight of 5700 kg which would be more than tripled if 28 Vdc electrical distribution system voltage was used. DC generators are still used in small modern aircraft as main and back up generation system. For example, ATR-600, Dornier 328 and Gulfstream G280 uses 28 Vdc starter-generators [5,10,35].

A timeline on DC power generation technology can be seen in Figure 11. Some outliers in the data has been omitted as no further development took place for those specific DC generators.

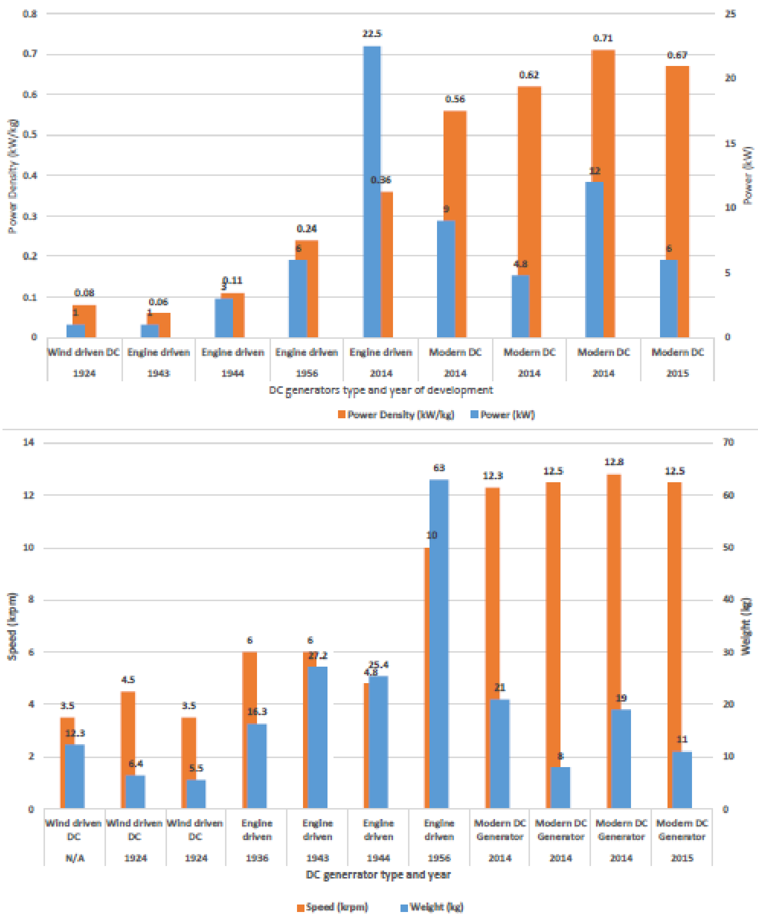

Figure 11. Dc generators in aircraft [5].

3.4.2. AC Power Generation

Increasing aircraft size and speed led to unprecedented increase in electric power together with improved specifications on power density and reliability. These changes shifted the power generation from DC to AC world-wide due to several advantages such as: smaller and lighter machine with improved power density, higher voltage and power levels and improved maintenance and lifetime performances. New challenges were introduced due to the need of managing reactive power and for having the choice of appropriate frequency and parallel operation [5].

3.4.3. AC Constant Frequency Systems

The three-stage wound-field synchronous generators are the most popular AC generators used in aircraft. This is mainly due to their inherent safety where the excitation can be removed instantaneously, allowing the machine to be re-energised using direct field control. There are three principle stages in wound-field synchronous generators, namely (1) Permanent magnet generator, (2) The main generator and (3) The exciter machine (Figure 12). The generation system is powered by the permanent magnet generator in the first stage whose rotating PMs induce a three-phase voltage in the stationary armature. The conversion of power from AC to DC is performed using a rectifier attached to the prime mover shaft. Various researches are on-going trying to integrate the different stages of the generator and achieve enhanced reliability and weight reduction. Some examples include Boeing B777, B757, B767 and B747 and Airbus A320, A330 and A340 [5,36,37].

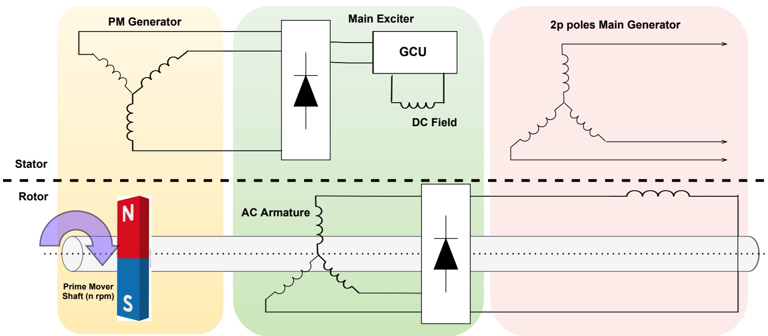

Figure 12. Architecture of the three-stage wound-field synchronous generator [6].

3.4.4. AC Variable Speed Constant Frequency System

The adopted constant speed drive used for the AC constant frequency (CF) systems contributed to increased size, weight and maintenance. Due to this reason, a new approach of variable speed constant frequency system was introduced which works without the heavy CSD (constant speed drive) whereby, the three-stage generator can be directly coupled with the shaft of main engine. In this case the generated voltage has a variable frequency therefore, to provide a constant frequency voltage, a dc link between the AC loads and AC generator can be implemented by means of an inverter and a rectifier. The Variable speed constant frequency system is still used in Boeing B777 aircraft for the 20-kVA backup generators. Another method to generate the constant frequency is by using an AC/AC converter such as the Matrix converter [5,38].

3.4.5. Power Generation Topologies in MEA

All the above systems are consolidated systems for on-board power generation; however, with the considerable shift towards MEA the traditional systems have been replaced by systems that are powered by electricity [5]. Some of the power generation and storage options in modern electric aircraft include:

- **Battery technology**: It provides high efficiency, zero emissions, low maintenance and no centre of gravity movement during flight. It has the disadvantage of increased system weight, battery recycling issues and reduction in flying range of the aircraft. For aircraft usage, Lithium ion batteries are used for large MEA and Lead Acid batteries are used for General Aviation and light aircraft; Nickel Cadmium batteries on helicopters and larger aircraft and Lithium-ion batteries in more electric aircraft. Aircraft such as, Airbus, E-fan and Boeing 787 Dreamliner uses Lithium-ion battery and has 207 Wh/kg specific energy per battery cell [39,40]. A twin-engine aircraft featured by SUGAR volt also relies on this battery technology to create a parallel hybrid propulsion system in the aircraft [11]. A block diagram which shows an overview of the battery technology can be observed in Figure 13.

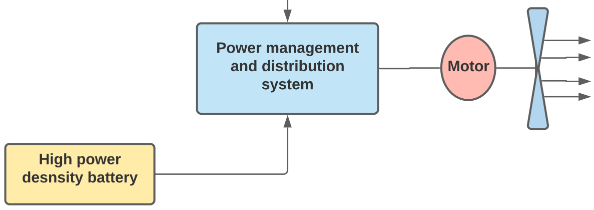

Figure 13. Battery technology used in MEA [39].

- **Super capacitors (ultra-capacitors)**: Produces higher power (kW/kg) but lower specific energy capacities than batteries. A common form of super capacitors is EDLC (electrical double layer capacitors) which stores the electrical energy in an electrostatic field, making it durable and offering fast charging and discharging rates, compared to battery technology. It excludes expensive materials such as Cobalt and Lithium in their manufacture, avoiding toxicity and flammability issues. Examples of EDLC can be seen in stop-start systems of modern road vehicles [41]. It can be an alternative to Lithium-ion batteries. Based on Lithium-ion technology, new types of hybrid supercapacitors are also currently being developed. Currently NASA Kennedy Space centre is investigating on the development of ultra-capacitors based on Graphene.
- **Hybrid electric**: It is the series/parallel hybrid arrangement of the electrical and mechanical drive components. In series arrangement, the electrical supply drives the propeller whereas, in parallel arrangement the propulsion mechanism can be driven by shaft and gears etc. Hybrid electric aircraft are classified as the logical step towards achieving the capabilities of fully electric aircraft [42].
- **Flywheels**: It stores energy mechanically and have high specific power ratio together with the capability of storing and releasing energy quickly. Recent developments in this technology have created ultra-high-speed flywheels of only tens of kilograms mass running in the magnetically levitated bearings of the housing, with a speed of more than 100,000 rpm. The general components and structure of flywheel can be seen in Figure 14. More details on the operation and principles of flywheel technology can be found in [39,41].

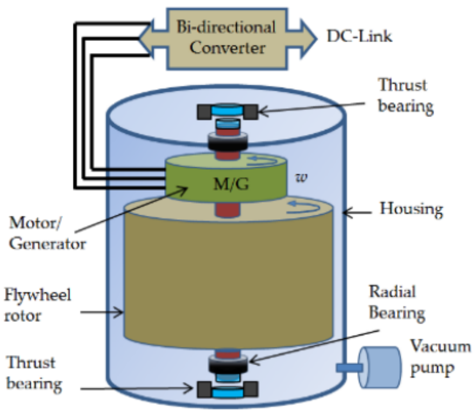

Figure 14. Flywheel technology used in MEA power generation [41].

- **Fuel cells**: It is similar to batteries and produce electricity based on a chemical reaction using chemicals such as oxygen and hydrogen. They offer high energy efficiency and low emissions as the energy is released as an electric current rather than heat. Fuel cells have demonstrated higher specific energies compared to Lithium-ion batteries even though their rate of energy release is much lower. This system requires a hybrid system approach installation on the aircraft to meet the power demands during landing and take-off. On-board hydrogen storage and air supply during the flight are also restricting factors for fuel cells [42]. Fuel cells was demonstrated in Boeing 787 Dreamliner by Sandia National Laboratories [43].

- **Photovoltaic technology**: The modern photovoltaic (PV) technology is developed with the silicon PC cell in USA. In the recent days there are number of PC technologies available, including organic cells, silicon-based, hybrid PV, polymer cells and thin-film solar cells. These technologies are capable of achieving efficiencies as high as 44%; however, silicon-based PV is the only suitable technology for aircraft that are solar powered due to the cost effectiveness [41].
  Power generation and storage are the two greatest hurdles faced by electrically powered aircraft designs in conjunction with achieving good aerodynamic efficiency and lowest weight. The current state of art of battery technology has limitations regarding the low values of specific power which restricts the performance on aircraft designs, to slower speed and shorten endurance flight envelops. Development of ground-based support to cope with the rapidly advancing aerospace technology are also becoming a necessity, for example, having novel airport features such as providing electrical power to support the take-off run [39].

3.4.6. Electrical Machine for Power Generation Application in Aircrafts

Electrical power on a conventional aircraft is generated using a wound-field synchronous generator using a PM exciter machine. The field current control is performed by the generator control unit to regulate the terminal voltage. The machine will be driven mechanically using the main engine shaft with the aid of a constant velocity gearbox. Power requirements are constantly rising in more electric aircraft, with estimation of more than 500 kW per engine in the future. Integration of engine is an alternative option to:

- Reduce system complexity.
- Reduce failure probabilities.
- Increase system efficiency and power density.

The expected power density specification for MEA can be seen in Table 4.

Table 4. Electrical machine expected power density specification for MEA [5] .

Timeline	Expected Power Density	Supporting Technology
2025	10 kVA/kg	Break down strength insulating materials Additive manufacturing Liquid cooling
2035	20 kVA/kg	Magnetic material based on nanocomposite Low loss steel
2050	40 kVA/kg	The list above and superconducting material

The most common electrical machine for MEA application is Permanent Magnet (PM) or Switched Reluctance Machine (SRM) [44]. PM machines are the most studied machine in MEA application particularly due to its unbeatable power density both in terms of volume and mass. PMSMs are not fault tolerant which is a major requirement for aircraft applications. PMSMs can be designed as fault tolerant; however, this reduces their power density significantly. It will also lose the torque capability with temperature as the flux reduction in PMSMs is much more than IM and SRMs. PMSMs also have the highest efficiency compared to other machines. High temperature is a huge requirement for aero-space generators which further reduces the difference between PMSM in comparison to SRM or IM. PMSM is only 25–30% more power dense than IM or SRM. Increased efficiency in PM machine means fewer losses; however, it does not mean the machine has effective cooling mechanisms. PMSMs are highly intolerant to high temperature due to the presence of PMs [45]. As the risk of demagnetisation is present in PMSM machines, careful assessment for high-temperature operation and transient operation is required. Although PMSMs are vulnerable to corrosion the use of permanent magnets such as Samarium-Cobalt can be advantageous considering its ability to operate up to 300/350 °C. Operating at such critical temperature could potentially impact the lifetime of the machine. Using stator cooling in this machine could aid in increasing the lifetime of insulation and reduce the temperature dependent copper losses. SRM on the other hand with limited cooling requirement could push the temperature boundary upto 400 °C range. This will offer SRM inherent adaptability for operating in harsh conditions. IM on the other hand could offer higher temperatures if a passive rotor configuration is considered. A summary of the maximum temperature potential for different power generation machine topology can be seen in Table 5 [46].

Table 5. Temperature comparison between different machine topologies.

	PMSM	SRM	IM
Temperature	up to 300 °C (Samarium-Cobalt PM)	up to 400 °C	up to 250 °C

The second most accepted generator technology is SRM particularly due to their ruggedness. This is not easily achievable as the rotor in SRM is made of steel laminations. It has no magnets or windings such as the PMSM or no squirrel cage such as IM. SRM has been a popular choice since 1980s for aerospace application. They are tolerant to harsh environments and high temperatures. It also has good fault tolerance and intrinsic redundancy making it a more robust choice for aircraft purposes [45,47]. Having good power density is one of the biggest requirements for electrical machines in aerospace application. A comparison of few aircraft used in industry and their common machine types including PMSM, SRM and WFSM (wound field synchronous machine) can be observed in Table 6.

Table 6. Comparison of large aircraft generator parameters [46,48,49].

Name	Motor Topology	Rating	Voltage	Efficiency
GE	SRM	0.25 MW	0.27 kV DC	93.1%
RR	PMSM	2.5 MW	3.00 kV DC	98.9%
Honeywell	WFSM	1.00 MW	0.60 kV DC	97.0%

On the traditional Boeing 787 power is extracted from engine in two ways to power the aircraft,

1. Generator driven by the engines to create electricity.
2. A pneumatic system that bleeds air off the engine to power other systems such as hydraulic system.
   On the other hand, a more electric aircraft will have the following factors,
   - Uses more electricity than pneumatics.
   - Increased fuel efficiency.
   - Less noise and drag.
   - Lower maintenance tasks and costs.
   - More efficient power generation, use and distribution.

Boeing creates electricity via 6 generators—two on auxiliary power unit (APU)and two on each engine. The two generators on each engine are the primary source of power and the ones on APU are secondary power unit. It also uses 235V AC distribution for their power generation system. A comparison between the power generation capabilities for two modern aircraft can be seen in Table 7. The requirement of power rating is increasing every year for the main generators in MEA. Aircraft component requirement for power generation can be observed in Table 8 [5].

Table 7. Power generation capabilities of more electric aircraft [5].

Parameters	Airbus A380	Boeing 787
Number of engines	4	2
Number of generators per engine	1	2
Voltage output generating	115V AC	230V AC
Rating of Generator	150 kVA	250 kVA
Number of generators per Axillary power unit	1	2
Generator rating per Axillary power unit	120 kVA	225 kVA

Table 8. Aircraft component requirements for power generation [2].

	Urban Air Transport	Sub-Regional Aircraft	Midsize Commercial Aircraft	Large Commercial Aircraft
Power requirement	150–200 kW	2 MW propulsive	22 MW propulsive	60 MW propulsive
Energy requirement	100–200 kWh	12 MWh	55 MWh	390 MWh
Energy Density target	20 kWh/L	250 kWh/L	1 MWh/L	>1 MWh/L
Power density targets	3 kW/kg	7.5 kW/kg	12 kW/kg	20 kW/kg
Operating voltage	230 V	540 V	3 kV	>3 kV
Efficiency (%)	90	93	96	>96
Machine power	25 kW	500 kW	2 MW	>5 MW
Energy Density target year	2018–2020	2024–2026	2028–2032	2035+
Advanced hybrid or electric architectures	-	Serial	Serial could be possible	Serial is difficult
More electric architecture	-	-	Evolved	Evolved

There is a large demand for increased power density in aircraft electrical machine, an estimated power density timeline can be observed in Figure 15.

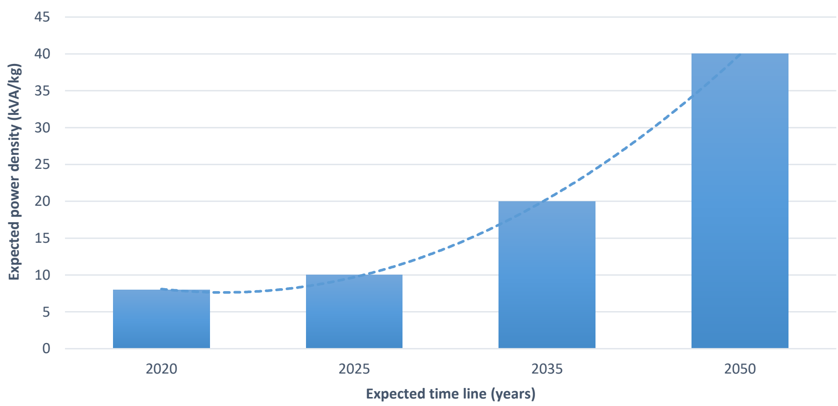

Figure 15. Expected power density trendline graph [41].

4. Actuation

An actuator is an operating device that is similar to a transducer. It is capable of converting energy from one form to other, usually electric current, pneumatic or hydraulic pressure. Traditionally for flight control systems, the pilot uses mechanical means to move the control surfaces. When flight control system became more complex they could no longer cope with the forces on control surface thus, fully powered hydraulic system became a requirement for these conventional actuators. However, in the recent days, the trend is diverting towards the more electric alternatives [50]. Classification of flight control actuation types can be observed in Figure 16.

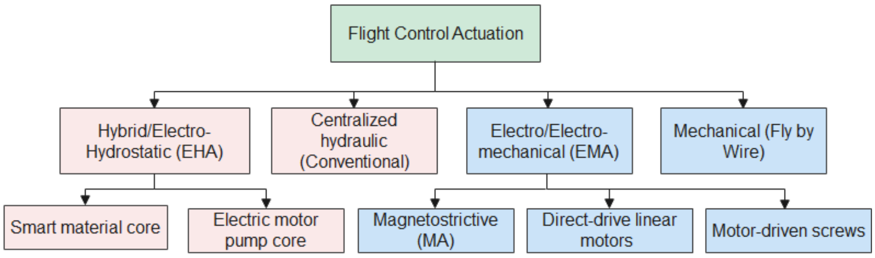

Figure 16. Classification of flight control actuation types [51].

4.1. Conventional Hydraulic System

The main components of the conventional hydraulic system include, hydraulic pumps (sources) and actuators (consumers). The conventional aircraft get power from both the electric generators and hydraulic pumps. Aircraft generally uses three separate hydraulic systems for redundancy, whilst the hydraulic pumps providing fluid power to the aircraft actuation systems such as, slats, flaps, landing gears, gear brakes, flight controls etc. Hydraulic systems are safe, efficient and reliable with two backup facilities in case of system failure. Some disadvantages of the conventional system include: fluid leakage, maintenance and assemble time, changes of fluid property over varying temperature, fluid contamination and transient application system sizing. Despite these limitations the hydraulic system has been widely used in the aerospace industry due to the advantages, including good force/power density, thermal capacity, ease of control, band-width control and application heritage [52]. In aircraft there are three degrees of controls: pitch, yaw and roll of the flight. These flight control surfaces are also known as primary actuators. They must be fail-proof with sufficient redundancy in their back up systems to ensure safe landing of the aircraft in case of fault occurrence [5,53].

4.2. Primary and Secondary Flight Control Actuation System

The critical primary actuators are as follows:

4.2.1. Ailerons

Ailerons are present on the outer trailing edge of the wings and controls the rotation amongst the longitudinal axis of the aircraft (roll). They are present in both wings and move conventionally in opposite directions.

4.2.2. Rudders

Rudders are situated on the tail and deflects to the right and left to alter the rotation along the horizontal axis of the aircraft (yaw). There are usually two rudders actuated with a pair of electrical backup hydraulic actuator to ensure that the rudder operates without any failure. The only surfaces to solely feature electro-hydraulic actuators are the rudders. A 20kW electro-mechanical actuator rudder was analysed in the literature, where an overall weight reduction and simplified maintenance procedures were observed [54,55].

4.2.3. Elevators

Elevators are observed on the tail fins and directs the pitch of the aircraft. They deflect up or down to direct the aircraft nose to point up or down.

The other category of control surface actuators is known as secondary actuators. These secondary actuators must be fault-tolerant but not necessarily fail-safe. These are useful for the efficiency and comfort of the flight, but the aircraft can be flown without these if required. Spoilers, flaps and slats are secondary flight control systems and are less critical to the safety of aircraft in flight. Therefore, the duty cycle is low and the dynamic response is much slower [53–55]. An overview of the primary and secondary flight control system can be observed in Figure 17. The secondary control surface actuators consist of.

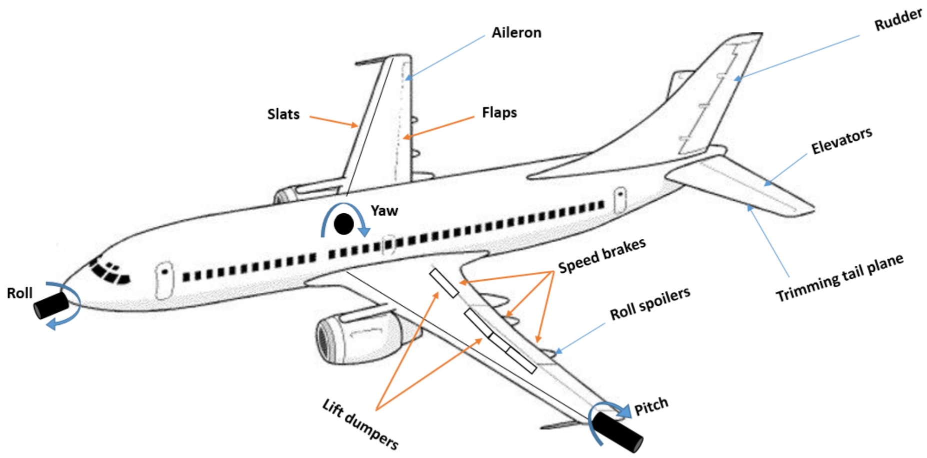

Figure 17. Overview of the airliner control surfaces: Red arrow represents secondary surfaces and blue arrow represents primary surfaces [51].

4.2.4. Spoilers

Spoilers are also known as airbrakes; they increase the wing drag allowing the altitude to reduce without increasing airspeed and pointing the nose downwards. There are eight spoiler surfaces on each wing of a conventional hydraulic actuator. Since the spoilers employ electro-hydraulic or hydraulic actuators, any failure can result in the actuator reverting into damping mode instead of a jam.

Various research has been developed for applications on the spoiler surfaces. Initial research used permanent magnet and brushless dc machine; however, a 4-phased switched reluctance motor was finally chosen for an actuator of 25 kW. A linear arrangement where the motor drives the gearbox to operate the ball screw mechanism was used in the actuator to move the spoiler [54,56]. A spoiler actuation system was also employed using a switched reluctance machine, the work is still in conceptual stages and the details can be found in [57].

4.2.5. Slats

Extendable, high lift devices on the leading edge of the wings of some fixed wing aircraft.

4.2.6. Flaps

Extended high lift device on the trailing edge. These devices increase wing lift or decrease stall speed during take-off, approach and landing. Slats and flaps perform the same function, where they temporarily alter the shape of the wing to increase the lift. They move along the metal tracks built into the wings and are used to maintain a stable flight in lower speed. Slats and flaps usually operate with hydraulic power from the hydraulic system. Alternatively, an electric motor system can be used where the position is controlled with the flap lever. More details can be found in [58].

4.2.7. Landing Gear

Landing gear is one of the important subsystems in an aircraft. Due to the substantial influence on aircraft, it is often configured with other aircraft structures. The purpose of this system is to offer a suspension system for the aircraft during taxi, take-off and landing. The kinetic energy of landing impact is designed to be absorbed and dissipated in the landing gears, thereby causing a reduction in the impact loads transferred to the airframe [59]. Multiple actuators are required for stowing, deployment and steering of landing gear [54].

4.3. Electric Actuator Architecture for MEA

In the recent days hydraulic actuators are replaced with electrically powered actuators. In 1960s commercial aircraft introduced the term 'fly-by-wire'. This system had a sensor on the cockpit lever together with a wired digital/analogue link to the actuator rather than having mechanical linkages between control lever in actuator and cockpit. Even though the control in this system is electric, the power is still produced by the pressurised hydraulic supply lines in the aircraft. Later, the term 'power-by-wire' was introduced where the actuator is powered completely by electrical supply. Various research is ongoing to increase the quantity 'power-by-wire' systems in MEA [6,53]. A simplified block diagram of the conventional and modern actuator can be observed in Figure 18.

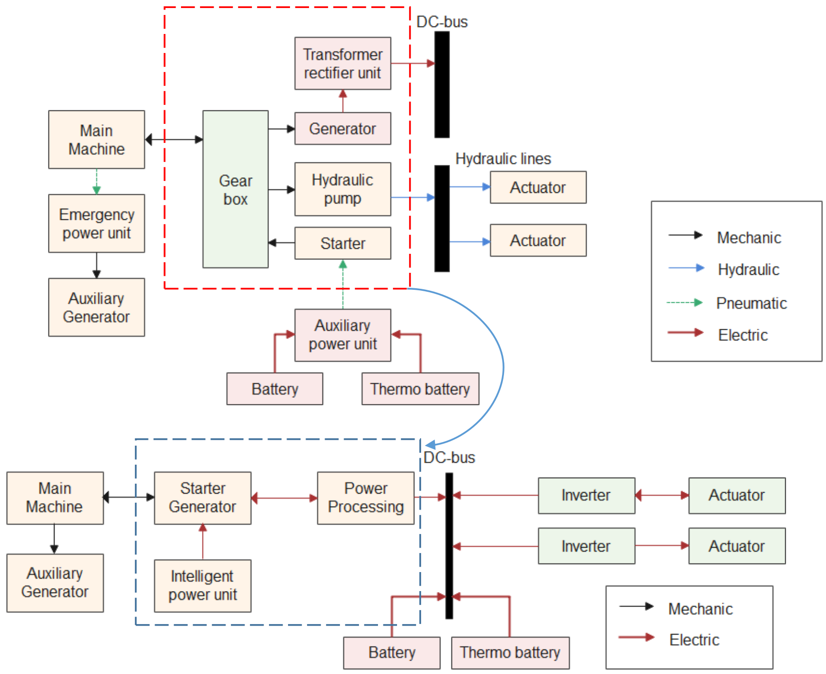

Figure 18. Simplified block diagram of the conventional and modern actuator [51].

4.3.1. Electro Hydrostatic Actuator

One of the first developments of More Electric Aircraft initiative was Electro Hydrostatic Actuator (EHA) which is a hybrid electrical/hydraulic device. EHA uses hydrostatic transmission instead of mechanical power therefore, the primary source of power would be electrical rather than hydraulic in this system. The EHA system is driven by local hydraulics and controlled using a fixed displacement pump that is driven using an electric motor. The position of the actuator moves by a fixed displacement for every revolution of the motor. It transfers the fluid from one cylindrical chamber to other back and forth, whilst the electric motor and the pump achieve the control of the piston position that is joined to the surface [11].

EHA has a benign failure mode as it does not have a direct mechanical connection between the arm of actuator and the motor, giving significant advantage to flight-control applications. Significant pressure is only needed for movement which results in energy saving in comparison to the conventional hydraulic servo actuator where pressure is maintained by holding. EHA uses 'power-by-wire' concept as only an electrical supply is needed. This will help reducing the system weight and maintenance requirements by removing the hydraulic supply networks [53,54,60]. An example of such system can be seen in Beoing 777 aircraft. A block diagram of EHA can be observed in Figure 19. Some of the challenges associated with EHA include:

- Pump performance and life—Pre-existing pumps are large displacement ones with standard efficiency; however, EHA requires high-speed, low-displacement, high-frequency reversals with low losses.
- Electric motor efficiency and fire risks.
- Packaging of the power electronics and reliability.
- Heat rejection problem.
- Cold start [61].

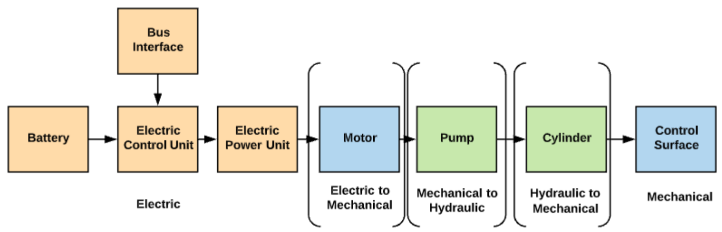

Figure 19. Block diagram of EHA.

4.3.2. Electro-Mechanical Actuator

When substituting hydraulic actuators to electrically powered actuators the most obvious choice is Electro-Mechanical Actuator (EMA). On the EMA system, by simply controlling the motor, the aircraft control surface can be fully controlled. A block diagram of the EMA system can be Figure 20. EMA only uses mechanical energy transmission therefore, it has the highest power density and overall system efficiency in comparison to other actuation systems [62]. It will also eliminate the dependence of fight control system on two separate power sources and will allow the system to be fully functioned using just electrical power source. Working principles of EHA can be obtained from [52].

Some of the benefits of using electro-mechanical actuator in aircraft include, reduced take-off weight, increased efficiency, decreased operation and maintenance cost and shortened production cycle. For flight control applications both EHA and EMA replaced to electric power from hydraulic power. EMA is smaller, less complex and lighter than EHA even though both EMA and EHA can perform equivalently to hydraulic actuators. Some of the other challenges associated with using electric actuation include:

- EMA suffers from fatigue failure such as, thermal failure and mechanical jam restricting the development of EMA. Therefore, EHA will be the main electrically powered actuator technology for the primary flight control of commercial aircraft.
- EMA's existing redundancy can increase the reliability unilaterally.
- Fault isolation, fault diagnosis and health management for EMA is not developed well.

Despite all these challenges EMA was introduced in the Boeing 787 commercial aircraft [53,60,62]. EHA and EMA is employed on Boeing 787 and Airbus 387. The adoption of EMA resulted in weight loss of 1500 kg in airbus 387.

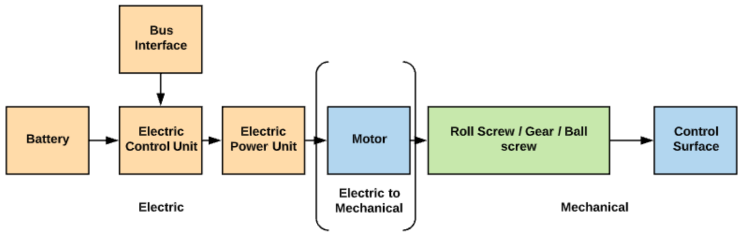

Figure 20. Block diagram of EMA.

4.4. *Electrical Machine Topology in Aircraft Actuators*

The hydraulic pump of the EHA is one of the most critical components for the control of an actuator. It requires a motor with high acceleration capacity and power density. From the literature, an overwhelming use of BLDC motors was identified for EHA. However, the main disadvantage with BLDC is the requirement of shaft position sensing. EHA is used in aerospace applications due to the advantages in weight, size and the absence of electrolytic capacitors [63]. Both EMA and EHA uses electric motor as well as a power converter and control system in their actuation systems. From the literature, it has been seen that BLDC and switched reluctance machines are quite promising due to their reliability and lightweight characteristics. Electrical machines in the actuation application have some requirements that include minimum size, weight and cost to reach the necessary performance requirements in addition to reliability and fault tolerance [64]. When it comes to electric motors in aircraft the most important parameters in order are, power density, torque density, efficiency and reliability. From the details obtained through the literature, the main electrical machines are ranked against the important performance indices. The results can be found in Figure 21, where 1 represents the least performing and 4 represents the highest performing machine topologies.

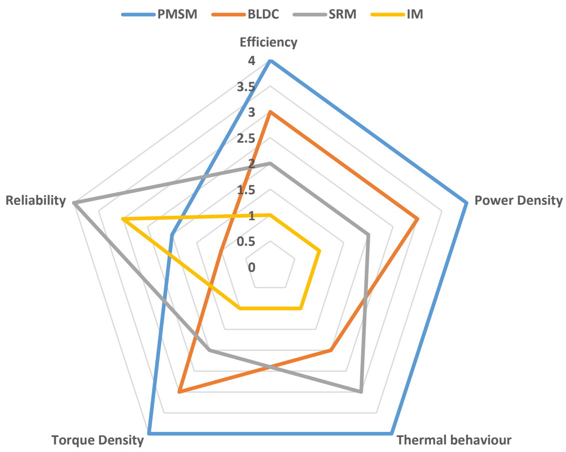

Figure 21. Machine ranking against key performance indicators (1 = Lowest and 4 = Highest) [51].

When analysing the main machine topologies used in aerospace actuation application, some details about their main benefits and drawbacks were identified.

It was found that permanent magnet motors are the most common candidate seen in aircraft actuation motors. They have higher power density in comparison to switch reluctance and induction machine. PM motors enable overloading of the motor with their strong and independent excitation systems. It has higher efficiency due to the low stator current, high torque density and PM rare earth material advancement. Fault tolerant capabilities, manufacturing simplicity and transient behaviour due to absence of copper are also seen in PM machines. A reduction in size and weight with same thermal constraints can be achieved much easily in PM machines compared to induction machines. However, inherent retention issues of PM motor make the rotor temperature higher than induction machine. PM machines could experience heavy saturation in order to achieve the desired output, resulting in distorted EMF and currents. Increased losses due to higher stator winding harmonics is another drawback commonly seen in PM machine [64,65].

The induction machine, on the other hand, has lower braking torque and short circuit than PM machine. It also has lower core saturation level compared to PM machine as the magnetic field in the rotor is already established, thus giving the capability of being further loaded. The induction machine's main drawback is derived from absence of independent electromagnetic excitation in rotor. To achieve adequate production of torque, it requires high current density to be flown into the stator. Therefore, IM requires a much larger envelope dimensions than PM machine to achieve equal torque output with the same current density level in the stator [66].

Switched reluctance motors is another candidate which also has the benefits of simple construction, good fault tolerance, high ruggedness, ability to be used in single-slot and no dragging torque produced in the case of phase short circuit. However, it brings the drawbacks of lower power and torque compared to PM machine, high ventilation losses, small air gap and it has the necessity of needing more complicated power converter. Brushless DC is also another topology for actuator motors. It is reliable and lightweight with magnetic, electrical, mechanical and thermal insulation between phases. They have high efficiency in full speed range and it is more power dense than switched reluctance machine. However, it has the drawback of having higher electronic cost, complex wiring, more motor drive complexity and relatively higher cost than brushed DC motors [6,44,67,68].

From Table 9, the general requirement of the motor parameters and the target year for a fault-tolerant and fully integrated actuator can be seen. This requirement is targeted at a commercial aircraft (A320 size) or a large civil aircraft size. A comparison of the key performance indicators against the common actuator machine topology can be see in Table 10.

Table 9. Aircraft actuator requirement for commercial aircraft [2].

	Slats/Flaps	Landing Gear	Ailerons	Rudder	Surface Actuation (Spoilers)
Common Machine Topology	PMSM	PMSM	PMSM	PMSM	PMSM/SRM
Power Requirement (kW)	1.19–3.5	<24	13	20–30	25–50 k
Torque (Nm)	34 k	<80	29	17.9–1.3 k	5–30
Speed (RPM)	<10,000	<800	∼450	2500–9047	16,000
Safe and fault-tolerant actuator target year			2022–2035+		
Fully integrated actuator and drives target year			2024–2035+		

Table 10. Comparison of key performance indicators for different machine topology.

Key Performance Indicators	PMSM	BLDC	SRM	IM
Power factor	High	High	Low	Low
Torque ripple	Low	Low	High	Low
Field weakening capability	Low	Low	High	High
Risk of demagnetisation	High	High	N/A	N/A
Impact of short circuit faults	High	High	Low	Low
Cost	High	High	Low	Low
Over voltage chances during speeding	High	High	N/A	N/A
Inverter requirement	Conventional	Conventional	Special	Conventional

5. Future Requirements and Development Discussion

In the recent days there has been a drive towards research and development of various topologies and novel ideas in aerospace electrical machine. From the literature analysed in this paper focussing on propulsion, power generation and actuation there are some key areas identified to be developed in future aircraft, which include:

- Motors, generators and inverters needs to be developed to obtain a specific weight, power and reliability for commercial application.
- Specific power will need to be improved by a factor of between 5 and 10 from current state of art.
- Thermal management targets need to be compatible with aircraft thermal management system.
- Efficiency needs improvements from 95 to 97/98%.
- Weight reduction.
- Circuit protection and high-power distribution for MW class aircraft power systems.
- Advanced materials: Motor power densities and efficiencies can be improved with better conductors, insulators, magnets, bearings etc. [2].

Some of the advanced technologies that can be implemented in aircraft to achieve and close the gap in existing designs are discussed here. After analysing the existing technologies it was identified that there is a large demand for increased power and torque densities in mobile application electrification such as aerospace and automotive. To enable this requirement various advancements in materials and design tool has been developed. However, this resulted in various thermal constraints within electrical machine. To overcome this limitation appropriate thermal management is required for avoiding over temperature.

Thermal management is a key factor that plays a major role in performance improvement and size reduction. From the literature, it has been identified that good thermal management improves the power and torque density and allows a higher current density to be achieved for the given winding temperature. It also allows more freedom during the design stages of the machine. Although various research has been taken place or considered not many thermal management strategies has actually been implemented in electrified aircraft machines. Current aircraft systems are employed with conventional air cooling systems such as housing fins, shaft mounted/external fans though they are effective for increased power density and elevated current density these measures might not be enough [33].

Some of the advanced cooling technologies that are explored and can be applied to close the gap between existing design and future design are as follows:

- Cooling methods employing high thermal conductivity insulation materials or high thermal conductivity fluid [69].
- Forced liquid cooling method that includes water jackets or channel ducts. This method could create adequate cooling on the winding active region but could also result in localised hotspots in the end winding [70].
- Embedded cooling tubes implemented in Litz wire to extract heat produced within the stator winding [71].
- Implementing liquid carrying pipe that directly cools stator end windings of radial flux. It is a cost effective method that can be added to existing machine designs [33].
- Thermal analysis using different slit thickness, high current density, oil cooling in stator and lumped parameter model performance analysis [72].

In addition to performance improvements and size reduction, having a good thermal management system is important, as having high temperature could result in increased losses, copper resistance, reduction in coercivity and remanence of permanent magnets, effects on machine torque, and demagnetisation of magnets. Different thermal management requirements are necessary for various types of electrical machine. Due to the lack of rotor accessibility, the machine is more difficult to cool. Careful design considerations on cooling technologies, heat generation, material properties and thermal analysis are vital for effective thermal management [73].

Having adequate materials in the aerospace machine is also another key area to improve power density, machine efficiency, performance and cost effectiveness. The selection of materials in aerospace can be challenging, as volume is a constraint; therefore, the machine must have good power density. This means the materials must result in lower losses and should be able to bear increased temperature [74]. From an aerospace material perspective, non-oriented steel laminations for rotor and stator are a common choice. The amount of alloy used can strongly affect the magnetic and thermal properties of these materials.

In the recent years, there has been various advancement in materials used for electrical machine. Some of the development that can be applied in aerospace machines to for weight reduction, power density improvement and better efficiency include

- Thin-gauge non-oriented steel to reduce iron losses.
- Higher-strength lamination material for the rotor to improve efficiency and reduce machine size [75].
- High-silicon-content laminations for reduced iron losses and increased electrical resistivity [6,76].

Machines with smaller iron loss and increased efficiency will aid the reduction in the cooling system and heat dissipation. Heat generated from iron losses in materials can be reduced by advanced steel materials with a thinner cut, such as cobalt iron [74].

The current main driving source for aerospace applications are PM-synchronous motors. The motor and converter in this system are currently not integrated, thus leading to a reduced power density and large machine. A shift from a traditional separated system to more compact, power-dense system has been seen over the last decade. Placing the conventional motor system in separate cabinets have many disadvantages which include increased volume and larger weight as well as longer wires, causing excessive losses and electromagnetic interference which also results in increased torque ripple. A potential solution for this is the integrated motor drive system. This will allow installation to the integral housing and connects the converter and windings using shorter wire cables [77,78]. An example of an integrated EMA system designed by Y. Bi et al. can be observed in [79].

All of the abovementioned improvements in terms of thermal management, material, or integration (weight reduction) are key advancements that is required for aerospace industry as we switch from traditional pneumatic or hydraulic systems to electric system. An overview of the predicted advancement timeline and the level of impact can be observed in Figure 22.

Material advancement is an ongoing development area where various thin-gauge materials are already developed and are available in the market. Since the existing materials offer good efficiency and size reduction, advancement in this area might not offer a massive impact towards aerospace industry, whereas thermal advancement methods mentioned above is an area that is relatively unexplored. Therefore, it will require a much longer time frame to research and implement these changes in the existing machines. Thermal advancement only offers medium level of impact towards the aircraft industry, as improvement in this area is co-related to other development areas such as the integration or materials. Thermal improvement alone would only make an average level of impact towards aerospace electrical machine. On the other hand, the integration of drives is an area that can potentially give an improvement of almost 30% to the total weight of the system. This means that this technology will lead to massive step forward in the aerospace industry, creating a much higher impact than the other discussed factors.

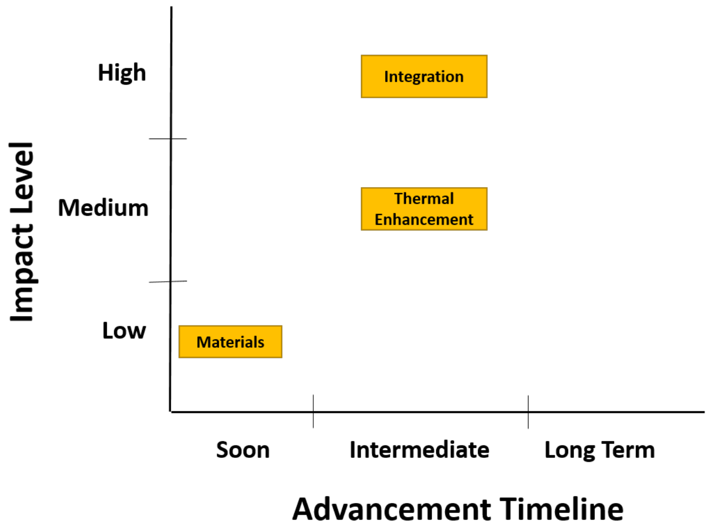

Figure 22. Impact level of main technology advancements against their predicted timeline.

From the literature analysed, a summary of the present scenario and future prediction based for power capability and power density can be observed in Table 11.

Table 11. Current and future prediction of different aircraft components.

	Year	Power Requirement	Power Density (kW/kg)
Propulsion	2020 2035–2040	600 kW 5.3 MW	3.5 kW/kg 6.5 kW/kg
Power Generation	2020 2035–2040	200 kW 60 MW	3 kW/kg 20 kW/kg
Actuation	2020 2035–2040	27 kW 50 kW	2.2 kW/kg 3.5 kW/kg

6. Conclusions

This paper reviewed various initiatives and topologies required for commercial aircraft electrification with respect to reduced greenhouse gas emission. The key areas of MEA explored are propulsion, power generation and actuation. MEA technology revolution has pointed out several challenges to obtain aircraft systems and sub-systems that are power-dense, lightweight, efficient and reliable. From the literature, it was identified that the current state of art and development trends in MEA point towards the increasing demand for power-dense aircraft systems. As represented in Table 11, by 2014, the power density for propulsion, power generation and actuation is expected to reach 6.5 kW/kg, 20 kW/kg and 3.5 kW/kg, respectively. A linear increase in power density was seen for power generation application from 1924 to 2020. By 2040, the power density in aircraft electric motors is expected to almost double compared to the current value. Various electrical machine topologies were also explored, including permanent magnet, switched reluctance, brushless DC and induction motors. In particular, permanent magnet motors were found to be the most efficient, power-dense and reliable motor for aircraft subsystems. Permanent magnet machines were found to be 60% more power dense than IM and 78% more power dense than SRM. It was identified that the efficiency of these motors in MEA needs to be improved by 2–3% and the specific machine power by a factor of 5–10 from the current state. By 2014, the power requirements for propulsion, power generation and actuation are expected to reach 5.3 MW, 60 MW and 50 kW, respectively, as shown in Table 11. The key development areas for electric motors and drive were also explored, including weight reduction, efficiency improvement, thermal management and material advancement. Researchers will continue to explore methods to confront any technological limitations and unlock the potential for more energy efficient and environmentally friendly aircraft with newer architecture.

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