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*Review Article*

# Perspectives and Development of Electrical Systems in More Electric Aircraft

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On-board electrical systems are the key components of each modern aircraft. They enable its safer, more comfortable, and environmentally friendlier operation. The strict regulations to reduce pollution and noise are produced by aircraft eventuated in projects like Clean Sky or ICAO Global Coalition for Sustainable Aviation. One solution to environmentally friendlier operation is the full electric propulsion of the aircraft, which enables the reduction of both noise and pollution. Such a concept requires a total change of all on-board power systems and enables the profound change in aircraft design. This paper presents the evolution of aircraft power systems into the so-called more electric aircraft (MEA) and discusses the state-of-the-art electrical systems. Furthermore, the concept of all-electric aircraft (AEA) is presented here.

## 1. Introduction

Climate change is one of the biggest issues the world must currently face. The negative effects of the transportation sector on air pollution have been increasing over the years. Its share in global emissions is 24% and ranks second place after the energy sector with a share of 45% [1]. Therefore, many developed countries are currently supporting the use of electric vehicles and simultaneously restricting vehicles with combustion engines. In recent decades, the trend of aircraft electrification can be clearly seen in the replacement of the conventional power systems (hydraulic and pneumatic) with electrical system. This trend is known as More/All Electric Aircraft (M/AEA) power concept [2–5].

The electrical systems have advantages over conventional systems in lower maintenance cost/time, lower weight/volume, and higher efficiency, which positively affect fuel consumption [6, 7]. The concept of M/AEA has been investigated for a long time. In early days, the biggest issue was electrical actuator reliability, protection from electromagnetic interference (EMI) and lightning, and protection from embedded software errors [8–13].

In recent years, vast research on MEA electrical systems has been performed, especially on power generation, hybrid-electric propulsion, power conversion, and power distribution. In the field of electric power generation, different types of integrated starter/generators (S/G) have been investigated [14, 15]. In the field of propulsion, various architectures have been proposed—all-electric [16, 17], where only electrical power is used for propulsion; hybrid electric [18], where both electrical power and combustion (fuel) power are used; and turboelectric [19–21], which is similar to hybrid propulsion concept without batteries. These new concepts enable, by implementing electric "traction" motors, a total change in aircraft design. In [22, 23], the distributed propulsion system with the utilization of boundary layer is investigated. The aim of these studies is to reduce the weight of the system, increase its efficiency, and reduce or eliminate the consumption of kerosene.

The concept of AEA, with its electric propulsion for mid-size and large-size aircraft, is not realistic today due to the limitations of electric power sources. For this reason, a combined/hybrid propulsion system, which uses at least two different power sources is proposed. This concept is known as Hybrid Electric Aircraft (HEA). The architecture of propulsion can be realized as a serial hybrid or parallel hybrid. Hybrid electric propulsion of ground vehicles was for the first time used at the end of the nineteenth century, and it has been again widely used in automotive from the beginning of the 21st century. However, hybrid propulsion is still under research in aviation. Many of the aircraft manufacturers and their suppliers are testing HEA concepts, e.g., Airbus E-Fan X [24], VoltAero Cassio 1 [25, 26], Zunum Aero ZA10 [27], ESAero ECO-150 [28], Diamond aircraft DA36 E-Star [29], and Ampaire EEL [30]. The biggest issue of HEA, besides the system's reliability, is the optimization of its power management—the balance of electrical and mechanical power [31–33]. The aim of HEA is to increase the fuel economy [34] and decrease the negative impact on the environment [35, 36].

MEA must generate a large amount of electrical power for many loads. To reduce the weight of the power distribution system, the ingenious system of electric power management has to be investigated. In [37, 38], the dimensioning of the electric power distribution system based on the actual power demand and priorities of individual loads is researched. A new type of decentralised distribution system/-architecture is proposed [39, 40], in which the traditional circuit breakers are replaced by solid-state power controllers (SSPC), also known as electronic circuit breakers (ECB).

In the field of power conversion, small and efficient solid-state power converters (SSPCv) enable to implement the concept of the frequency wild AC system. The main idea of this concept is the elimination of the constant speed drive (CSD) or integrated drive generator (IDG), which positively affects the weight of the aircraft. In this concept, the generated frequency wild AC supplies resistive loads and regulated constant frequency AC supplies reactive loads [41]. In [42], the CSD/IDG is replaced by DC-Link, i.e., AC (variable)—-DC—AC (constant) electrical power system converter.

Owing to the demand of very high energy density of electrical machines, the superconducting materials operating in normal temperature range are investigated [43–46].

In this paper, the electrical systems of current and future aircraft are presented. The authors try to point out on their advantages/disadvantages and perspectives for use on-board the aircraft. The paper is organized as follows: in Section 2, the history of aircraft electrical systems and the role of electricity for aircraft rapid expansion are discussed. Section 3 presents the evolution of the conventional aircraft power concept into the MEA and AEA and compares these concepts. Section 4 describes the areas in which electrical systems are/will be used in the MEA and AEA. Moreover, the advantages and shortcomings of these systems are presented here.

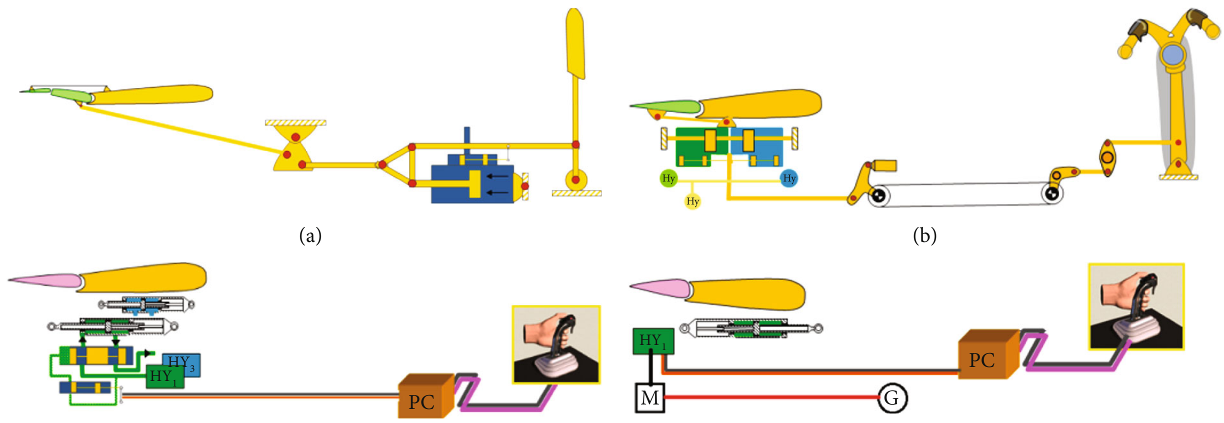
## 2. History of Aircraft Electrical Systems

Before the first heavier-than-air aircraft was constructed, hot-air balloons and later airships were used. At the beginning, the airships were powered by heavy and bulky steam engines, which required very long starting times, and later electric motors were used. The first electric flight is attributed to the Tissandier brothers with their "La France" airship in 1883 [47].

Although there had been several attempts before, the first successful flight of heavier-than-air aircraft was achieved by the Wright brothers in 1903 [48, 49]. This step represents the beginning of technological developments in the field of aviation. One of the first issues to be solved was the manoeuvrability of the aircraft. The 3-axis control system was designed and constructed by the Wright brothers [50]. Louis Bleriot designed the central stick and rudder pedals [51]. Later high-lift control surfaces (flaps) were proposed. The mechanical linkage was necessary to transfer the shift of the control stick and rudder pedals to the control surfaces. However, the pilot's effort to move the control surfaces rose linearly with their increasing size and quadratic with the increasing speed of the aircraft. The first power boosters had to emerge to help the pilot to operate the aircraft. As an example, in 1949, SNCASE S.E.2010 Armagnac used the classical mechanical linkage of control surfaces and hydraulic booster (Figure 1(a)). Later, in 1955, SNCASE S.E. 210 Caravelle used the first hydromechanical servo control, where power necessary to move the control surfaces was produced by hydraulic pumps (Figure 1(b)). Hydraulic pressure was provided by the engine-driven hydraulic pumps—central hydraulic system. In 1969, the Concorde used an analogue computer to assist the pilot in flight control. The second generation of electrical flight control came with Airbus A320 in 1984 (Figure 1(c)). It used a digital computer. In 2001, Airbus A340 proposed full-electric flight control with no mechanical back-up, however, the power to move the control surfaces was still produced and distributed in the same way as in SNCASE Caravelle in 1955. Finally, in 2001, Airbus A380 used electro-hydrostatic actuators (EHA), which used local hydraulic pumps powered by electric motors (Figure 1(d)).

An aircraft with four electrically driven propellers was proposed by A.N. Lodygin in 1914. The concept was designed in such a way that the combustion engines drove the generator which supplied electrical power to the motors [53]. Today, such a design is known as hybrid electric aircraft (HEA).

The first sources of electrical power on-board the aircraft were batteries, however, they had low power densities and very limited time of operation [54]. The first electrical systems required on-board the aircraft were the ignition systems and means for radio communication. Later, electric starter motors, external and internal lights, and electric heating were required. At this time, electricity was supplied mainly by small wind-driven DC generators located on the chassis and by rechargeable battery. Typical generated power was up to 250 W at 6 V and up to 500 W at 12 V in 1936 [53, 55]. Such generators were not powerful enough to drive starter motors, so engine-driven generators were introduced in 1934. Such a design decreased the drag of the aircraft and could even implement a retractable landing gear that even more improved the aerodynamic properties. The limitation of this concept was the increasing rotational speed of




(a) (b) (c) (d)

Figure 1: Aircraft control system with (a) hydraulic booster, (b) hydromechanical servo control, (c) electrical flight control, (d) electro-hydrostatic actuator. Adapted from [52].

new aircraft engines. New technologies for high-speed generators had to be developed. The typical power output of early engine-driven DC generators was up to 1 kW at 28 V.

Different voltage levels of AC and DC power were required, so power converters (secondary sources of electrical power) had to be used (Figure 2(a)). To be implemented on-board the aircraft, they had to fulfill strict specifications like high power rate, low weight, and thermic values. The total power of loads consuming electric current on the highly electrified aircraft was about 5 kW in 1932. In 1940, it was six times more.

The first ground-to-air communication was provided by various visual aids, e.g., coloured paddles, signal flares, and hand signs. These methods were effective for ground crews; however, there was no way pilots could communicate back. The wireless telegraph system was used to send messages in Morse code. At first, it was from ground-to-air and later from air-to-ground. This system evolved fast into the first air-to-ground radio communication system in 1915 [56]. The problem of early radio communication technology was its operating distance which was smaller than the distance aircraft were able to travel. The required signal had to be carried over several airports to its recipient aircraft, which was a time-consuming process. As the aircraft grew faster, they reached their destination before the message. The first air-to-air radio communication between aircraft was in 1916 [57].

During World War II, the radar technology was improved. It enabled to track aircraft in the air and determine its distance, speed, and direction. In 1990's, the first satellite systems for aircraft positioning were proposed—Global Positioning System (GPS) in 1994 and Global Navigation Satellite System (GLONASS) in 1996 [58]. All this communication/-navigation and positioning systems evolved in to the stage that the presence of the pilot is not necessary in the aircraft, so-called unmanned aerial vehicle (UAV).

The evolution of early aircraft electrical systems resulted in to a demand for higher-rated generators. In the 1950's, the power output of DC generators was up to 12 kW at 28 V [59]. The highest-rated aircraft DC generator reached 18 kW [60]. This limitation was due to the arcing occurring on the generator's commutator at high altitudes. To supply power for all electrical loads, several parallel-connected DC generators were used on multiengine aircraft. There were also efforts to use the 120 V-DC system; however, the problem with bulky converters and batteries and insufficient insulation material properties occurred. Another problem of DC generators was increasing the speed of engines. The limitation of insufficient amount of generated power was solved with the introduction of AC generators. However, the alternating current distribution system imposed new problems. The constant-speed-constant-frequency (CSCF) AC system was used (Figure 2(b)). AC generators, to generate constant frequency, were driven by specifically dedicated internal combustion (IC) engines. AC system had many advantages over DC system [61, 62]. AC generators could produce higher power output and were lighter—their power density was two times better. The weak arcing in the AC system did not cause significant problems [63]. Higher generated voltage level, 120 V, enabled the reduction of wires' cross-section. AC motors were two-three times lighter than the corresponding DC motors. The change of AC voltage level could be easily done by transformers or auto-transformers, contrary to bulky and inefficient rotary converters in the case of DC voltage. In addition to frequency, another disadvantage of the AC system is the presence of reactive power and very complicated parallel generator operation [64–66].

With the introduction of semiconductors, the small aircraft, in terms of weight reduction, preferred variable speed AC generators and germanium rectifier (Figure 2(c)). Later, germanium was replaced by silicon.

The post-war, long-haul, commercial aircraft offered luxury services like sleeping accommodations [67]. Such aircraft needed electrical energy not only to supply vital avionics systems and important electrical systems but also to satisfy passenger demands—the galleys' ovens were used to prepare warm dishes [68]. Later, with the developing technology, the first cabin entertainment systems have been added to these services [69].

Reactive AC loads are very sensitive to frequency instability. Driving AC generators with dedicated constant-speed IC

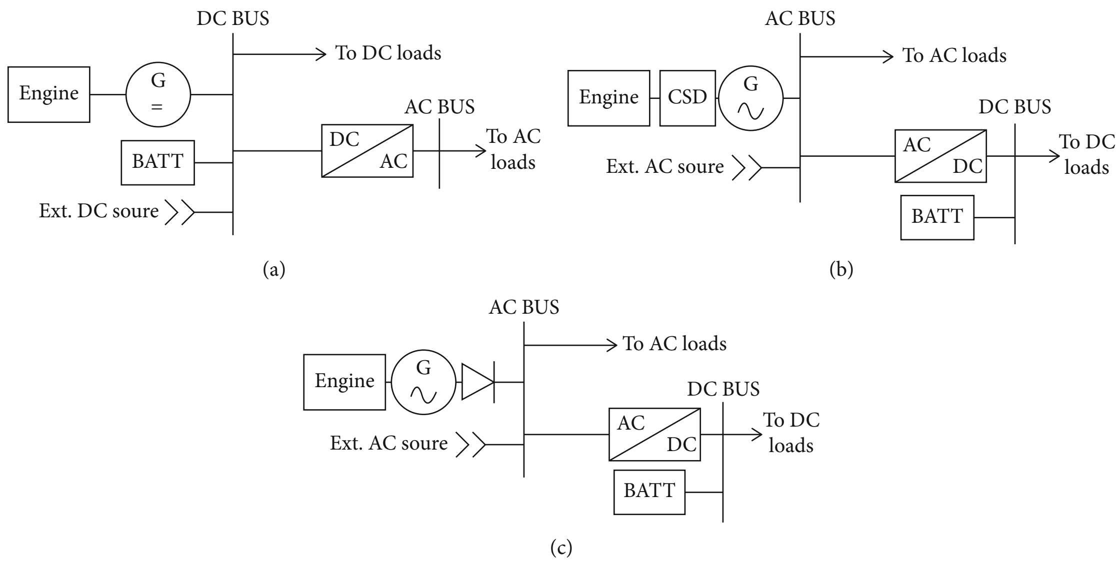



Figure 2: Power distribution: (a) for DC system; (b) for AC system; (c) for AC-DC system.

engines was not efficient, so a new type of frequency stabilisation had to be developed. In 1960's, the constant speed drive (CSD) was introduced [70]. Primarily the hydromechanical type; i.e., the generator speed was trimmed using hydraulic devices, and later, pneumatically trimmed units were used [71]. CSD is a type of transmission which the input shaft has a variable speed, proportional to the speed of the engine, and the output shaft, driving the generator, has a constant speed. In 1970's, the CSD evolved into an integrated drive generator (IDG), which is a connection of CSD and generator, sharing the same housing and cooling fluids [72–74].

Another solution to obtain constant frequency was to use a DC-link [42, 75, 76] or a cycloconverter [77, 78]. However, both these systems were used only by several aircraft models. Early AC generators were using slip rings. Later, three-stage wound field synchronous generators were used, and they are still in use today in many aircraft models due to their robustness, simplicity, and high efficiency [79–81]. These generators enable not to use of carbon brushes; so-called contactless construction. The next evolution in the field of generators is the removal of IDG. Instead of IDG, variable-frequency starter-generators can be used [82, 83]. Such a solution enables to remove pneumatic starters and bulky pneumatic ducting.

## 3. Evolution to More/All-Electric Aircraft Concept

To provide the necessary power for all aircraft systems (flight control, fuel and oil pumps, breaking, de-icing, lightning, cabin pressurization and air conditioning, gear extension/retraction, avionics, etc.), mechanical, electrical, pneumatic, and hydraulic power sources are used [68, 84, 85]. Once the engine is started, it is a source of power to each of these systems [86]. The power from the engine's shaft is transferred to the gearbox from which the hydraulic pumps (source of hydraulic power) and generators (source of electrical power) are driven. From the engine's compressor section (source of pneumatic power), the compressed air (bleed air) is taken. In the conventional aircraft power concept (CAPC), the pneumatic power is supplied for cabin pressurization, for anti-icing and de-icing, and for engine starting [67, 87]. Hydraulic power is supplied for flight control, landing gear extension/retraction, nose-wheel steering, braking, and thrust reversing [88]. Electric power is mainly supplied for lighting, avionics, and galleys. Mechanical power is supplied for fuel and oil pumps. In CAPC, these four powers are in relation presented in Figure 3(a).

The typical power output of one three-stage wound field synchronous generator used in midclass CAPC has been 90 kVA with the voltage level 115/200 V–400 Hz [62, 89]. Such a power output was sufficient to supply all electrical loads on-board the aircraft. The gradual aircraft electrification, termed as MEA, led to a transformation of the mechanical, pneumatic, and hydraulic systems into electrical systems (Figure 3(b)) [90]. These changes had remarkable benefits on weight and fuel consumption reduction, easier component monitoring, improved system reliability, and easier and less time consuming maintenance [6, 67, 91]. There are more benefits of a single electrical system. To transfer power, there is no need to use flammable hydraulic fluids or bleed air ducting which is prone to leakage of hot air [92].

Electric motors are one of the most power-consuming electrical loads on MEA. To supply sufficient power for the motors, high-rated generators must be used. The typical power output of the starter-generators used on Boeing 787, the typical representative of MEA, is 250 kVA for the main S/G and 225 kVA for auxiliary S/G. The voltage level is three-phase 230/400 V-AC at variable frequency (frequency wild system) and ±270 V-DC. The convenient S/Gs for MEA are induction, reluctance, and permanent magnet machines [93, 94].

In the concept of MEA, the bleed-less engine architecture is proposed; the pneumatic power is supplied only for the anti-icing system of engines' cowl [95]. A bleed-less system can decrease fuel consumption in the range of 1-2% [96].

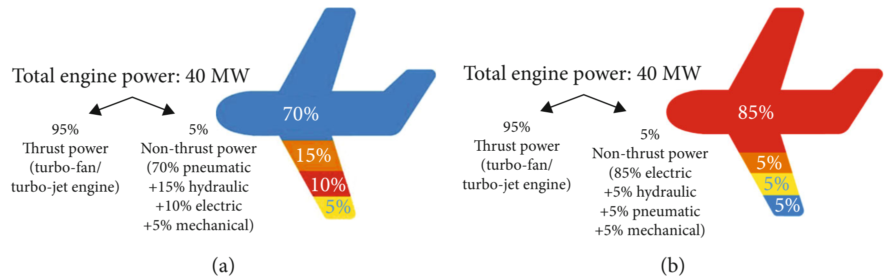



Figure 3: The nonpropulsive powers of (a) CAPC and (b) MEA.

The actuators of the control surfaces still use hydraulic power, but their local hydraulic pumps are powered electrically. Such a design, mostly used for primary flight control, is known as EHA [97, 98]. Up to now, in MEA, hydraulic power is still used for gear extension/retraction. Electrical power is used for thrust reversers [99, 100] and brakes [101, 102], for engine starting, for anti/de-icing of wings [103, 104], for galley's appliances [62, 105], for cabin entertainment system [106, 107], and for avionics. It is also used for electric motors of the cabin pressurization system [108, 109]. In this solution, the compressed air is not drawn from engines, but is compressed by electrically driven compressors.

Another factor which is typical for the MEA concept is the use of a decentralised/distributed power system (Figure 4). Load protection is not realized by standard mechanical circuit breakers, which must be placed in the cockpit. As a result, less wires are used. Instead of mechanical circuit breaker, the solid-state power controllers (SSPC) are used. These "electrical" circuit breakers can be placed in remote locations of the aircraft due to the possibility of digital control from the cockpit. Another advantage of SSPC is the use of MOSFET or IGBT transistors which enable soft switching of the DC or AC loads [110, 111]. The relays and contactors are not used in the distributed power system. Such a system is much more fault-tolerant; there is no arcing and contact bouncing [112–114].

One of the systems typical for MEA is the electrical engine starting. In CAPC, the starting process is tedious. At first, the auxiliary power unit (APU) has to be started with the electrical starter motor. Then, the bleed air is fed from the APU to the pneumatic motor which is in the engine's nacelle and drives the main engine. Such a solution is also bulky due to the presence of gearbox and pneumatic ducting and suffers from higher wear and tear of the engine [83, 115]. In MEA, the starting process is as follows: the APU is started with the starter generator. When APU has sufficient speed, its S/G produces electrical power. This power is used to drive S/G of the main engine. The advantage is that both main engines can be started simultaneously, contrary to the conventional starting system [116].

Temperature is one of the biggest problems of electrical machines implemented in aircraft. The high operating temperature is caused by high rotational speed and friction and by the power loss of the electrical system. The speed of S/G proposed in [115] is in the range of 20000 to 32000 rpm. The effect of temperature on electrical machines is investigated in [117, 118].

## 4. The Electrical Systems Used in M/AEA

*4.1. Electrical Machines.* There are many physical and operational differences between electrical machines which are used in industry and aviation [119]. The most notable difference is the voltage level. In industry, a 230/400 V-AC system at 50 or 60 Hz is used. In aviation, 115/200 V-AC at 400 Hz or 230/400 V-AC at variable frequency and 28 V-DC or ±270 V-DC is used [62].

There is restricted space on-board the aircraft, so the size of the components should be kept as small as possible. The selection of the electrical machine depends not only on its size and power but also on its weight. A very high power density of machines is necessary [120, 121]. Rolls Royce developed, for E Fan-X model, 2.5 MW S/G with a power density of 10 kW/kg [122]. Additionally, the operational conditions of machines have to be considered because aircraft machines operate at a very wide range of temperatures and air pressures. The winding temperature cannot exceed 180°C for standard H-class insulation and 220°C for R-class insulation [123]. Sufficient cooling has to be secured. Several cooling methods are proposed: cooling by using the phase change enthalpy, cooling with cold gas, oil bath cooling, water jacket cooling, and heat pipe cooling [123, 124]. Studies on stator iron thermal enhancement, interwinding cooling, and intrawinding cooling have been performed and concluded that the improvement in the current density can be in the range of 10 to 20 A/mm$^2$, depending on the implemented cooling method [124]. In [125], the new topologies for high-temperature machines are investigated and concluded that synchronous motors with permanent magnets can be used up to 300°C; above 300°C, the variable reluctance machines are preferred.

In the past, aircraft was using DC brushed S/G. The purpose of this combined system was the reduction of machine size and weight because all heavy components were for both machines shared within one case. Once the engine is started, it drives the generator which produces 28 V.

Due to the development of power transistors (MOSFETs, IGBTs), which can be easily digitally controlled, it is possible to use AC S/G [116, 126]. In [20], the integration of S/G and its associated converter is investigated. Such a solution proposes a relatively good current density of 10–12 A/mm2 within a small package. In [41], the implementation of the permanent magnet S/G is analysed with emphasis on the flux weakening protection, as these machines suffer from the de-excitation problem.

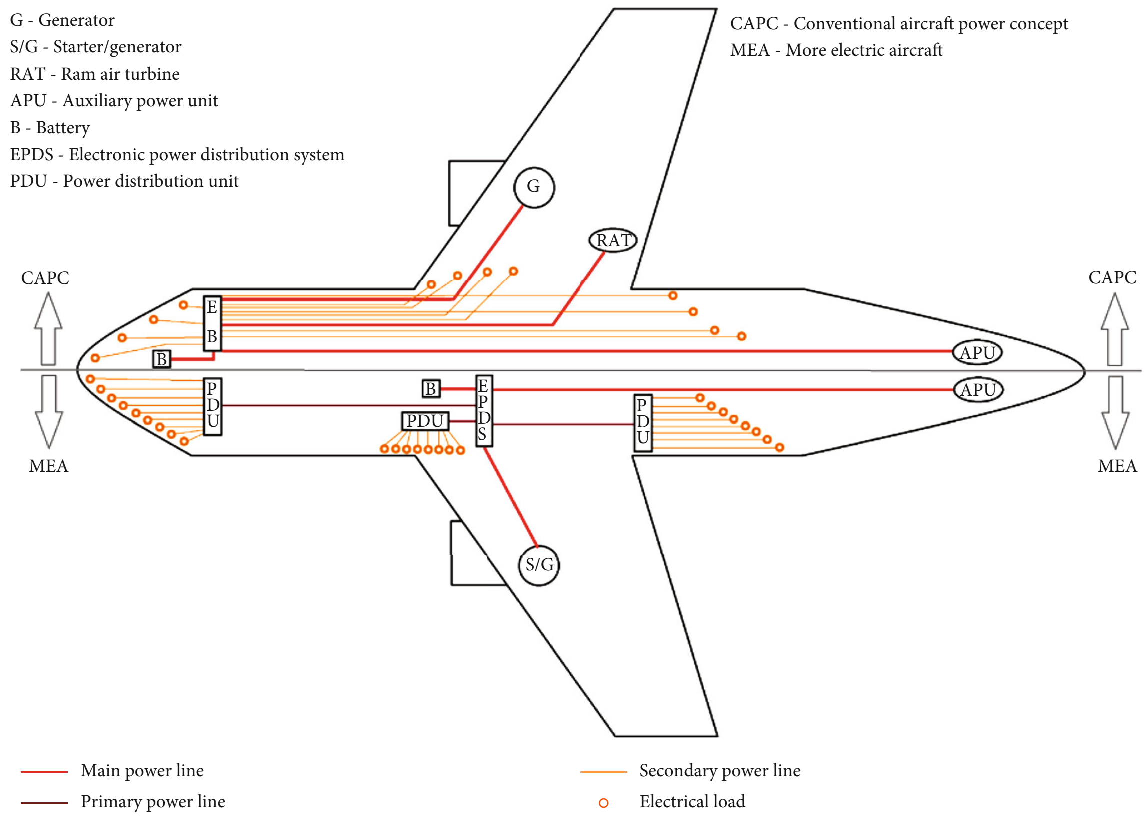



Figure 4: The comparison of centralised (top portion) and decentralised (bottom portion) distribution system.

The concept of integrated S/G has been defined as one of the key technologies for More Electric Engine (MEE) since the early 1990s. The integration of S/G within the engine enables to eliminate the gearbox. However, the problem with the generator position sensor occurs, which must operate within the harsh environment. In [127], the sensorless integrated S/G is proposed. Many various S/Gs are being studied for aerospace applications (Figure 5); these are permanent magnet synchronous machines (PMSMs) [128–131], induction machines (IMs) [132–135], switched reluctance machines (SRMs) [136–143], and wound rotor synchronous machine (WRSM) [94, 144–147].

WRSMs are widely used in CAPC as AC generators; however, due to the digital control of power converters, they can find its application in MEA as S/G with high power density, high reliability, and simple maintenance features [147]. Additionally, high power factor at wide speed range, reduced voltage transients, and improved electrical safety is the advantages of WRSM [144]. On the other hand, complicated control schemes, complex starting control, and running speed limit are considered as disadvantages [145].

IMs are very often used in industry. They are reliable, require low maintenance, and they have a low cost of construction. IMs are suitable for operation in harsh environment, they can withstand very high temperatures [148]. They can be easily controlled to operate in a wide speed range. Their drawback is low torque value during starting mode, low power factor, and the power decrease during high-speed operation [149].

Permanent magnet synchronous machines have gained popularity with the emergence of stronger magnetic materials in recent years. PMSMs are highly efficient and have high power density since there is no active component in the rotor. On the other hand, they require a supplementary protection system for safety, and if power electronic components fails, high terminal voltage could appear [150]. They have complex control strategies for magnetic flux control, and there is a risk of demagnetization of magnets [151].

SRM has superior fault tolerance for operation in a harsh environment, easy and low-cost maintenance, and has high start-up torque and inherent overcurrent protection [139, 141]. However, the control of SRMs is quite complicated. They have also low efficiency, around 80%, and high voltage ripples in generator mode [142].

*4.2. Flight Control Surfaces.* The hydraulics is still the main power source used for the operation of flight controls on both, MEA and CAPC. The main aircraft control surfaces and their power supplies are presented in Figure 6. Usually, two flaps on each wing are operated hydraulically and electrical power is used as a backup. The same principle is used for spoilers, elevators, and rudders. However, hydraulic systems have many disadvantages [152]:

(i) The use of flammable and not environmentally friendly hydraulic fluid

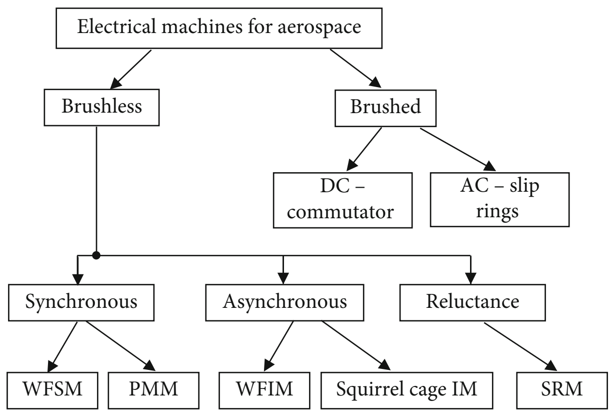



Figure 5: Electrical machines for aerospace applications.

(ii) The leakage of hydraulic fluid results in the loss of actuation power

(iii) The need to maintain the full system pressure (3000 psi to 5000 psi), also when the system is not used

(iv) The hydraulic system is bulky and requires costly maintenance

To eliminate these disadvantages, the flight controls in MEA will be operated electrically [153]. The electrification process can be seen in Figure 5 at the horizontal stabilizer, which is operated solely by electric power. The electrical machines to be used must operate as reliably as conventional systems with an overall fault probability of $10^{-9}$ [154]. Considering these working conditions, PMSMs with the high power density and high efficiency can be implemented here as electromechanical actuator (EMA) [153].

## 5. Electric Steering and Taxiing Systems

Another component that is hydraulically operated in today's aircraft is the nose wheel steering system. A steering mechanism is used to enable the plane to turn to the right or left during taxiing. In MEA, the steering mechanism will be electrically driven.

Linear actuators that use three-phase axial flux permanent magnet machines are potential candidates to operate the steering mechanism [155–157], as they provide high torque at low speed, and they are very compact [157]. An electric steering system can be preferably used with electric taxiing, so during the taxiing, only electric power can be used.

Another system to be implemented in MEA is the electric taxiing system (ETS). ETS enables the aircraft to move from an airport platform to the runway entirely with electric power, without the use of main engines. This will be achieved by electrical machines powered by fuel cells integrated in the landing gear.

Electric taxiing will provide fuel savings and a decrease of noise and air pollution, normally caused by the engines [158]. At Heathrow airport in 2002, it was estimated that 56% of the NOx were from taxi operations [159]. It is estimated that the global family of short-haul aircraft burns around five million tons of fuel per year during taxiing [160]. ETS will save up to 2/3 of what airlines currently spend on fuel for taxi operations [160]. There will be also time savings because the use of tractors for push-back is not necessary.

There are two methods of ETS which are under inspection—on-board and external taxiing. External ETS uses an external source of electricity—electric tug tractors. Current research and tests are focused on on-board ETS which can be installed on the nose wheel or main landing gear. The advantage of on-board ETS is that the aircraft can be fully autonomous on each airfield. However, if there is a requirement for short-radius turning, the ETS on nose wheel has restricted ability [161].

There are several types of drive units considered for ETS, i.e., IM, PMSM, and PM brushless DC motors [162]. When ETS is integrated in the main landing gear, the issue of increased temperatures has to be solved. PMSMs are not stable with temperature. Moreover, high back-EMF values could be a problem when using PMSMs what leads to winding failure [158].

*5.1. High-Temperature Superconductor Machines.* The AEA is an aircraft with electric propulsion, in which all nonpropulsive powers are entirely electric. Conventional electric motors do not provide sufficient power density to be used for electric propulsion on large aircraft [120]. The implementation of superconducting materials in electrical drives was not realisable, due to the requirement of very low temperatures, reaching only several Kelvins.

With the discovery of high-temperature superconductors in 1986 [163, 164], the work in the field of electric propulsion gained speed. Many HTS engine designs and tests have been performed [165–170]. The advantages of HTS motors are low weight, compact size, very high power densities, and negligible DC loss; however, AC loss of HTS winding must be minimised [168]. For that purpose, HTS rotor and stator windings, instead of conventional copper windings, are used [169].

Two cooling methods are proposed for HTS machines, the cryocooler ,and cryogenic liquid. Cryocoolers are designed mostly for ground operations. Their efficiency is lower than 10% [165]. Cryogenic liquids can be used in open-loop or close-loop systems. The close-loop systems are heavier, so their application is rather convenient for large aircraft. Contrary, the open-loop system is lighter and needs only cryogenic liquid, so it can be applied also to small aircraft [169]. In [170], hydrogen at 20 K is proposed as the cooling liquid for HTS generator with effective power 10 MW, power density $20\,kW\,kg^{-1}$, line voltage 3 kV, and coils' current density $300\,A\,mm^{-2}$.

*5.2. Fuel Cells for M/AEA Aircraft.* The AEAs rely entirely on electrical power. Present technologies, in general, do not enable aircraft to use only electric motors for propulsion, due to the limitations of power sources. Typical energy densities of today's lithium-ion batteries are 100-265 Wh/kg depending on whether the battery is optimized for peak power or long life [171]. Such energy densities are sufficient only for small aircraft with a restricted range of flight.

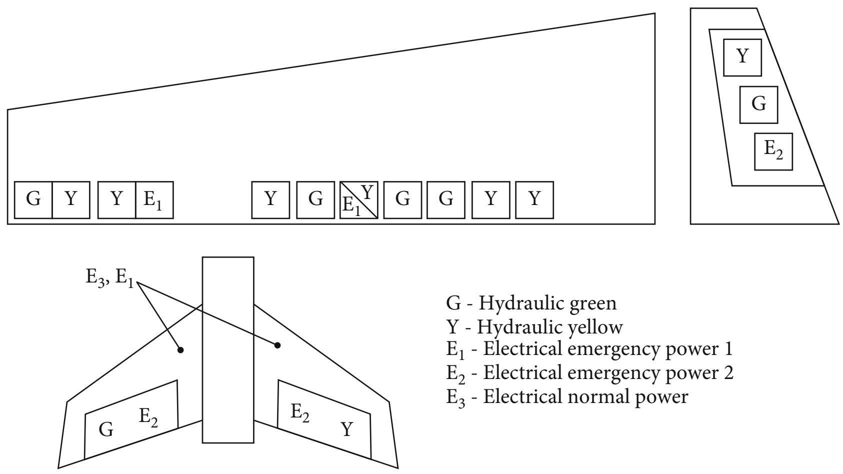



Figure 6: Aircraft main control surfaces.

According to many studies, the battery energy density for long-haul AEA has to be at least 500 Wh/kg [172, 173]. Such an energy density can be achieved by lithium-sulphur batteries with a theoretical limit of 2700 Wh/kg [173].

Another approach to on-board electric power sources is the use of FCs based on the chemical reactions of hydrogen and oxygen. There are several tests of FCs suitable for aviation [174]; these are solid-oxide FC and proton exchange membrane FC. At first, the use of FCs is meant as a replacement for APU's jet engine. Such a solution can be combined with electric taxiing. Another goal of FC is to supply energy for propulsion to enhance the overall efficiency of the propulsion system. Such a combination of jet engine and electric motor for propulsion is termed as hybrid-electric aircraft.

The product of FC is not only electrical energy but also heat, water, and air depleted of oxygen, which can be further utilized on-board the aircraft [175]. The efficiency of the current FC is around 50%, while the efficiency of APU is after many years of improvement not more than 20% [176].

The current drawback of using FC on-board the aircraft is its heavier weight and volume compared to the traditional system, mainly due to the storage problems of hydrogen. There are three possibilities of how to store hydrogen. The first one is to use compressed gaseous hydrogen; however, this solution is very bulky. The second solution is to use cryo-compressed hydrogen, and the third possibility is to use liquid hydrogen (LH2). LH2 must be stored within cryogenic temperature (at most 33 K) in spherical-shaped tanks, which are very impractical compared to traditional fuel tanks. The volume of LH2 is four times bigger than the volume of kerosene at the same energy content; however, its weight is 2.8 times smaller [177].

*5.3. Energy Harvesting in Aviation.* The AEA will be acceptable only if they can fly for long distances; therefore, the weight of the aircraft should be kept as low as possible. The low weight and complex aircraft structure will require constant structural health monitoring (SHM). The traditional SHM uses sensors supplied from the primary cells and the signal is supplied to the computer by wire. In this regard, the wireless sensor network (WSN) for SHM is proposed [178, 179]. The power levels of these sensors are in the range of 10-50 MW, depending on the data rate [180]. These sensors will harvest energy from the environment. There are proposed several energy harvesting (EH) methods for aeronautical applications, i.e., the usage of thermal gradients, solar radiation, vibration, and airflow. The transducers such as photovoltaic generators, thermoelectric generators, electromagnetic, piezoelectric and triboelectric converters, and radio frequency transducers are used. Experiments on the integration of piezoelectric EH elements into the carbon-fiber composite structure are performed to eliminate the major drawback of piezoelectric element—brittleness [181]. In [182], the EH concept for treating electrostatic energy produced by flying composite aircrafts is proposed. Static charges can be collected with capacitive collectors. Energy harvesting is especially preferable for UAVs [182]. In [183, 184], a wireless communication system with EH to transfer information from UAV to ground is proposed. Another research on EH is aimed at prolonging the UAV flight time by dynamic soaring [185] or the use of solar power [186].

## 6. Conclusions

Current aircraft are very complex. They use hydraulic, pneumatic, mechanical, and electrical systems to handle extreme operational conditions. However, the use of four different powers on-board the aircraft results in their bigger overall weight and complexity. This has a negative impact on fuel consumption and maintenance cost/time. Therefore, there is long-term effort to use only one, the most effective power system—electrical system. The use of electrical power is a more efficient way to supply loads than the extraction of the engine's bleed air (pneumatic power). Bleed-less architecture is supposed to extract 35% less power from the engine [187].

As a result, a lot of studies on M/AEA have been performed. The key component of aircraft electrification is the use of high power density electrical machines (generators, motors, and converters) and a new type of "intelligent" power distribution system with digitally controlled electronic circuit breakers.

Regarding the environment, there is a big effort to reduce the emissions produced by aircraft. This can be achieved by replacing the traditional engines, combusting fuel based on hydrocarbons, by propulsion with electric motors—AEA. However, this concept is still not feasible for midsize and large-size aircraft due to the restricted capacity of electrical power sources, but is vital for small private and general aviation aircraft. By the time the power sources for AEA would be improved, the concept of HEA is a promising idea. The fuel saving of 20–30% is expected by 2035, within the short-medium range HEA [188].

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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