Effective Pathway to High-Performance More-Electric Aircraft

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Abstract. The current battery and power system technologies are adequate for electric cars but still not mature enough to be implemented in commercial electric aircraft. This research aims to provide an overview of potential solutions for the electrification of the major systems of conventional aircraft, which includes advancements in the efficiency of the energy systems and reduction in greenhouse gas (GHG) emissions. The background of the evolution of electric aircraft is given in the beginning. The challenges faced by engineers in electrifying the current commercial airliners are introduced and analyzed. Efforts are given to provide an outlook of the current progress of development of this field along with the key technologies applied by current more-electric aircraft (MEA). Finally, several promising future trends in the development of MEA are discussed.

Keywords: More-electric aircraft, the energy system, Electro-Hydrostatic Actuator, PMAC motor.

1. Introduction

The global ecosystem is undergoing significant changes, and for this reason, our habits need to shift as well if we want to find a solution. Developing electric aircraft is crucial, as Narrow-body aircraft are responsible for around 43% of aviation's greenhouse gas emissions. In contrast, wide-body aircraft like the Airbus 380 are responsible for approximately 33% of greenhouse gas emissions due to aviation. In 2018, aviation greenhouse gas emissions accounted for approximately 2.4% of the total greenhouse gas emissions in the US [1]. Aside from that, there is another reason: operating costs. Aircraft have high operational costs, making them a costly means of transportation for just a few people. An Airbus A380 costs about 305,735 Dollars for a 14-hour journey, and about 244,534 is only for fuel. However, electric planes have a low operational cost owing to reduced maintenance costs. They also employ renewable power sources, which are less expensive than jet fuel.

Since passenger air traffic has climbed at a 9% annual pace since the 1960s, this situation has become even more catastrophic [2]. This implies that we need to shift toward modes of transportation that are greener and more energy-efficient. Higher energy efficiencies, reduced GHG emissions, and less noise for airplanes have become crucial challenges that must be handled now because of the impacts on the life quality and even the long-term survival of our future generations. These issues must be addressed because the modern world has become more dangerous. In order to accomplish these goals, people have been concentrating on the concept of MEAs or airplanes, each of which derives its whole energy supply and powertrain from electrical energy. The improvement of this knowledge is a shared goal by all human societies.

An electric propulsion system has the potential to produce zero emissions in the immediate area. These systems also benefit from increased efficiencies in the way that they convert energy. How the electricity is generated is the primary issue that must be answered to determine whether this is a more environmentally friendly technology or an alternative one. Electric airplanes have an edge in emissions in nations where the primary energy source for manufacturing is made up of renewable resources. On the other hand, if an electric aircraft's batteries are charged using energy generated by a coal power plant, the electric aircraft would have a greater total emission rate than a gasoline-powered aircraft. The proportion of a country's total electrical energy that comes from renewable sources is shown in Figure 1. This number may be found in certain nations. Electric cars are considered more environmentally friendly than conventional automobiles in the nations represented by the green bar in this figure.

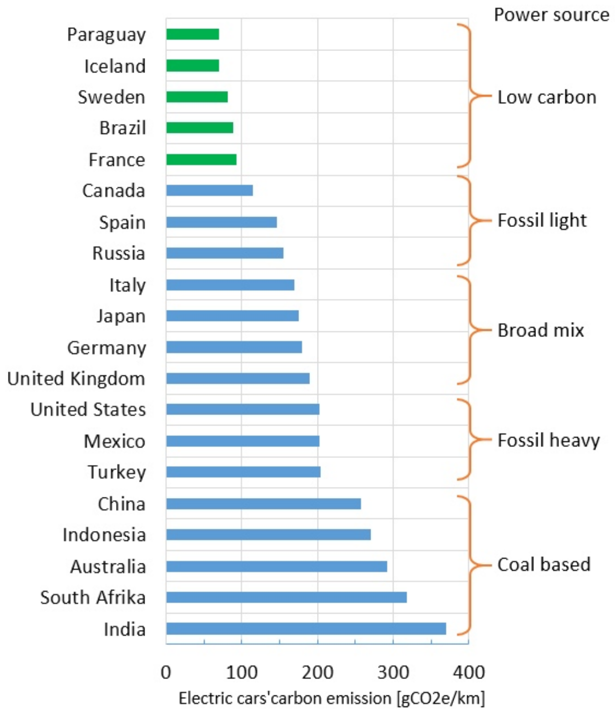

Figure 1. Diagram of total CO_2 emissions of electric vehicles [3]

Compared to its deployment in the aviation industry, incorporating electric propulsion systems into land transport is less complicated. Because the mass of land vehicles is not nearly as important as that of aerial aircraft, adding battery mass will result in fewer complications. In addition, aerial vehicles have a substantially larger journey distance, which means they need to store significantly more energy. Additionally, the criteria for aerial safety are exceedingly strict, which makes it more difficult to integrate electronic or hybrid propulsion systems. This paper is intended to provide an overview of the key challenges, current technologies and future trends in developing more-electric aircraft (MEA) and all-electric aircraft (AEA).

2. Development History of Electric Aircraft

The technology behind electric flight is not fresh. The bulk of the airplane was the sole obstacle, and it was not conceivable for a long period. Fred Militky became the earliest to employ electric motors to fly airplane prototypes in 1940. However, he could not succeed due to the motors' weight and the lead batteries he used. He never stopped believing in the potential of his concept, and in 1960, he finally brought a scale model of an aircraft to market. In this type, there was a limited amount of lead batteries and an electric motor that was quite efficient. In 1972, when Ni-Cd batteries with greater power densities were available on the market, he finally made the first radio-controlled model that was successful enough to be sold commercially [4]. After that, he began his work on developing the first manned aircraft capable of flying only on electric power. On October 21, 1973, the first manned-aircraft flight was accomplished by Heino Brditschka. The aircraft was an adapted form of the HB-3, a power glider, and it flew over 300 meters from the airfield ground in Wels, which was located near Linz. Brditschka and Fred Militky were the 2 brains responsible for making the fantasy of flying with an electrical motor a reality [5]. Because there were not enough advanced battery systems available, further development of this was hampered. However, continuous development is being made in this area, eventually leading to more environmentally friendly aviation industry.

Recent aviation history was created by an electric aircraft at a large airstrip surrounded by countryside in central Washington State in 2020. The largest commercial aircraft to ever take off and operate entirely on electricity. It was a Cessna Caravan 208B that had been adapted to carry up to nine people. Additionally, the test aircraft was solely equipped with a pilot's seat. It is a long way from the 200- to 300-seater jet, much alone the enormous double-decker aircraft that fly across countries. But the test flight for the "eCaravan" was a success. AeroTEC and magniX are supporting it. The chief executive of magniX, Roei Ganzarski, noted that the Cessna costs only $6 (£4.80) to fly. The cost of the 30-minute trip would have been $300–400 (£240–320) if they had used standard engine gasoline [6].

3. Main Challenges of Electric Aviation

Since we know the advantages electric aircraft have over gasoline-powered ones, the issue is what obstacles stand in the way of electric air transport. The limited specific energy of batteries is the most difficult obstacle to overcome. The specific energy of jet fuel is around 12,000Wh/kg, while the specific energy of commercially available lithium-ion batteries at the cell level is approximately 250Wh/kg. Jet fuel is used in jet engines. In most cases, the specific energy of the pack is around 20% lower. This considers the weight penalty associated with thermal-runaway confinement and other protective measures [7]. The low specific energy leads to two issues. First, electric aircraft require much greater weight to achieve the same performance as conventional aircraft. Second, electric aircraft have a very limited range in one charge with the same fuel mass. The two obstacles discussed above are the most significant, or we might even claim that there are no obstacles, in the area of electric aircraft. Even though there are quite a few more problems, the ones listed above are the only repercussions we have to face due to these two obstacles.

3.1. Greater Weight of the Whole Aircraft

Schafer and co-authors analyzed whether or not it would be possible to scale up these designs and recognized the potential advantages to the environment and the economy [8]. They evaluated the battery's particular energy needs because weight is one of the most important factors in air travel. The specific energy of a battery indicates how much energy it can store relative to its weight. This measurement considers both the weight of the individual cells as well as the packing material that surrounds them. They determined that the minimum specific energy needed for a battery pack for an airplane the size of an Airbus A320 or Boeing 737, capable of flying missions of 600 nautical miles, was 800Wh/kg based on a comparison of the weight factor and the efficiency of propulsion systems between jet engines and electric motors. This demand is four to five times more than the specific energy of the most advanced battery packs currently available. Even with chemistries beyond Li-ion, such as the most modern Li-S and $Li\text{-}O_2$ batteries, the exact energy demand will not be reached.

3.2. Limited Range in One Charge

Because of its low energy density, an electric aircraft can only fly for a certain distance before it has to be recharged again. The IFB-Stuttgart E-Genius is an electric aircraft with 2 seats that established a new record in 2013 by flying around 400 kilometers on a single charge. Electric airplanes lag substantially behind our traditional aircraft in terms of distance traveled. And distance is among the most important aspects determining the transportation mode used.

3.3. Other Challenges

Schafer stated that silicon anodes, high voltage cathodes, and lithium metal are among the commercial battery technologies available today but are not yet able to meet the battery-specific energy demand. As a result, advancements in motors and power electronics are also required in parallel to make a practical commercial all-electric aircraft design. Furthermore, the profitability of all-electric airplanes is contingent on the frequency with which costly battery packs need to be replaced. This frequency is directly proportional to the average lifetime of Li-ion batteries. Energy fade is a factor that may be used to estimate the lifetime of the batteries that power electric vehicles. This phenomenon describes the gradual loss of around 20% of the total energy stored in a battery pack. The second concern is power fade, which occurs when the battery releases energy less effectively. This might lower the amount of power that is available for take-off. It is still uncertain whether the power fade or the energy fade will be the factor that determines when airplane batteries have reached their end of life.

4. MEA Technologies

It is common knowledge that typical airplanes have two sources of energy: the primary source, which consists of the aircraft's propellers, and the secondary sources, which include electric, hydraulic, and pneumatic systems driven by the primary source. MEA focuses on replacing secondary energy sources with electrical systems.

4.1. Electric Power System

In order to mix the energy produced by several generators operating at various frequencies and output voltages, power circuits must connect the generator and the distributor network. Low input current distortions to reduce waste, high power supply component to reduce reactive needs, transformer separation for security, a reduction in the proportion of current to the ground point, and minimal size and weight to increase mobility and power intensity are just a few of the characteristics that power electronic converters must have in order to be used in aircraft. [9].

The generating machine is linked to the major engine with a mechanical drive in the conventional design for constant voltage and frequency. This maintains the speed of the mechanical system. Therefore, the electrical frequency is steady on the aircraft. As a result of the fact that the primary engine starts, integrated environmental system, de-icing, and hydraulics in this aircraft do not need electrical energy, the ratio of necessary power output to the engine is lower than in most modern aircraft are more electric [10]. Constant voltage and changing frequency buses have become the more traditional constant voltage and constant frequency buses in recently developed aircraft such as the Boeing 787, the Airbus A380, and the Airbus A350. In this case, the bus frequency fluctuates proportionately to engine velocity depending on the engine and aircraft design. The frequency may range anywhere from 360 to 800 Hz. Even though the voltage is controlled to 110 or 225 Vac, the bus frequency does alter. This shift in perspective necessitates power conversion for several loads and motor drives; hence, electrical converters are required to convert electricity from alternating current to direct current and the other way around. For many systems, like battery chargers, DC-to-DC power conversion is also required.

The ability to produce and transfer electricity effectively close to where it is utilized is a further benefit of the shift to MEA. According to the conventional aircraft concept, all of the power is produced near the primary engines on the wings and near the APU in the back before being sent to the front for control and protection. This conventional design, known as a centralized power system distribution, is seen in the first picture of Figure 2. The newly designed power controllers and switching devices with enhanced connectivity provide the option of doing away with this network arrangement in favor of distant distribution in a more electric paradigm. Due to the shorter distances between generating and consumption, line losses are reduced, increasing the effectiveness of the distribution network. Furthermore, by lowering the power rating of the primary conductors, considerable weight and volume reductions may be achieved. These weight reductions and equipment rating cuts help the aircraft fly more efficiently while also costing less overall since the lower-rated components may be available at a cheaper price. The distributed energy system architecture also reduces maintenance expenses. The second picture in Figure 2 depicts the Boeing 787 as an illustration of this contemporary network design [10].

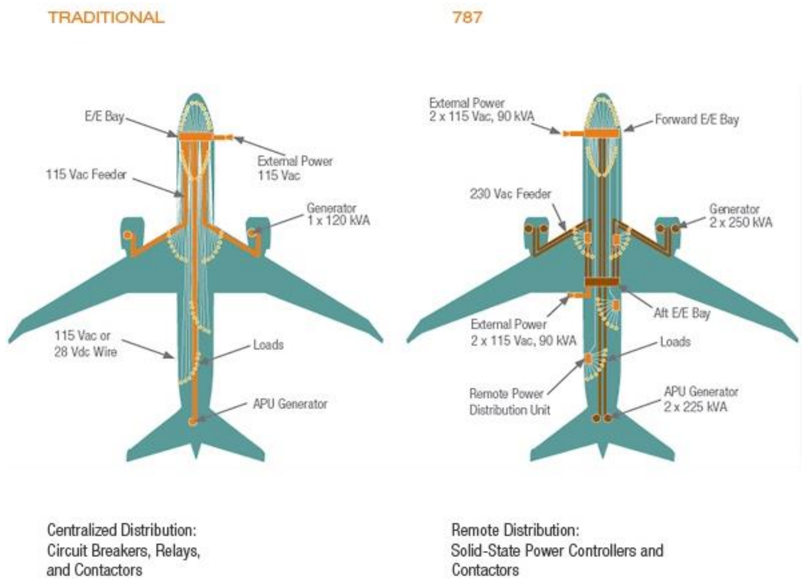

Figure 2. The Boeing 787 solution to the more-electric power system [11]

4.2. Electrifying the Hydraulic Systems

Traditional airplanes employ hydraulic systems for braking, landing gear, primary and secondary surface controls, and many other crucial operations. Actuators with mechanical drives are necessary for these hydraulic systems.

The use of an electro-mechanical actuator (EMA), as seen in Figure 3, is the logical solution for displacing hydraulic actuators using electrically driven actuators [12]. An EMA system allows simple motor control to operate an aircraft control surface. The ball screw is often moved via a reduction gearbox when the motor rotates. Due to the direct coupling between the motor and ball screw, the actuator is moved by a defined amount with each motor rotation. However, it has proven to be quite challenging to ensure that the ball screw would never be stuck when employing EMAs for main controlling purposes on massive aircraft. In the present design of airplanes, a jam in an actuator for essential control of flights would be problematic since the system would not be controlled unless a benign failure mechanism is ensured. As every other actuator within the same controlling surface will be unable to operate when one actuator is stuck, a ball-screw jam is not a benign failure.

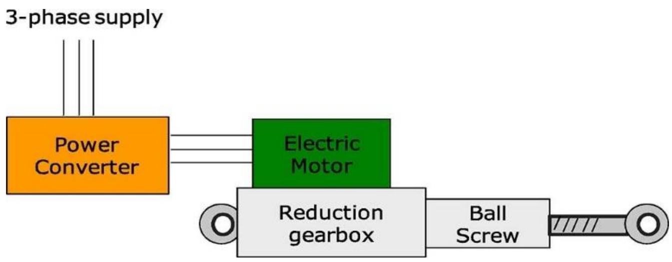

Figure 3. Diagram for an EMA [12]

The Electro-Hydrostatic Actuator (EHA), which features a component powered by local hydraulics and is operated by a fixed displacement pump powered by a motor, is an alternative to the EMA. As shown in Figure 4, the actuator placement shifts by a set displacement for each motor rotation. The EHA has a benign failure mechanism since there is no mechanical contact between the motor and actuator arm, which gives the system a considerable benefit over EMAs for main combat control applications.

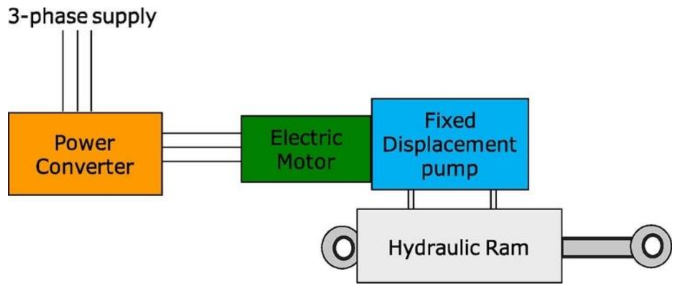

Figure 4. Diagram for an EHA [12]

4.3. Electric Motors

In aircraft applications, very strict dependability and power intensity are placed on the electrical device. Electrical motors are critical in any electrical drivetrain, and aerospace applications impose these requirements on the electrical machine. Electrical machines using brushes or commutators are not considered due to their high maintenance needs, insufficient torque density, and unreliability. Therefore, as illustrated in Figure 5, the list of practical candidate machines is restricted to induction, reluctance, and PM motors [13].

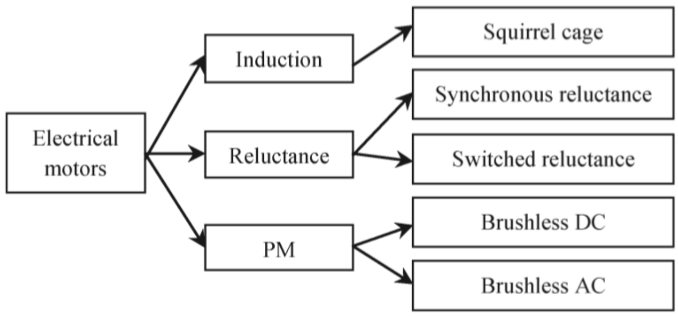

Figure 5. Candidate motors for MEA drive systems [13]

4.3.1 Induction Motors

Because of their ease of use, affordability, durability, and dependability, squirrel-cage induction motors find widespread use in industrial settings [14]. However, separating the motor into magnetically separated modules would be almost difficult due to mutual interaction between all phases and the rotor.

4.3.2 Reluctance Motors

The rotor construction of the reluctance motor is strong, devoid of PMs or windings, and able to handle high thermal or mechanical pressures. It has become the perfect device for low-cost applications as a consequence. Rotor saliency is created in synchronous reluctance motors by prominent poles or by installing flux barriers that channel the magnetic flux along the axis. Due to the absence of rotor joule loss, the motor is more efficient than induction motors as long as the rotor is operating at synchronous velocity and no electromotive force is generated in the rotor. Stator windings are dispersed around the air gap in a sinusoidal pattern, much like induction motors, which results in significant phase coupling and restricts the use of the device in airplanes owing to its low fault tolerance. However, the switching reluctance motor (SRM) has now been widely used in direct drive applications. It is currently beginning to find employment in aerospace prototypes due to its inherent fault tolerance capabilities.

4.3.3 PMAC Motors

PMAC motors, in general, may be used to refer to any brushless AC synchronous permanent magnet motor. PMAC motors are less fault-tolerant, although it is generally acknowledged that they provide better torque density than the previous motors. Due to the persistence of the magnet-induced back electromotive force in standard PM machine designs, currents may continue to flow in a failing lane long after the lane has been cut off from the electrical supply. They may, however, withstand such a flaw with the careful optimization method and are often the best option [15]. To summarize, enhanced PMAC motors have the potential to provide the smallest answer to actuation needs; nevertheless, the management of defects in these motors is much more complicated than that in switching reluctance (SR) devices.

5. Future trends in the development of MEA

5.1. Wide Bandgap Devices

Power and voltage ranges might vary depending on the application. MEAs should employ the semiconductor that provides optimal performance in this voltage and power range at a switching frequency. Silicon-based components have hit their natural limit regarding high switching frequency and power. Aviation places much emphasis on component power densities. Passive devices may be made lighter by using semiconductors with high switching frequencies. Given their physical characteristics, materials like SiC and GaN provide a wider operating range. Figure 6 depicts the various power levels concerning their normal switching frequency range and semiconductor employed [16].

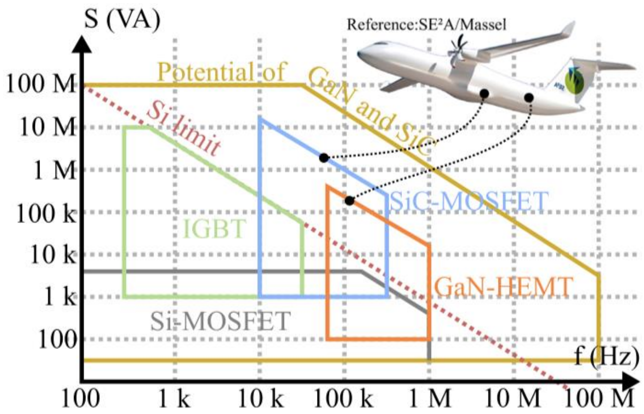

Figure 6. Power levels vs. Switching frequencies diagram [16]

5.2. Electric Taxi

The best method for reducing the number of engines used on the ground is to utilize an electric taxi. One of the most modern ways of powering airplanes is electric taxi technology. As long as an aircraft departs from the gate, it utilizes engine power to navigate the airport runways, which is unwanted since main engines burn a lot of fuel and produce a lot of emissions [17]. To address this issue, electronic motors should be installed on the major gears and front wheels so that the plane may taxi without starting its engine before take-off. The airplane can obtain an electric taxi towards the terminal after landing by turning off the engines and using electric motors. A motor, power electronic converters, control systems, cockpit connectors, and auxiliary power units are required. It would be necessary to condition power from the APU for the traction motor using converters [18]; the process is called e-taxi. This developing subsystem has the potential to reduce fuel consumption, minimize emissions, and improve operational flexibility.

5.3. Fuel Cell System

Fuel cells are more efficient and quieter than diesel or gas engines, with much lower hazardous gas emissions. Although the idea for fuel cells was first put out in the 1800s, it was not until the late 20th century that research on the subject took off. Since then, fuel cells have been considered the best option for lightweight energy storage applications. Fuel cells are enticing energy options for MEA since they are lightweight and have no hazardous emissions. Even though they have been tested in smaller aircraft, further study and technical advancement are still required before fuel cells are used as the primary power source in commercial aircraft. The application of fuel cells for specific purposes in passenger airliners is now being investigated. In MEA, fuel cells are increasingly being used to supplement the present APU supply. This would increase the aircraft's efficiency while still meeting energy requirements by reducing the dimensions and mass of the APUs. Future APUs will be completely replaced by fuel cell technology or hybrid systems [19].

6. Conclusion

A detailed review of the current and future technologies is provided in this paper, in the case of large commercial airliners. The history of the electric aircraft, including the first scale model of the electric aircraft by Fred Militky, is briefly given. The idea of restricted specific energy of the Li-ion battery being the origin of the obstacles to the electrification of traditional aircraft is deliberated. The two main problems extended from this are the heavier aircraft and the reduced one-charge range, which are put forward. The electric aircraft's profitability and battery power fade are also mentioned. The three main technologies including the power system with constant voltage changing frequency adopted by modern MEA along with the new energy system distribution, the electrification of the on-board hydraulic system by Electro-Mechanical Actuator (EMA) and Electro-Hydrostatic Actuator (EHA), and the three motor technologies which are induction motor, reluctance motor and PMAC motor are discussed and examined.

In conclusion, the advanced power system has advantages like the improvement of efficiency and reduction in weight, dimensions and cost. The EHA is the better hydraulic system alternative as it ensures a benign failure mechanism. The PMAC motor is the best choice among the three due to its higher torque density. Lastly, for the future trends in achieving high-performance MEAs, the wide bandgap devices, the electric taxing technologies and the fuel cell system are reviewed. The field of electric aircraft is still developing with considerable progress every year, and the future ahead is approaching.

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